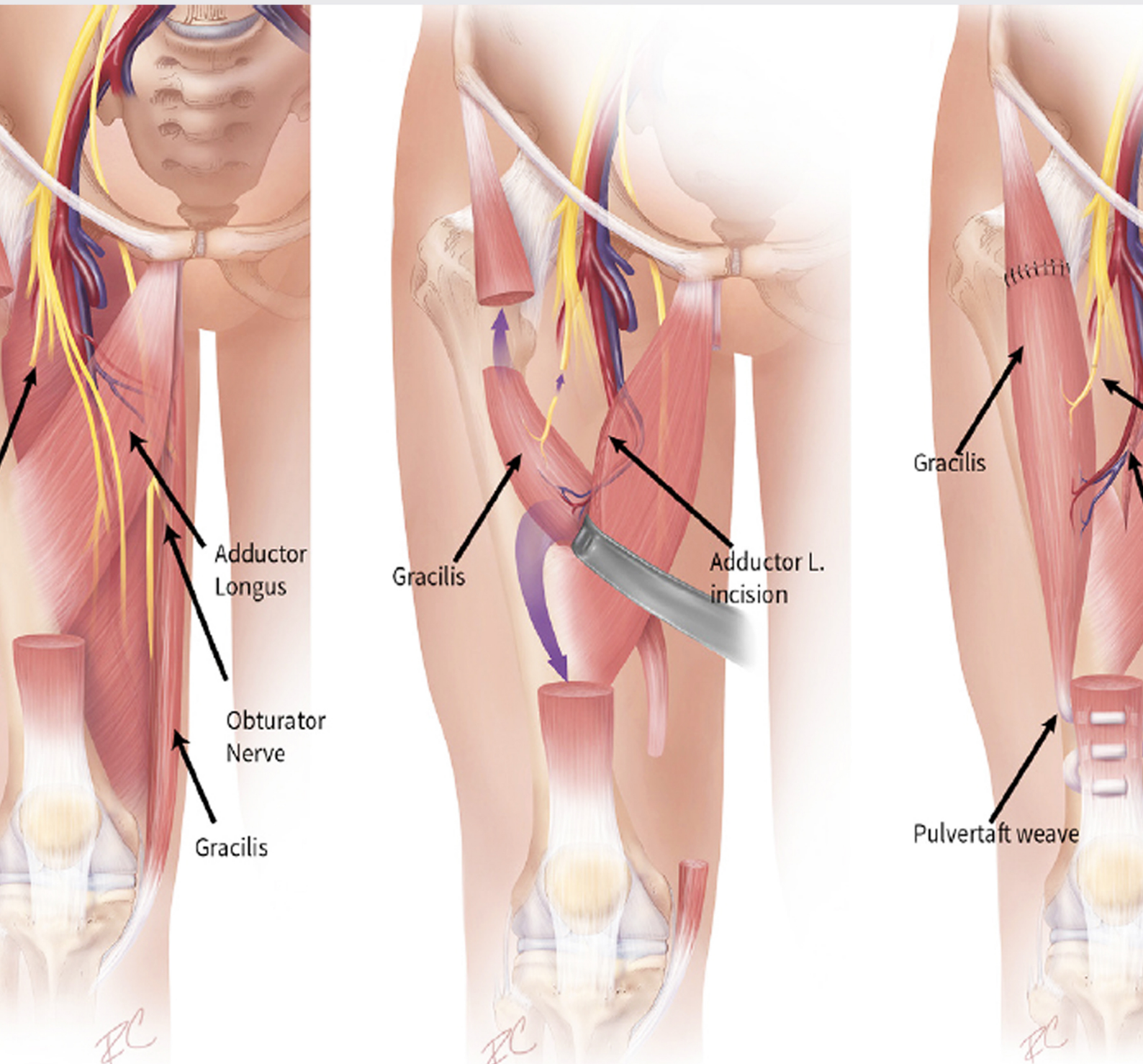


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Original Article

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The role of plastic surgeons in extremity reconstruction following mass casualty incidents

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Abstract

Aim: Mass casualty incidents (MCIs) are a devastating source of morbidity and mortality, testing the infrastructure of acute care management and challenging the ability to reconstruct limbs. Herein, we look to further a discussion on upper and lower limb reconstruction following MCIs.

Methods: Review of the literature, including our institute's experience with the 2013 Boston Marathon Bombings, the 2015-2016 Terror Attacks in Ankara, and the 2010 earthquake in Haiti, pertaining to extremity reconstruction following MCIs.

Results: The three aforementioned case profiles highlight extremity wounds associated with MCIs and the subsequent reconstructive role of plastic surgeons. Surgical intervention or temporization of extremity wounds is a critical responsibility of plastic surgeons in this setting. Limb salvage is possible and often the preferred option following disasters.

Conclusion: Intentional or naturally occurring MCIs are a grim reality. Successful response to these events requires prompt mobilization of emergency medical staff and hospital activation. Plastic surgeons play a paramount role in multidisciplinary management of trauma with a particularly important involvement in limb reconstruction.

Keywords: Upper extremity reconstruction, lower extremity reconstruction, mass casualty incidents, microsurgery



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INTRODUCTION

Initiated intentionally or as a result of natural disaster, mass casualty incidents (MCIs) continue to pose a significant challenge for emergency medical resources and multidisciplinary trauma teams. From earthquakes to landslides, geographical disasters frequently highlight multi-national relief efforts in resource constrained environments. In an era of domestic and international terrorism, deliberate episodes of mass violence utilizing explosives and firearms have disturbed the core of social intimacy and tested the resilience of regional care centers. Of particular concern in MCIs are crush and blast injuries to the upper and lower extremities, etiologies of which are rooted in the diversity of disaster types.

Specifically, the polytrauma associated with explosions results from a primary high-pressure blast wave and secondary discharge of fragmented projectiles causing injuries ranging from soft tissue loss to complete traumatic amputation^[1,2]. In a clinical review of conflict and terrorist related trauma, Dussault *et al.*^[2] found that on average, 54% of blast injuries affect the extremities. Similarly, a review by Clover *et al.*^[3] concluded that 60% of earthquake injuries are thought to localize to extremities, with 8%-13% associated with significant open fractures. The broad mechanisms of injury and bodily involvement seen within MCIs suggests an indispensable role for plastic surgeons in multidisciplinary teams comprised of colleagues from various specialties including orthopedic and trauma surgery^[4]. As disasters become unfortunately more unexceptional, plastic surgeons need to prepare for and respond to civilian MCIs.

With the evolution of extremity reconstruction from skin grafts to local tissue rearrangements and microvascular free flap transfer, painstaking decisions regarding limb salvage efforts in MCIs must be determined by plastic surgeons. This concept is further influenced by resource constraints particular to the region where a disaster occurs. The purpose of this study is to highlight the various means of upper and lower limb reconstruction following MCIs.

METHODS

A review of the literature was performed using the following MEDLINE search terms: ("Limb Salvage"[Mesh] OR Extremity Reconstruct*[tiab] OR "Surgery, Plastic"[MeSH] OR "Trauma Surgery"[Tiab] OR "Orthoplastic"[tiab]) AND (Mass Casualty[tiab] OR Terrorism[tiab] OR Earthquake[tiab] OR Blast Injur*[tiab] OR Explosion[tiab] OR Triage[tiab]). Titles and abstracts were screened for relevance. The initial search was limited to English-only articles and constrained to the past 30 years. Citations of assessed manuscripts were screened for applicable articles.

RESULTS

Three events including our institution's experience with the 2013 Boston Marathon Bombing, the 2015-2016 Ankara Terrorist Attacks, and the 2010 Earthquake in Haiti were specifically chosen to highlight extremity wounds associated with MCIs and the subsequent reconstructive role of plastic surgeons.

Boston bombing

On 15 Apr 2013, two pressure cooker bombs exploded along the route of the 117th Boston Marathon. The ground-level positioning and shrapnel components of the explosives lead to significant extremity trauma^[5]. In total, 66% of admitted patients had lower extremity soft tissue and/or bony injuries^[6].

Our institution received 24 patients, 11 of whom were cared for by the plastic surgery service. All 11 patients had lower extremity injuries, while 4 had concomitant upper extremity injuries^[7]. Wounds were grossly contaminated by foreign bodies, foreign tissue, and weaponized debris deliberately intended to inflict secondary damage on patients. Three patients required lower extremity flap reconstruction in the acute to subacute setting.

The first patient presented with an open left fibula fracture, left medial and right posterior calf wounds, and a left thigh wound. After debridement and washout, the fibula fracture was reduced, and tissue reconstruction was performed with a local soleus muscle flap^[7]. A second patient presented with a partial left lower extremity traumatic amputation, an open right tibia/fibula fracture, and several leg and buttock wounds. A completion left below-the-knee amputation and several washouts with debridement were necessary. After external fixation and negative pressure wound therapy, a free latissimus dorsi muscle flap and split thickness skin graft were used for right lower extremity reconstruction^[7]. The third patient presented with an open left tibia/fibula fracture and non-viable left foot. Completion amputation and negative pressure wound therapy followed by revision amputation were performed. A local gastrocnemius flap with split thickness skin grafting was required for closure of the complex amputation defect^[7].

At our affiliate hospital, 13 patients required emergent surgery. Among those patients, 72 procedures would be completed, of which a remarkable 37% were performed by plastic surgery^[8]. Moreover, nearly 50% of these emergent surgery patients required free flaps for limb salvage^[8]. Among all receiving hospitals, 54 patients underwent emergent surgery and 12 patients underwent definitive amputation for control of life-threatening hemorrhage and/or severe, unsalvageable extremity wounds^[6].

2015-2016 terror attacks in Ankara, Turkey

In a period of one year the capital city of Turkey, Ankara, was struck by two major terrorist attacks. On 10 Oct 2015, a suicide bomber detonated an explosive in Ankara's central railway station. This was followed on 13 Mar 2016 by a car bomb detonated during rush hour at Kızılay Square-Güvenpark. In total, there were 434 casualties, 178 of whom would receive care at Ankara Numune Training and Research Hospital, a tertiary health and trauma center within Ankara^[9].

Of the casualties received, 28% sustained an upper extremity injury and 50% sustained a lower extremity injury^[9]. A retrospective review was conducted on 34 victims who required surgical treatment by the plastic surgery service at Ankara Numune Hospital^[9]. Of note, patients treated in the emergency department for minor injuries and small primary closures were not included in this review. In total, one patient required thumb replantation while an additional eight patients had hand surgery for phalynx fractures, flexor tendon repairs, and peripheral nerve injuries. One presenting patient required a local trapezius muscle flap for a shoulder soft tissue defect. Another required a free radial forearm fasciocutaneous flap for soft tissue trauma to the medial foot. Lastly, a third patient presented with a Gustilo IIIB fracture requiring a free anterolateral thigh fasciocutaneous flap for coverage of exposed tibia. Partial flap necrosis occurred, prompting salvage treatment by means of a cross-leg flap^[9].

Importantly, the authors highlight that the lack of plastic surgeons in their hospital trauma advisory council and their delayed consultation following the incidents were barriers to providing services. Although no amputations were reported in their cohort, the surgeons note that amputations were performed prior to consultation.

2010 earthquake in Haiti

On January 12, 2010, a 7.0-magnitude earthquake struck the nation of Haiti. In an already resource constrained nation, the humanitarian crisis which followed was of mass proportion. Part of the relief experience was captured by a responding British orthoplastic envoy^[10]. Similar to experiences documented from a 7.4-magnitude earthquake in Turkey^[11], the predominant injury received by the surgical team were extremity crush injuries^[10].

In total, 348 operations were performed by the orthoplastic limb salvage team on 158 patients. The 73% of procedures were of soft-tissue origin and performed by plastic surgeons, while 18% of procedures were of

Table 1. Indications for amputation vs. limb salvage following mass casualty incidents

Amputation	Limb salvage
Life-threatening hemorrhage or refractory hypotension	Minimal-to-no distal sensation, peripheral nerve disruption ^[13]
Warm lower limb and upper limb ischemia for > 6 or > 8 h, respectively ^[49]	Stable distal extremity vascular assessment
Severe partial traumatic amputation and/or multi-level soft tissue, osseous, and vascular defects ^[31,49]	Limited access to prosthesis centers or limited potential for rehabilitation in the patient (i.e., access or functional capacity) ^[50]
Resource and infrastructure constraints	Viable, non-injured donor sites for tissue transfer

Uniformly: patient preference, age, and comorbidities should be considered

bony and soft-tissue origin necessitating joint orthoplastic involvement^[10]. The most frequently performed procedures included wound dressing changes, surgical debridements, and split thickness skin grafts. Notably, 10% of patients received pedicled flaps for local reconstruction and coverage of exposed bone, as free flaps were technically impossible within the field hospital^[10]. Ultimately, there were six amputations in this series, three below-the-knee, one above-the-knee, and two digital amputations. Of these amputations, only two were in cases of failed limb salvage^[10].

DISCUSSION

The aforementioned case profiles highlight the significant reality that MCIs are an ever-possible occurrence in our society. Of particular concern is the high prevalence of extremity wounds following disasters such as earthquakes or bombings^[2,3]. Subsequent decisions regarding limb salvage in this setting are complex and are impaired by resource availability [Table 1].

Following resuscitation, early assessment of distal neurovascular stability is critical to appraise the utility of reconstruction [Figure 1]. Vascular assessment and doppler ultrasound interrogation should be performed prior to considering CT-angiography. As evidenced by reports from French terror attacks, peripheral nerve injuries are common in MCIs^[12], however they do not definitively preclude reconstruction. Data from the Lower Extremity Assessment Project (LEAP) challenged historical beliefs that a lack of plantar sensation is an indicator for amputation. The authors found that those with insensate lower limbs who underwent reconstruction had proportionally similar plantar sensation on testing at two years when compared to those who had intact plantar sensation prior to reconstruction^[13]. Adding complexity to the situation, delayed access to patients at the location of disasters interrupts transport and evaluation and lengthens ischemia time, thereby increasing risk of compartment syndrome and rates of amputation^[6,14].

As our case profiles depict, amputation in the setting of MCIs should be reserved for those with life threatening hemorrhage and severe wounds beyond that of conceivable reconstruction. Further complicating decisions of mangled extremity limb salvage, a prospective study from the LEAP found that no single extremity trauma scoring system can effectively guide amputation decisions^[15]. The limiting factors for salvage in the described MCIs were patient stability, wound severity, and resource availability. Life-saving amputations must be made definitively, however, as noted at the Bégin Military Teaching Hospital following terror attacks in Paris, stable amputations should always involve discussion with the patient^[16].

The utility and quality of life following amputation is subject to significant debate when compared to reconstruction. A large prospective series by Bosse *et al.*^[17] identified similar self-reported functional outcomes at two years between those who underwent amputation or lower extremity reconstruction. Comparatively, a 2008 systematic review reported that the mean percentage of patients returning to work was higher in those who received amputation compared to reconstruction^[18]. More recently, cost-utility analyses of lower extremity trauma found that amputation was significantly more expensive^[19], and yielded slightly less quality-adjusted life years^[19], when compared to reconstruction.

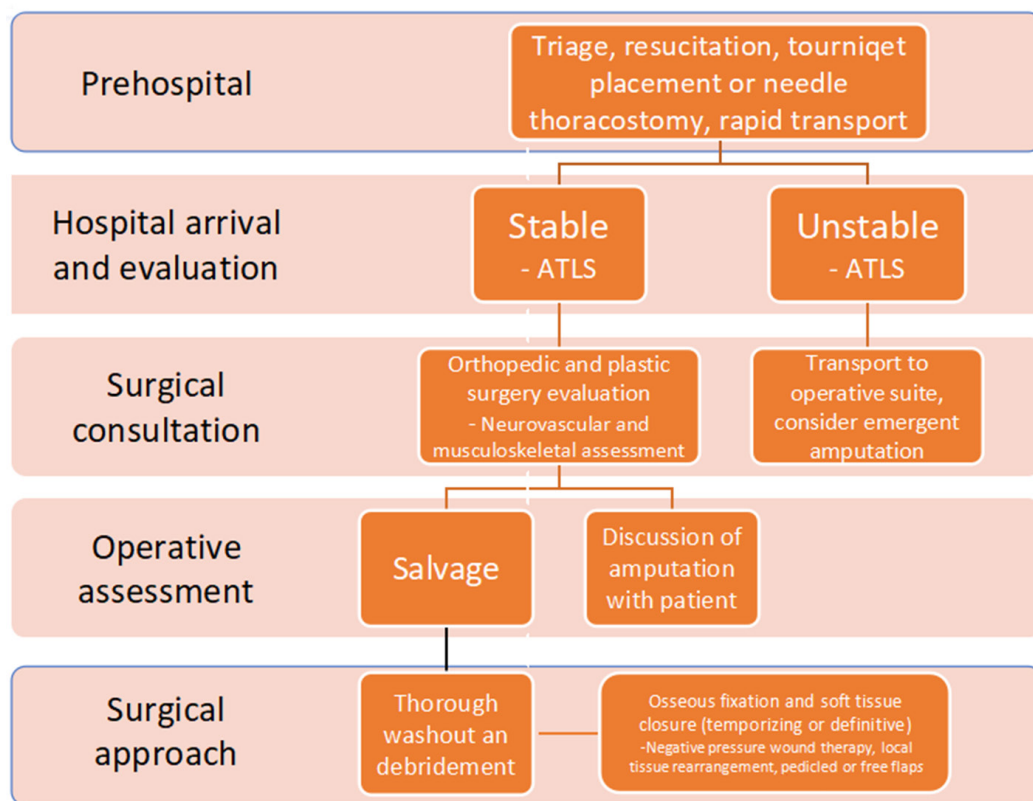


Figure 1. Approaches to triage and patient management following mass casualty incidents. ATLS: advanced trauma life support

The discussion is considerably more germane in resource constrained regions where rehabilitation services and prosthetics are extremely costly and often unavailable. A review on land mine induced lower extremity injuries in developing countries highlights poor post-amputation outcomes associated with a significant inability to access rehabilitation, return to work, and provide for families^[20]. With post-earthquake amputation rates around 6%^[21], deployment of salvage teams helps curtail such significant societal losses.

This guides conversation towards the importance of limb salvage. Ideal extremity trauma reconstruction aims to obtain soft-tissue coverage, restore appropriate form, and maintain or improve function^[22]. In the acute to subacute setting of MCIs, the feasibility of reconstruction is challenged. As numerous patients present with contamination and injuries to several body zones, a balance between otherwise reliable local tissue rearrangements and their complex free flap alternatives must be achieved.

Following the Boston Bombings, our institution utilized both local and free flaps for extremity reconstruction. Playing a fundamental role in early soft tissue closure, local flaps are associated with shorter procedure times, reduced complexity, and are of similar tissue quality and color to that of the recipient site^[23]. Based on a pedicle, local flaps offer considerable adaptability with tailored thinning and a rotational advantage. Moreover, as depicted from experience following the 2015 Earthquake in Haiti, local flap coverage can be performed in field hospitals lacking the infrastructure necessary for free flap microsurgery^[10]. With a significant influx of patients, the use of local flaps effectively allows for durable soft tissue coverage in the acute to subacute period providing an equitable distribution of services to patients.

With the high incidence of hand injuries following MCIs, there is particular utility in local reconstructive flaps including V-Y advancement flaps for dorsal fingertip reconstruction, the dorsal metacarpal artery flap for thumb reconstruction, and cross-finger transposition flaps^[24]. Local forearm and elbow reconstruction

can be performed with a pedicled radial forearm flap (RFF) or lateral arm flap (LAF). Supplied by a long vascular pedicle from the anterograde radial artery or retrograde palmar arch, the adipofascial to fasciocutaneous RFF is considerably resourceful. With traumatic elbow injuries often exposing bone, tendon, or neurovasculature, the RFF and LAF can effectively resurface the thin yet tenacious native tissue^[25]. Although the latissimus dorsi muscle flap (LDF) is a more sizeable regional alternative for elbow reconstruction, Choudry *et al.*^[25] showed increased rates of flap failure when pedicled LDFs were compared to pedicled RFFs or local fasciocutaneous flaps for elbow reconstruction. Moreover, RFFs and LAFs can be harvested as composites, with radial or humeral bone grafts and/or tendon for complex defects. Sacrifice of the radial artery in RFFs must be considered, however there appears to be minimal patient-reported hand function impairment, independent of donor site closure strategy^[26]. In proximal arm and shoulder trauma, local tissue advancements and scapular or parascapular flaps are readily applied. A trapezius flap was utilized to reconstruct a shoulder defect following the Ankara bombings^[9]. As a pedicle supplied by the dorsal scapular artery, this approach has minimal reported donor site morbidity^[27]. Based on the thoracodorsal artery, the pedicled LDF provides a well vascularized muscle to fasciocutaneous flap employed for proximal upper extremity and axillary soft tissue defects^[28,29]. The use of functional, pedicled LDFs have been described to restore upper arm strength and function following reconstruction with considerable success^[28,30]. This said, a systematic review assessing donor site morbidity highlighted several publications which report symptomatic shoulder strength limitations following latissimus dorsi transfer, partly reduced by muscle sparing and perforator based approaches^[29].

With regard to lower extremity reconstruction, conventional practice suggests use of gastrocnemius and soleus flaps for coverage of injuries at the proximal and middle thirds of the leg, respectively^[31]. The complication rates of these local flaps are often cited as minimal; however, studies have identified a quantifiable decrease in donor limb strength following reconstruction^[32]. Representative claims of such nature are often challenging to quantify as the untried alternative is recipient limb amputation. Subsequently, in our series, a soleus muscle flap was employed for tissue closure while another patient required a gastrocnemius muscle flap for amputation site closure without complication^[7]. Additional local flaps, such as the innervated sural flap and reverse hemisoleus flap, have been described for reconstruction of the distal third of the leg and foot with good functional outcomes^[23,33,34]. These distally oriented flaps are potential alternatives to free flap tissue transfer in resource constrained locations. Still, they are technically demanding local flaps - a victim of the November 2015 France terror attacks ultimately required secondary amputation after failure of a pedicled sural flap utilized for posterior ankle reconstruction^[16]. A review by Follmar *et al.*^[35] found that distally oriented sural flaps had complication rates of 50%-59%, with relatively high rates of venous congestion. Sugg *et al.*^[33] retrospectively identified similar complication rates, but prevented venous congestion by widening the flap pedicle. In contrast to the leg and foot, significant bulk and musculature of the thigh affords exceptional flexibility for local tissue rearrangements if not direct primary closure. Supported by the medial and lateral femoral circumflex arteries, the thigh provides reliable vasculature for local flaps and is an ideal donor site for free flap transfer.

Unfortunately, local flaps become less utile as traumatic wounds become more complex, involve composite defects, and occur more distally [Table 2]. In these situations, free flap transfer is preferred^[31]. The robust anterolateral thigh flap (ALT) and previously described LDF and RFF serve as versatile approaches to upper and lower extremity reconstruction. Used in the Boston Bombings and Ankara Terrorist Attacks, these workhorse free flaps are dependable for large or distal defects seen after explosions or natural disasters. As a testament to their utility, several series on extremity free flap reconstruction have reported flap failure rates < 10% with few cases requiring secondary amputation^[36,37]. Liberated from their pedicles, the LDF and RFF combine previously described advantages and limited donor site morbidity with a freedom of recipient site location and orientation. Notably, the ALT provides a tailored thickness fasciocutaneous or

Table 2. Advantages and limitations of local and free flaps for extremity reconstruction

	Local flaps	Free flaps
Advantages	<p>Reduced procedure time and less technically demanding^[23]</p> <p>Donor tissue is similar in characteristic to that of the recipient site^[23]</p> <p>Pedicle provides a reliable, durable, and native blood supply</p> <p>Can be performed under local anesthesia or conscious sedation</p>	<p>Superior diversity for donor and recipient site combinations</p> <p>Covering large, tridimensional soft tissue defects</p> <p>Greater capacity for harvesting as composite or chimeric grafts</p> <p>Preferred option in distal lower extremity reconstruction^[31]</p>
Limitations	<p>Range of transfer is limited by pedicle length</p> <p>Extremity trauma may impact nearby tissue and preclude or limit local rearrangements</p> <p>Less utile in composite tissue defects</p>	<p>Requires infrastructure and equipment to support microvascular surgery</p> <p>Higher risk of complication due to reliance on non-native microvascular anastomosis</p> <p>Greater need for post-operative monitoring</p>

musculocutaneous flap supplied by perforators of the descending branch of the lateral circumflex femoral artery. Its reliable dissection pattern affords a long pedicle, large tissue paddle, and minimal donor site morbidity, all of which are ideal for upper or lower limb reconstruction^[24,38,39]. Thinning to 2-4 mm has safely been reported^[39,40]. Further advantages of the ALT include an ability for innervation via the lateral femoral cutaneous nerve, offering improved recipient-site sensation, and options to co-harvest with the fascia lata for tendon reconstruction^[38,39]. Moreover, in severe extremity trauma with noted recipient vessel damage, multidisciplinary teams of plastic and vascular surgeons can facilitate free flap techniques with concurrent arterial reconstructions, vascular bypass, or arteriovenous-loop formation^[41].

Current debate regarding the efficacy and outcomes of fasciocutaneous vs. muscle flaps for traumatic reconstruction is controversial. Conventional belief has assigned superiority to muscle flaps, particularly in large, tridimensional extremity defects with exposed bone and high risk of infection^[42]. Recently, Stranix *et al.*^[43] reported a 40-year retrospective series in which fasciocutaneous flaps had statistically significant increased take-back rates but superior salvage rates compared to muscle flaps, owed largely to the cutaneous clinical monitoring of fasciocutaneous flaps. A retrospective series on traumatic upper and lower limb reconstruction in wounded warriors demonstrated no statistically significant differences in overall complication rate or days to ambulation among patients treated with muscle or fasciocutaneous flaps, but found that muscle flaps had statistically significant increased rates of flap failure^[44]. However, a recent multicenter analysis reported comparable limb salvage rates of 90% and 88%-94% when muscle or fasciocutaneous flaps, respectively, were employed for lower extremity trauma reconstruction^[45].

There is considerable discussion regarding the appropriate timing of extremity reconstruction following trauma. Historically, advocates have suggested soft tissue coverage of extremity defects within 24-72 h of the initial trauma^[46]. A more contemporary systematic review of upper extremity reconstruction found no statistically significant association between reconstruction timing and flap complications including infection, bony nonunion, and flap loss^[22]. However, lending support for the original works of Marko Godina^[46], an in-press systematic review of lower extremity reconstruction concluded that rates of flap loss and infection were lower in those who received soft tissue reconstruction within 72 h^[47]. In our experience with the Boston bombings, flap reconstruction was performed in the acute to subacute time period. This is not always feasible, and experience from the 2015 Earthquake in Haiti demonstrated that negative pressure wound therapy was an invaluable adjunct to temporize and protect wounds until reconstructive specialists arrived and offered definitive tissue closure in the subacute period^[48].

In conclusion, we must acknowledge that the heterogenous nature of extremity wounds following MCIs remains a unique challenge for reconstructive surgeons. With the lack of high quality randomized prospective trials; clinical expertise, available resources, and patient presentation will continue to guide reconstructive decision making.

DECLARATIONS

Authors' contributions

Conception and design, acquisition of data, or analysis and interpretation of data, approved the final version to be published, and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved: Crystal DT, Ibrahim AMS, Lin SJ

Drafted the article: Crystal DT

Revised the article critically for important intellectual content: Ibrahim AMS, Lin SJ

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Consent for publication

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REFERENCES

1. Peleg K, Aharonson-Daniel L, Michael M, Shapira SC; The Israel Trauma Group. Patterns of injury in hospitalized terrorist victims. *Am J Emerg Med* 2003;21:258-62.
2. Dussault MC, Smith M, Osseltun D. Blast injury and the human skeleton: an important emerging aspect of conflict-related trauma. *J Forensic Sci* 2014;59:606-12.
3. Clover AJ, Jemec B, Redmond AD. The extent of soft tissue and musculoskeletal injuries after earthquakes; describing a role for reconstructive surgeons in an emergency response. *World J Surg* 2014;38:2543-50.
4. Thakar HJ, Pepe PE, Rohrich RJ. The role of the plastic surgeon in disaster relief. *Plast Reconstr Surg* 2009;124:975-81.
5. Kolata G, Longman J, Pilon M. Doctors saved lives, if not legs, in Boston. *The New York Times* April 16, 2013. Retrieved August 28, 2015. Available from: <http://www.nytimes.com/2013/04/17/us/physical-legacy-of-bomb-blasts-could-be-cruel-for-boston-marathon-victims.html>. [Last accessed on 14 Jan 2019]
6. Gates JD, Arabian S, Biddinger P, Blansfield J, Burke P, et al. The initial response to the Boston marathon bombing. *Ann Surg* 2014;260:960-6.
7. Kim PS, Malin E, Kirkham JC, Helliwell LA, Ibrahim AM, et al. The Boston marathon bombings: the early plastic surgery experience of one Boston hospital. *Plast Reconstr Surg* 2013;132:1351-63.
8. Caterson EJ, Carty MJ, Weaver MJ, Holt EF. Boston bombings: a surgical view of lessons learned from combat casualty care and the applicability to Boston's terrorist attack. *J Craniofac Surg* 2013;24:1061-7.
9. İğde M, Kaplan A. Plastic surgery management of victims of terrorist violence in Ankara, Turkey. *Ann Plast Surg* 2017;79:600-5.
10. Clover AJ, Rannan-Eliya S, Saeed W, Buxton R, Majumder S, et al. Experience of an orthoplastic limb salvage team after the Haiti earthquake: analysis of caseload and early outcomes. *Plast Reconstr Surg* 2013;127:2373-80.
11. Wolf Y, Bar-Dayana Y, Mankuta D, Finestone A, Onn E, et al. An earthquake disaster in Turkey: assessment of the need for plastic surgery services in a crisis intervention field hospital. *Plast Reconstr Surg* 2001;107:163-8.
12. Gregory TM, Bihel T, Guigui P, Pierrart J, Bouyer B, et al. Terrorist attacks in Paris: surgical trauma experience in a referral center. *Injury* 2016;47:2122-6.
13. Bosse MJ, McCarthy ML, Jones AL, Webb LX, Sims SH, et al. The insensate foot following severe lower extremity trauma: an indication for amputation? *J Bone Joint Surg Am* 2005;87:2601-8.

14. Chunguang Z, Rigao C, Fuguo H, Chongqi T, Yueming S, et al. Characteristics of crush syndrome caused by prolonged limb compression longer than 24 h in the Sichuan earthquake. *Emerg Med J* 2010;27:627-30.
15. Bosse MJ, MacKenzie EJ, Kellam JF, Burgess AR, Webb LX, et al. A prospective evaluation of the clinical utility of the lower-extremity injury-severity scores. *J Bone Joint Surg Am* 2001;83-A:3-14.
16. Barbier O, Malgras B, Choufani C, Bouchard A, Ollat D, et al. Surgical support during the terrorist attacks in Paris, November 13, 2015: experience at Bégin military teaching hospital. *J Trauma Acute Care Surg* 2017;82:1122-8.
17. Bosse MJ, MacKenzie EJ, Kellam JF, Burgess AR, Webb LX, et al. An analysis of outcomes of reconstruction or amputation after leg-threatening injuries. *N Engl J Med* 2002;347:1924-31.
18. Saddawi-Konefka D, Kim HM, Chung KC. A systematic review of outcomes and complications of reconstruction and amputation for type IIIB and IIIC fractures of the tibia. *Plast Reconstr Surg* 2008;122:1796-805.
19. Chung KC, Saddawi-Konefka D, Haase SC, Kaul G. A cost-utility analysis of amputation versus salvage for Gustilo type IIIB and IIIC open tibial fractures. *Plast Reconstr Surg* 2009;124:1965-73.
20. Walsh NE, Walsh WS. Rehabilitation of landmine victims--the ultimate challenge. *Bull World Health Organ* 2003;81:665-70.
21. Yang C, Wang HY, Zhong HJ, Zhou L, Jiang DM, et al. The epidemiological analyses of trauma patients in Chongqing teaching hospitals following the Wenchuan earthquake. *Injury* 2009;40:488-92.
22. Harrison BL, Lakhiani C, Lee MR, Saint-Cyr M. Timing of traumatic upper extremity free flap reconstruction: a systematic review and progress report. *Plast Reconstr Surg* 2013;132:591-6.
23. Parrett BM, Talbot SG, Pribaz JJ, Lee BT. A review of local and regional flaps for distal leg reconstruction. *J Reconstr Microsurg* 2009;25:445-55.
24. Griffin M, Hindocha S, Malahias M, Saleh M, Juma A. Flap decisions and options in soft tissue coverage of the upper limb. *Open Orthop J* 2014;8:409-14.
25. Choudry UH, Moran SL, Li S, Khan S. Soft-tissue coverage of the elbow: an outcome analysis and reconstructive algorithm. *Plast Reconstr Surg* 2007;119:1852-7.
26. Ho T, Couch M, Carson K, Schimberg A, Manley K, et al. Radial forearm free flap donor site outcomes comparison by closure methods. *Otolaryngol Head Neck Surg* 2006;134:309-15.
27. Rasheed MZ, Tan BK, Tan KC. The extended lower trapezius flap for the reconstruction of shoulder tip defects. *Ann Plast Surg* 2009;63:184-7.
28. Pierce TD, Tomaino MM. Use of the pedicled latissimus muscle flap for upper-extremity reconstruction. *J Am Acad of Orthop Surg* 2000;8:324-31.
29. Lee KT, Mun GH. A systematic review of functional donor-site morbidity after latissimus dorsi muscle transfer. *Plast Reconstr Surg* 2014;134:303-14.
30. Sood A, Therattil PJ, Russo G, Lee ES. Functional latissimus dorsi transfer for upper-extremity reconstruction: a case report and review of the literature. *Eplasty* 2017;17:51-63.
31. Ong YS, Levin LS. Lower limb salvage in trauma. *Plast Reconstr Surg* 2010;125:582-8.
32. Kramers-de Quervain IA, Läufer JM, Käch K, Trentz O, Stüssi E. Functional donor-site morbidity during level and uphill gait after a gastrocnemius or soleus muscle-flap procedure. *J Bone and Joint Surg Am* 2001;83-A:239-46.
33. Sugg KB, Schaub TA, Concannon MJ, Cederna PS, Brown DL. The reverse superficial sural artery flap revisited for complex lower extremity and foot reconstruction. *Plast Reconstr Surg Glob Open* 2015;3:1-9.
34. Pu LL. Further experience with the medial hemisoleus muscle flap for soft-tissue coverage of a tibial wound in the distal third of the leg. *Plast Reconstr Surg* 2008;121:2024-8.
35. Follmar KE, Baccarani A, Baumeister SP, Levin LS, Erdmann D. The distally based sural flap. *Plast Reconstr Surg* 2007;119:58-62.
36. Yazar S, Lin CH, Lin YT, Ulusal AE, Wei FC. Outcome comparison between free muscle and free fasciocutaneous flaps for reconstruction of distal third and ankle traumatic open tibial fractures. *Plast Reconstr Surg* 2006;117:2468-75.
37. Derderian CA, Olivier WAM, Baux G, Levine J, Gurtner GC. Microvascular free-tissue transfer for traumatic defects of the upper extremity: a 25-year experience. *J Reconstr Microsurg* 2003;19:455-62.
38. Wang HT, Fletcher JW, Erdmann D, Levin LS. Use of the anterolateral thigh free flap for upper-extremity reconstruction. *J Hand Surg* 2005;30:859-64.
39. Yildirim S, Avci G, Aköz T. Soft-tissue reconstruction using a free anterolateral thigh flap: experience with 28 patients. *Ann Plast Surg* 2003;51:37-44.
40. Kimura N, Satoh K, Hasumi T, Ostuka T. Clinical application of the free thin anterolateral thigh flap in 31 consecutive patients. *Plast Reconstr Surg* 2001;108:1197-208.
41. Meyer A, Horch RE, Schoengart E, Beier JP, Taeger CD, et al. Results of combined vascular reconstruction by means of AV loops and free flap transfer in patients with soft tissue defects. *J Plast Reconstr Aesthet Surg* 2016;69:545-53.
42. Chan JK, Harry L, Williams G, Nanchahal J. Soft tissue reconstruction of open fractures of the lower limb: muscle versus fasciocutaneous flaps. *Plast Reconstr Surg* 2012;130:284-95e.
43. Stranix JT, Lee ZH, Jacoby A, Anzai L, Mirrer J, et al. Forty years of lower extremity take-backs: flap type influences salvage outcomes. *Plast Reconstr Surg* 2018;141:1282-7.
44. Sabino J, Polfer E, Tintle S, Jessie E, Fleming M, et al. A decade of conflict: flap coverage options and outcomes in traumatic war-related extremity reconstruction. *Plast Reconstr Surg* 2015;135:895-902.
45. Cho EH, Shammass RL, Carney MJ, Weissler JM, Bauder AR, et al. Muscle versus fasciocutaneous free flaps in lower extremity traumatic reconstruction: a multicenter outcomes analysis. *Plast Reconstr Surg* 2018;141:191-9.
46. Godina M. Early microsurgical reconstruction of complex trauma of the extremities. *Plast Reconstr Surg* 1986;78:285-92.
47. Qiu E, Kurlander DE, Ghaznavi AM. Godina revisited: a systematic review of traumatic lower extremity wound reconstruction timing. *J*

- Plast Surg Hand Surg 2018;1-6.
48. Gabriel A, Gialich S, Kirk J, Edwards S, Beck B, et al. The Haiti earthquake: the provision of wound care for mass casualties utilizing negative-pressure wound therapy. *Adv Skin Wound Care* 2011;24:456-62.
 49. Prasarn ML, Helfet DL, Kloen P. Management of the mangled extremity. *Strategies Trauma Limb Reconstr* 2012;7:57-66.
 50. Pinzur MS. Outcomes-oriented amputation surgery. *Plast Reconstr Surg* 2011;127:241-7S.

Review

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Use of homologous costal cartilage in rhinoplasty

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Abstract

This review specifically addresses the use of homologous costal cartilage in rhinoplasty with a particular focus on the related complications that can be encountered. It is important to stress that autologous cartilage is probably the preferred material for grafting in rhinoplasty. However, concerns of donor-site morbidity and extensive surgery have motivated the development and use of homologous costal cartilage. Because homologous costal cartilage is readily available, it has been widely used as an alternative to autologous costal cartilage when restoring nasal contour. Both favorable and unfavorable reports can be found in the literature, however, controversy still exists regarding the complications that can occur with using homologous cartilage as a graft material in rhinoplasty. Therefore, the aim of this review is to summarize the current understanding of the usefulness and the problems related with the use of homologous costal cartilage in rhinoplasty.

Keywords: Rhinoplasty, homologous cartilage, processed cartilage, irradiated cartilage, preserved cartilage

INTRODUCTION

In rhinoplasty, surgeons often need ample graft material for septal reconstruction, dorsal augmentation, and tip surgery. Autologous costal cartilage is a preferred source of graft material, especially in Asian patients, as it provides cartilage of enough quantity and quality^[1]. Theoretically, when it is needed, using autologous costal cartilage is the most ideal surgical strategy. However, autologous costal cartilage may be difficult



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to harvest and may be associated with significant donor site morbidity. Donor site complications such as pneumothorax, seroma, scar-related problems, intercostal neuralgia and intensive postoperative pain are deterring factors for the use of autologous costal cartilage. Increased surgical time can be another concern^[2].

In that context, although there can be is limited availability and increased cost for purchasing the graft, the use of homologous costal cartilage in rhinoplasty can be an attractive surgical option as it can avoid donor morbidity and additional operative time. Homologous costal cartilage is harvested from cadaveric donors and is processed in various ways. It has been shown to be useful in rhinoplasty. The tissue processing methods typically involve a high dose of ionizing radiation, osmotic destruction, freeze drying, and chemical sterilization- either alone or in combination- to eliminate the cellularity of the tissue and to sterilize the grafts^[3-7]. Numerous surgeons have reported their results of using homologous costal cartilage, treated with different processing methods in rhinoplasty. However, controversy still exists in the literature regarding the complications associated with the use of homologous cartilage as a grafting material in rhinoplasty. Therefore, in this paper, we aim to summarize current understanding of the usefulness and the problems related with the use of homologous costal cartilage in rhinoplasty.

REVIEW OF CASE SERIES

Published reports have mostly dealt with case series of homologous costal cartilage grafts that have been processed in different ways [Table 1]. Mühlbauer *et al.*^[8] reported their experience with the use of L-shaped homologous costal cartilage grafts for saddle nose correction that were preserved in merthiolate saline and stored at 4 °C. Thirty out of the 40 reported cases showed no sign of absorption, moderate absorption was seen in 8 cases and in 2 cases, where syphilis was the underlying pathology, the grafts almost totally disappeared. They believed that the calcification of homologous cartilage began approximately 1 year after insertion and, as time passed, the degree of calcification became more complete and contiguous.

Lefkovits^[9] published a retrospective study of 27 augmentation rhinoplasty cases using irradiated homologous costal cartilage (IHCC). The reported complications included infection in 7.4% (2 of 27) of cases, warping 14.8% (4 of 27), no resorption was seen. Clark and Cook^[10] studied the usefulness of IHCC in immediate reconstruction of extruded alloplastic nasal implants in 18 patients. They noted that resorption of IHCC was minimal with a mean follow-up of 26 months. There was only one case of warping that was reported and revised by another IHCC. Strauch and Wallach^[11] presented the results of 130 IHCC grafts. There were 2 cases of graft exposure (1.5%) of immediate complication. Four (3.1%) cases of late complication, including 1 case of fracture and 2 cases of displacement. There was partial resorption of one graft demonstrated at 6 months postoperatively. Kridel *et al.*^[12] published their experience with the long-term use of HICC in a large series of 357 patients. Among 357 patients, there were 83 primary cases and 274 revision cases. The mean follow-up period was 13.45 years. The overall complication was 3.25%, including 10 cases of warping (1.06%), 9 cases of infection (0.86%), 5 cases of non-infectious resorption (0.53%), 5 cases of infectious resorption (0.48%), 3 cases of mobility (0.31%) and there was no extrusion noted.

TutoplastTM processing is a specific method of tissue processing developed by TutoplastTM over forty years ago. The process includes, delipidization, osmotic treatment, oxidative treatment, solvent dehydration, double-sterile packaging, and terminal gamma irradiation (17.8-25.0 kGy). TutoplastTM-processed costal cartilage has very different characteristics than autologous costal cartilage because of its complex chemical process. Demirhan *et al.*^[13] reported their experience with TutoplastTM-processed homologous costal cartilage use in rhinoplasty in 65 patients, with a mean follow-up period of 33 months. There was no significant resorption detected in any of the cases. However, there were 4 cases (6%) of minor complications such as deformity of the dorsal graft, excessive graft length, and erythematous nasal tip. Song *et al.*^[14] studied the surgical outcome of rhinoplasty using TutoplastTM-processed costal cartilage. They reported a relatively high complications rate of 31%. These included 6 (17%) cases of partial resorption, 3 (9%) cases of warping, 1 (3%)

Table 1. A summary of study characteristics

References	Processing type	Complications	Follow-up period mean (range)
Mühlbauer <i>et al.</i> ^[8] , 1971 (n = 40)	Merthiolate	Absorption, 25% Warping, 2.5% Late infection, 0%	Mean, 6 years (range, 1 month-10 years)
Lefkovits ^[9] , 1990 (n = 24)	Irradiation	Absorption, 0% Warping, 14.8% Infection, 7.4%	(range, 1-27 months)
Clark and Cook ^[10] , 2002 (n = 18)	Irradiation	Warping, 5.6% Infection, 0% Extrusion, 0%	Mean, 26 months
Strauch and Wallach ^[11] , 2003 (n = 51)	Irradiation	Extrusion, 1.5% Displacement, 1.5% Absorption, 0.8% Fracture, 0.8% Infection, 0% Warping, 0%	(range, 7 months-12 years)
Song <i>et al.</i> ^[14] , 2008 (n = 35)	Tutoplast	Resorption, 17% Warping, 9% Visible contour, 3% Fracture, 3% Infection, 0%	Mean, 15.6 months (range, 9-35 months)
Kridel <i>et al.</i> ^[12] , 2009 (n = 357)	Irradiation	Warping, 1.06% Noninfection resorption, 0.53% Infection resorption, 0.48% Infection, 0.87% Mobility, 0.31% Extrusion, 0%	Mean, 13.45 years (range, 4 days-24 years)
Suh <i>et al.</i> ^[15] , 2013 (n = 30)	Tutoplast Allowash	Fracture, 6.7% Nasal obstruction, 3.3% Resorption, 0% Warping, 0% Extrusion, 0% Tip stiffness, 73.3%	Mean, 29 months

graft fracture and 1 (3%) visible graft contour [Figure 1]. Lohuis *et al.*^[15] used diced TutoplastTM homologous cartilage for dorsal augmentation. Their 9 patients showed no complications during the follow-up period of 20 months.

Homologous costal cartilage was mostly used for dorsal augmentation, but it can serve as a useful grafting material for septal reconstruction. Suh *et al.*^[16] reported their 2-year follow-up data in 30 cases on the use of irradiated homologous costal cartilage as a septal extension graft for the correction of the contracted nose in Asians. There were 2 cases of graft fracture observed. Three patients underwent revision rhinoplasty, one for nasal obstruction and 2 because of dissatisfaction with the shape of the nasal tip.

Our review of these case series indicates that TutoplastTM-processing methods have higher complication rate than IHCC^[14]. This observation has already been confirmed by a systematic review by Lee *et al.*^[17] As described in the literature, the use of homologous costal cartilage in rhinoplasty has yielded conflicting results regarding the rate of resorption and warping. Although it is difficult to directly compare the surgical outcomes of all the reports because of the differences in follow-up period and processing methods of the cartilage, the rate of complications including resorption, warping, fracture, and infection varies greatly between different studies. The factors responsible for increased graft resorption and warping are not clear, but they may include the size and site of the implant, the carving technique of the graft, the nature of the host recipient site, and thermal and mechanical damage caused during carving. The degree of warping may also depend on the amount of radiation to which the cartilage has been exposed^[18]. Although, Adams *et al.*^[19] showed that there was no significant difference in warping between irradiated and non-irradiated homologous cartilage *in vitro*, it is generally believed that the radiation dose has some impact on warping. Donald *et al.*^[18] postulated that the factor governing different absorption rates of IHCC from different studies might be the radiation dose. And the study reported that high-dose irradiation appears to

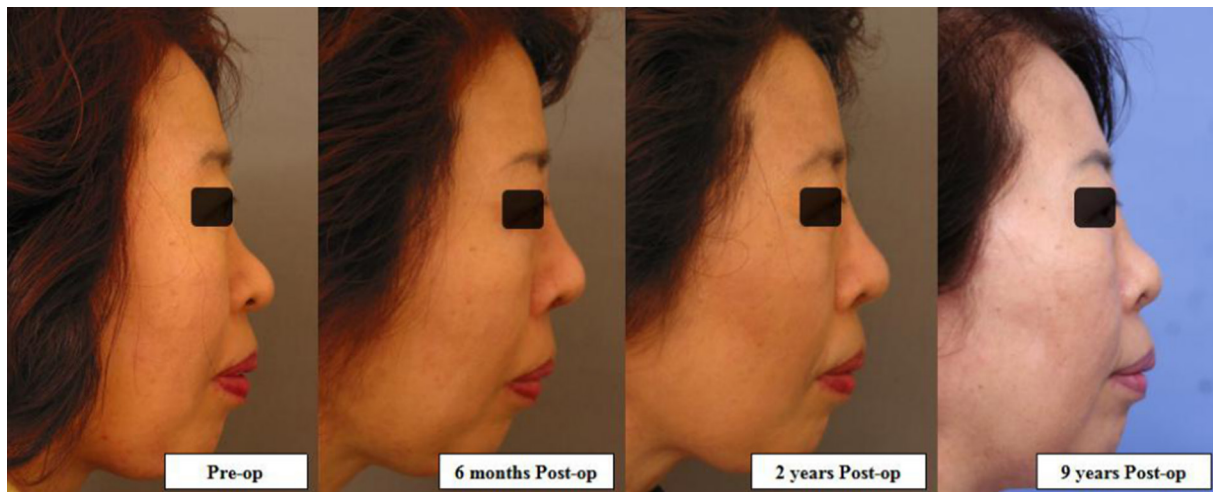


Figure 1. Surgical outcome of rhinoplasty using Tutoplast-processed costal cartilage

lessen greatly the stiffness of cartilage grafts and may be responsible for increasing absorption of the graft. Not only the tissue processing method, but also a consistent and meticulous way of tissue handling may be an important factor in reducing complication rates. Kridel and Sturm^[20] recommended that sterile handling, followed by a rinse with saline and antibiotics, removal of perichondrium, waiting 20 min after carving to allow time for initial warping, and the use of perioperative antibiotics are important elements to reduce complications.

The fate of implanted homologous cartilage has been studied. Suh *et al.*^[16] took biopsies of the irradiated cartilage grafts at 18 months and 5 years postoperatively from the study group were compared with preoperative IHCC samples and normal rib cartilage from other patients. They noted that the normal rib cartilage showed intact chondrocytes with extensive HLA-B expression, whereas the preoperative IHCC samples showed no visible normal chondrocytes despite well-maintained lacunar structures, and with much less HLA-B antigen expression. They also found the formation of the thin capsule-like tissue surrounding the IHCC.

It is noteworthy to mention that other than the commonly noted complications of homologous costal cartilage, the possibility of transmission of unknown viral or prion disease which is difficult to screen can be a potential concern when we consider the use of homologous costal cartilage in rhinoplasty. However, studies are lacking on this subject. Freeze drying is a different method of tissue processing, but there is a paucity of studies showing the performance of homologous costal cartilage processed with this particular technique.

CONCLUSION

Previous reports frequently indicate that homologous cartilage is often more easily absorbed than autologous cartilage, and the senior author has had a similar experience. Furthermore, since cartilage differs in physical characteristics based on tissue processing methods and the cadavers from which the cartilage is harvested are of different age groups, it is hard to expect a consistent quality of cartilage from this implant. The authors have abundant experience in rhinoplasty using TutoplastTM processed costal cartilage^[14]. According to the author's experience, this cartilage is generally useful for septal reconstruction or tip surgery. However, when used for the nasal dorsum, complications such as resorption, fracture, and deformation are somewhat frequent. Therefore, we came to the conclusion that it is not the optimal material to be used for dorsal grafting. However, this graft is still a useful alternative for patients that require ample graft material, where

the harvest of autologous costal cartilage is a problem. Patients who do not want a donor site scar and older patients that may have extensive ossification of costal cartilage can be ideal candidates for the use of homologous costal cartilage.

DECLARATIONS

Authors' contributions

Conception of the study and performed data analysis and interpretation, involved in drafting and revising the manuscript: Jang YJ

Performed data acquisition and drafting the manuscript: Zheng T

Availability of data and materials

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Both authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

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Not applicable.

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REFERENCES

1. Gunter JP, Cochran CS, Marin VP. Dorsal augmentation with autogenous rib cartilage. *Semin Plast Surg* 2008;22:74-89.
2. Varadharajan K, Sethukumar P, Anwar M, Patel K. Complications associated with the use of autologous costal cartilage in rhinoplasty: a systematic review. *Aesthet Surg J* 2015;35:644-52.
3. Rasi HB. The fate of preserved human cartilage. *Plast Reconstr Surg* 1959;24:24-33.
4. Dingman RO, Grabb WC. Costal cartilage homografts preserved by irradiation. *Plast Reconstr Surg* 1961;28:562-7.
5. O'Connor GB, Pierce GW. Refrigerated cartilage isografts. *Surg Gynecol Obstet* 1938;67:796-8.
6. Peer LA. *Transplantation of Tissues*. Vol 1. Baltimore, MD: William and Wilkins Co; 1955.
7. Asbury RB, Dingman R, Lynch JD. The effectiveness of sterilization of canine costal cartilage by cobalt60 irradiation and its fate when used in homografts. *Surg Forum* 1956;6:581-5.
8. Mühlbauer WD, Schmidt-Tintemann U, Glaser M. Long-term behaviour of preserved homologous rib cartilage in the correction of saddle nose deformity. *Br J Plast Surg* 1971;24:325-33.
9. Lefkovits G. Irradiated homologous costal cartilage for augmentation rhinoplasty. *Ann Plast Surg* 1990;25:317-27.
10. Clark JM, Cook TA. Immediate reconstruction of extruded alloplastic nasal implants with irradiated homograft costal cartilage. *Laryngoscope* 2002;112:968-74.
11. Strauch B, Wallach SG. Reconstruction with irradiated homograft costal cartilage. *Plast Reconstr Surg* 2003;111:2405-11; discussion 2412-3.
12. Kridel RW, Ashoori F, Liu ES, Hart CG. Long-term use and follow-up of irradiated homologous costal cartilage grafts in the nose. *Arch Facial Plast Surg* 2009;11:378-94.
13. Demirkan F, Arslan E, Unal S, Aksoy A. Irradiated homologous costal cartilage: versatile grafting material for rhinoplasty. *Aesthetic Plast Surg* 2003;27:213-20.
14. Song HM, Lee BJ, Jang YJ. Processed costal cartilage homograft in rhinoplasty: the Asan Medical Center experience. *Arch Otolaryngol Head Neck Surg* 2008;134:485-9.
15. Lohuis PJ, Joshi A, Bran GM, Datema FR, Vermeeren L. Dorsal onlay with diced homologous processed rib cartilage grafts. *Aesthetic Plast Surg* 2017;41:140-5.

16. Suh MK, Ahn ES, Kim HR, Dhong ES. A 2-year follow-up of irradiated homologous costal cartilage used as a septal extension graft for the correction of contracted nose in Asians. *Ann Plast Surg* 2013;71:45-9.
17. Lee MR, Unger JG, Rohrich RJ. Management of the nasal dorsum in rhinoplasty: a systematic review of the literature regarding technique, outcomes, and complications. *Plast Reconstr Surg* 2011;128:538-50e.
18. Donald PJ, Deckard-Janatpour K, Sharkey N, Lagunas-Solar M. The effects of irradiation dose on the stiffness of cartilage grafts. *Ann Plast Surg* 1996;36:297-303.
19. Adams WP Jr, Rohrich RJ, Gunter JP, Clark CP, Robinson JB Jr. The rate of warping in irradiated and nonirradiated homograft rib cartilage: a controlled comparison and clinical implications. *Plast Reconstr Surg* 1999;103:265-70.
20. Kridel RW, Sturm AK. Dorsal Augmentation with Homologous Rib. *Facial Plast Surg* 2017;33:195-201.

Original Article

Open Access



The current trend of autologous costal cartilage harvest by facial plastic surgeons for rhinoplasty in the United States

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Abstract

Aim: To assess the safety profile and practice trend of autologous costal cartilage harvest by facial plastic surgeons in the United States (US).

Methods: A 10-question online survey was distributed by the American Academy of Facial Plastic and Reconstructive Surgery to its members.

Results: Of the 2,639 members, 2,379 received the survey with 137 (5.76%) members responded. The majority (33.6%) of the respondents were expert facial plastic surgeons. One hundred and nine (79.6%) of the respondents performed rib harvest with 49.6% of them performing the procedure at a hospital facility. Among them, 21.5% exclusively performed their surgery at an ambulatory surgical center not physically attached to a hospital while 6.67% of them at the in-office accredited operating room. When comparing techniques, 64.7% performed only full-thickness rib grafts *vs.* 12.0% harvesting partial-thickness rib grafts. Most used an incision length between 2.1 and 4 cm (64.4%) while 2 surgeons used < 1 cm incision. The occurrence of pneumothorax after autologous rib harvest remained low (< 1%) in most (73.1%). Regarding safety practices of the surgeons, only 24.6% would order a chest X-ray post-operatively while 54.5% would not. In addition, 58.7% of respondents never kept their patients overnight for observation after autologous rib grafting while 15.0% always would. For pain management, most respondents (50.4%) did not utilize any additional analgesia protocol besides oral pain medications.



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Conclusion: Two thirds of the US facial plastic surgeons performed autologous costal cartilage harvest in a hospital setting. Routine chest imaging or overnight observation post-operatively was not warranted as the percentage of pneumothorax remained low and pain control was adequate.

Keywords: Rib graft, autologous costal cartilage, rhinoplasty, current practice, pneumothorax

INTRODUCTION

Rhinoplasty remains one of the most demanding operations of the cosmetic and reconstructive surgeon due to the complex three-dimensional anatomy of the nose, which serves both form and function. The nose sits in the center of a face, even the slightest asymmetry or imperfection is apparent causing significant patient distress and dissatisfaction. This may explain how rhinoplasty was the fifth most popular cosmetic procedure in 2015, with close to 218,000 performed, according to the data from the American Society of Plastic Surgeons^[1]. In 2017, the American Academy of Facial Plastic & Reconstructive Surgery (AAFPRS) published a membership study which showed rhinoplasty was the most commonly performed surgical procedure among facial plastic surgeons with each surgeon performing 60 of those annually on average^[2]. The revision rhinoplasty rate had been reported in the literature between 5% and 15.5% even in the hands of experienced surgeons^[3,4]. Despite our best efforts, the primary surgical outcome may not be acceptable to the patient, physician or both. Many patients seek revision rhinoplasty to correct minor deformities. However, some of these cases are more involved requiring repair of cosmetic and/or functional defects.

The challenges presented by revision rhinoplasty are not only with regard to scarring and distorted anatomy, but the amount of material available for reconstruction. Residual septal cartilage and auricular conchal cartilage are first considered but often depleted especially in a multiple revision case. Auricular conchal cartilage, being a type of elastic cartilage, is also not as structurally strong as hyaline cartilages found in septum and ribs. As a result, autologous costal cartilage harvest becomes a common practice to provide cartilage material in revision rhinoplasties. Costal cartilage is sometimes used in augmentation rhinoplasty for congenitally small noses as well as in ethnic rhinoplasty for African Americans and Asians. Other options for graft source include irradiated cadaveric rib, allografts [e.g., silicone, expanded polytetrafluoroethylene (e-PTFE, Gore-tex, WL Gore and Associates, Flagstaff, AZ) and porous polyethylene (Medpor, Porex Surgical, Newnan, GA)].

METHODS

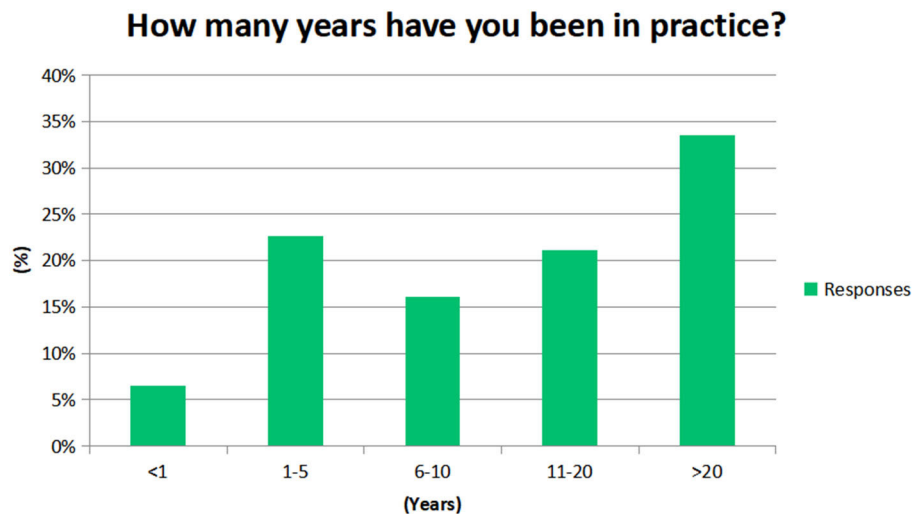
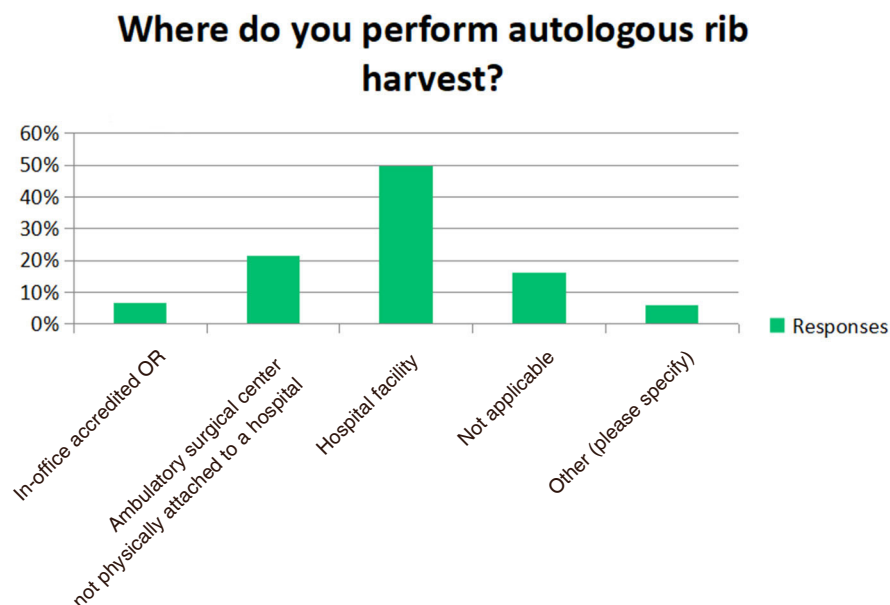
An online 10-question survey [Table 1] was distributed to 2,639 members of the American Academy of Facial Plastic & Reconstructive Surgery. Survey respondents were asked about their years of experience, number of autologous costal cartilage harvest performed annually, their techniques, rate of pneumothorax, safety practices and post-operative management. Data were exported and analyzed in Excel software (Microsoft corporation).

RESULTS

Of the 2,639 AAFPRS members, 2,379 members received the survey and 137 (5.76%) members responded. The majority (46 of 137, 33.6%) of the respondents were facial plastic surgeons with > 20 years experience [Figure 1]. One hundred and nine (79.6%, $n = 137$) of the respondents performed autologous rib harvest with 49.6% of them performing the procedure at a hospital facility. Among them, 21.5% exclusively performed their rhinoplasty with autologous rib harvest at an ambulatory surgical center (ASC) not physically attached to a hospital while 6.67% of them at the in-office accredited operating room. Four respondents (2.92%) chose between a hospital facility and ASC on a case-by-case basis [Figure 2]. The number of autologous rib harvests performed annually range between 1 and > 50. Many respondents (36.6%) performed between

Table 1. Survey questions

Q1. How many years have you been in practice?
Q2. Do you perform autologous rib (costal cartilage) grafting for rhinoplasty?
Q3. Where do you perform autologous rib harvest?
Q4. Do you harvest full-thickness or partial-thickness rib grafts?
Q5. What is the average length of incision you use for rib graft harvest?
Q6. How many autologous rib harvest do you perform per year on average?
Q7. What is the percentage of your patients getting a pneumothorax after autologous rib harvest?
Q8. Do you routinely keep your patients overnight for observation after autologous rib grafting?
Q9. Do you routinely perform chest X-ray after autologous rib harvest?
Q10. Do you routinely utilize any additional analgesia protocol (other than oral pain medications) after autologous rib harvest?

**Figure 1.** Number of years in practice of survey respondents**Figure 2.** Location of surgical center

1 and 5 per year while two reported > 50 cases per year [Figure 3]. When comparing the surgeon's techniques, 64.7% of them performed only full-thickness rib grafts vs. 12.0% harvesting partial-thickness

How many autologous rib harvest do you perform per year on average?

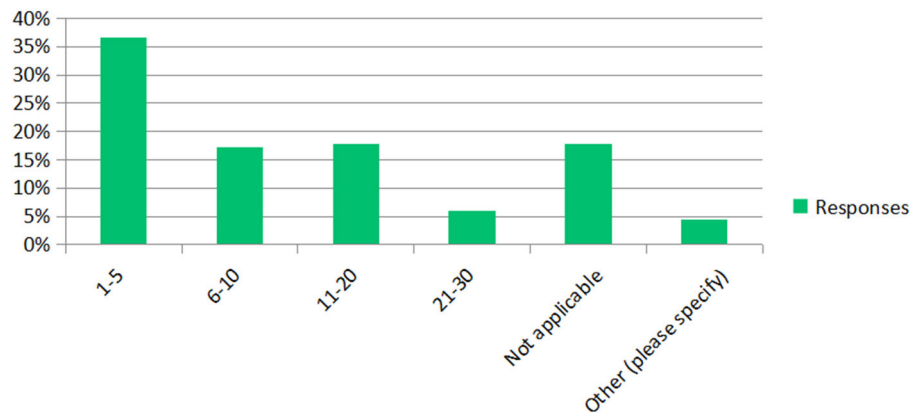


Figure 3. The average number of autologous rib harvest performed annually

What is the average length of incision you use for rib graft harvest?

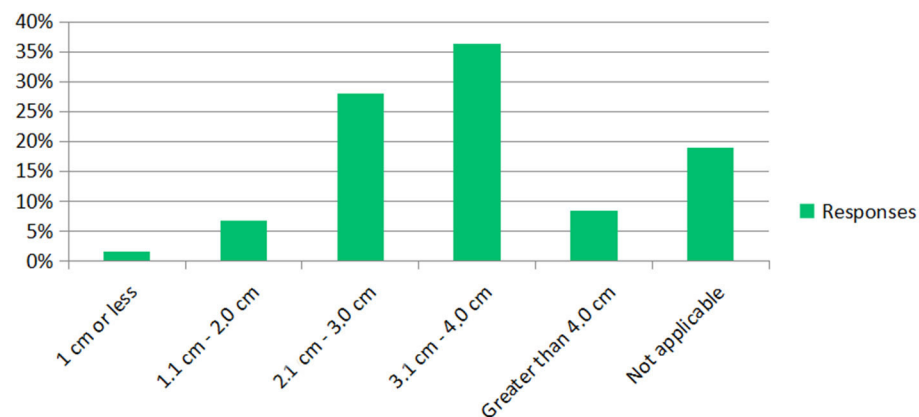


Figure 4. Incision length

rib grafts. Seven (5.11%) of the respondents would consider both full and partial-thickness depending on the circumstance. Most surgeons used an incision length between 2.1 and 4 cm (64.4%) while 2 surgeons used < 1 cm incision [Figure 4]. The occurrence of pneumothorax after autologous rib harvest remained low (< 1%) in most of the respondents (73.1%) while one surgeon reported 6%-10% of patients getting a pneumothorax [Figure 5]. Regarding safety practices of the surgeons, only 24.6% ($n = 33$) would order a chest X-ray routinely post-operatively while 54.5% of respondents would not. In addition, 58.7% of respondents did not keep their patients overnight for observation after autologous rib grafting while 15.0% of them always would. Nine surgeons would decide based on the patients (whether they are from out-of-town, have post-operative nausea, medical comorbidities, pain and degree of rib harvested). For pain management with rib harvest, the majority of respondents (50.4%) did not utilize any additional analgesia protocol (other than oral pain medications). Others preferred intraoperative liposomal bupivacaine injection, indwelling catheter for pain medication delivery, scheduled intravenous pain medications, pain management consult and intercostal nerve block [Figure 6].

What is the percentage of your patients getting a pneumothorax after autologous rib harvest?

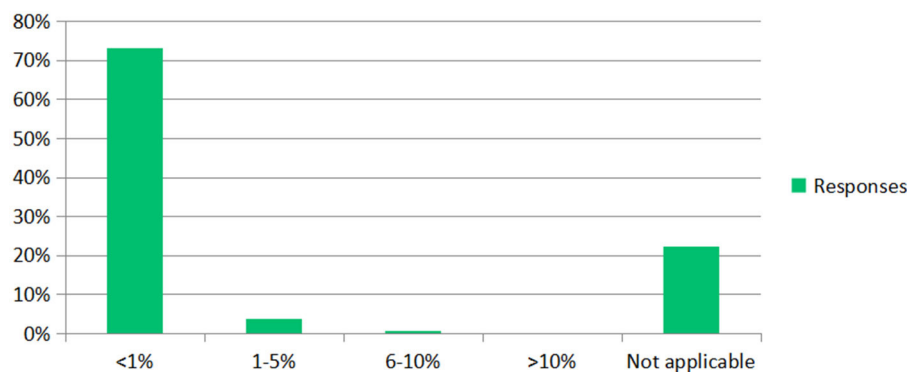


Figure 5. The percentage of patients getting a pneumothorax post-op

DISCUSSION

Revision rhinoplasty routinely requires repairing structural deformities resulting from over-zealous resection of the bony-cartilaginous framework from prior procedures. This surgery is often technically challenging, particularly when cartilage material is limited. Autologous costal cartilage has been a workhorse for rhinoplasty surgeons since it provides the most abundant source of cartilage for graft design as well as being the most reliable for structural support^[5]. However, the rate of warping was reported at 3.0%, reabsorption at 0.2%, infection at 0.5%, migration at 0.3%, unfavorable chest scar at 3.0%, and pneumothorax at 0% (0.13%-0.32%) according to a recent meta-analysis^[6]. Given the convenience of irradiated cadaveric rib graft, the lack of donor-site morbidity and potential scarring, it is a popular alternative. Kridel *et al.*^[7] reported the largest available case series to date in irradiated rib graft for 1,025 rhinoplasties with outcomes after long-term follow-up in some of the patients of greater than 10 years. Overall, the authors described the rate of warping at 3.25%, infection at 0.9%, and reabsorption at 1.2%. Alternatively, alloplastic materials have the advantages of being easy to use and readily available with an unlimited supply. Unfortunately, many of these alloplastic materials are fraught with long-term complications, such as infection, migration, extrusion and palpability. The risk of infection up to 12.6% and extrusion rate of 16.0% had been reported by a recent case series and meta-analysis by Loyo and Ishii^[8]. Occasionally, the extrusion happened many years after implantation.

Our study demonstrated that autologous rib grafts were still commonly performed by facial plastic surgeons in the United States (US). However, as with most online survey studies, our study was limited by the small number of responses and user bias. Most surgeons preferred full-thickness rib graft harvest with a medium size (2-4 cm) incision. However, it was not surprising to see a trend towards “short-scar” technique with incision < 2 cm. The majority of the surgeons were not concerned about post-operative pulmonary complications as the incidence remained low. This corresponded to the low percentage of surgeons keeping patients overnight for observation or getting a routine chest X-ray post-operatively. As the opioid epidemic continues in the US, it was interesting to see most of the US facial plastic surgeons did not utilize any additional analgesia for rib grafts other than oral pain medications. Intraoperative liposomal bupivacaine injection at the surgical site that provides an opioid-free regional anesthesia, has gained some popularity as 21.8% of the survey responders incorporated it into their post-operative pain management. Indwelling catheter for pain medication delivery (e.g., bupivacaine) was also an option among the facial plastic surgeons, however, such delivery system would often require hospital monitoring which might negate its routine use.

Twenty eight percent of the responding surgeons reported harvesting rib grafts in an ambulatory or an office-based surgical facility compared to approximately 50% of them performing the procedure at a hospital

Do you routinely utilize any additional analgesia protocol (other than oral pain medications) after autologous rib harvest?

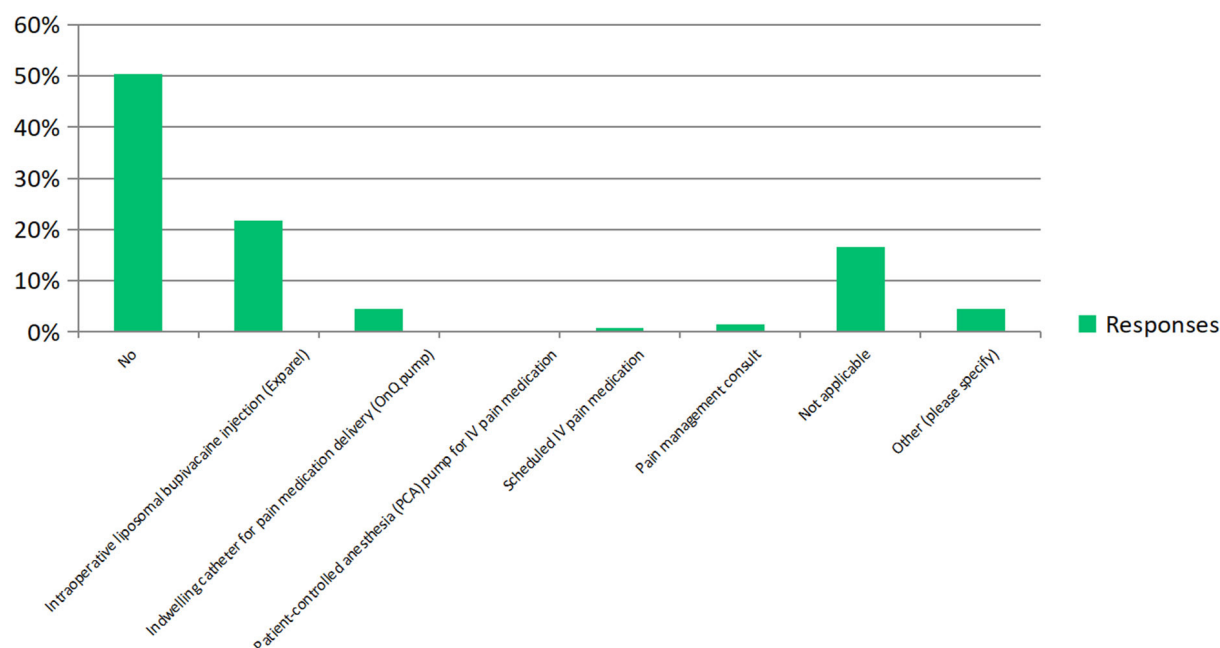


Figure 6. Post-operative pain management

facility. There was less difference between in-office vs. ambulatory facilities (14.8%) than there was between in-office or ambulatory facility and a hospital (21.5%). This indicated that the decision of location choice was mainly on hospital vs. non-hospital facilities rather than ambulatory vs. office-based surgery centers.

In order to keep the survey simple, specific medical services available at non-hospital facilities were not solicited. These included the availability of X-ray, chest tube set, thoracic surgeons and the proximity to a hospital for transfer and admission. This is a significant limitation of the study. In addition, our online survey was distributed via email by the AAFPRS which might have explained the lower response rate when mass emails were frequently ignored by members.

A suggestion to future study should include a discussion of the intervention performed by the surgeons if an air leak is found or suspected intraoperatively since a formal chest tube is rarely needed. Typically, an intraoperative air leak can be detected by a visual rent in the posterior perichondrium and pleura. Most surgeons also have the anesthesia provider perform a Valsalva maneuver while looking for air bubbles forming under saline irrigation at the rib graft harvest site. If an air leak is detected, the next step will be to first place a small red-rubber catheter through the pleural defect, temporarily secure it with a purse-string suture in multiple layers, then withdraw the catheter under suction. Patients are then observed for shortness of breath and an elective chest X-ray is obtained in the post-anesthesia care unit, at a nearby radiology facility or emergency department. A small pneumothorax may be seen in those situations and treatment often is observation. In rare cases, insertion of a small suction catheter (much smaller than a conventional chest tube) may be required and placed by a thoracic surgeon, which will be left in place for a few days.

In conclusion, we summarized the current practice trend of US facial plastic surgeons in autologous costal cartilage harvest for rhinoplasty. The very low percentage of pneumothorax after rib harvest and the use

of post-operative advanced analgesic control techniques remained low and did not warrant routine post-operative chest imaging or overnight observation. Two thirds of the US facial plastic surgeons continued to perform their rib harvest in a hospital setting.

DECLARATIONS

Authors' contributions

Made substantial contributions to conception and design of the study and performed data analysis and interpretation: Olcott CM, Pearlman SJ

Availability of data and materials

Data can be requested from the corresponding author.

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All authors declared that there are no conflicts of interest.

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REFERENCES

1. American Society of Plastic Surgeons. 2017 plastic surgery statistics report. Available from: <https://www.plasticsurgery.org/documents/News/Statistics/2017/plastic-surgery-statistics-full-report-2017.pdf>. [Last accessed on 12 Feb 2019]
2. Facial Plastic Surgery. AAFPRS Membership Study 2017. SSRS 2017-2018.
3. Neaman KC, Boettcher AK, Do VH, Mulder C, Baca M, et al. Cosmetic rhinoplasty: revision rates revisited. *Aesthet Surg J* 2013;33:31-7.
4. Mazzola RF, Felisati G. Secondary rhinoplasty: analysis of the deformity and guidelines for management. *Facial Plast Surg* 1997;13:163-77.
5. Cochran CS. Harvesting rib cartilage in primary and secondary rhinoplasty. *Clin Plastic Surg* 2016;43:195-200.
6. Wee JH, Park MH, Oh S, Jin HR. Complications associated with autologous rib cartilage use in rhinoplasty: a meta-analysis. *JAMA Facial Plast Surg* 2015;17:49-55.
7. Kridel RW, Ashoori F, Liu ES, Hart CG. Long-term use and follow-up of irradiated homologous costal cartilage grafts in the nose. *Arch Facial Plast Surg* 2009;11:378-94.
8. Loyo M, Ishii LE. Safety of alloplastic materials in rhinoplasty. *JAMA Facial Plast Surg* 2013;15:162-3.

Review

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Prosthetic and orthotic options for lower extremity amputation and reconstruction

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Abstract

Lower extremity injury and deformity can result from a number of etiologies. Regardless of the underlying cause, the decision to pursue amputation or reconstruction of a lower limb is challenging for both patients and practitioners. This decision is largely dependent on the patient's premorbid health and function, functional goals and preferences, and characteristics and viability of the affected limb. The role of adaptive devices following surgery should never be underestimated. Advances in prostheses and orthoses have provided patients with a wider range of options to consider when deciding between limb reconstruction and amputation. The primary goals of any adaptive device are to improve function, prevent recurrence or ulceration of the defect, and allow for use of conventional footwear and/or clothing. When a lower extremity amputation is indicated, selection of the correct level is of critical importance in order to optimize healing potential and function. Each distinct level has certain inherent prosthetic and orthotic considerations. Likewise, the application of an adaptive device following reconstruction of the lower extremity also has demonstrable benefits and must be tailored to the specific defect and procedure performed. Knowledge of available prosthetic and orthotic options is of considerable importance for the reconstructive surgeon tasked with limb salvage or resurfacing an amputated extremity. This article reviews considerations of various types of lower extremity amputation and reconstruction, and provides a framework for the role of adaptive devices following surgery.

Keywords: Prosthesis, orthosis, amputation, reconstruction, rehabilitation, lower extremity



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INTRODUCTION

Lower extremity injuries resulting in dysfunction and deformities can be due to a variety of conditions including congenital abnormalities, trauma, burns, vascular disease, and neuropathic disorders (including diabetes, leprosy, nutritional deficiency, axonal degeneration and demyelinating processes). Regardless of etiology, surgical reconstruction or amputation is often considered to restore function in the extremity when more conservative treatments are unsuccessful^[1]. The decision about which option is optimal for an individual patient can be challenging. Substantial prior research has compared reconstruction with amputation in terms of function^[2,3], quality of life^[4,5], and cost-effectiveness^[6,7]. One of the most important considerations in determining optimal surgical treatment is the prosthetic and orthotic options to restore function after surgery. Recently, advances in prostheses and orthoses have provided patients with a wider range of options to consider when deciding limb reconstruction *vs.* amputation.

Prosthetic restoration following lower extremity amputation has several goals. The first, and arguably the most important, is to reestablish functional mobility and static positioning of the limb. Ambulation using a prosthesis requires increased energy expenditure as the amputation level moves proximally^[8]. Therefore, a lower limb prosthesis should be designed and fit to minimize this increase in energy expenditure^[9,10]. Secondly, well-fitting prostheses also serve to prevent breakdown of remaining soft tissue by redistributing compressive force during weight bearing and minimize the amount of shearing force on the skin^[11]. Lastly, the use of conventional footwear and clothing should be considered when prescribing an adaptive prosthesis, though this may not always be of patient concern. The psychological impact of amputation and its effect on social functioning and identity should not be underestimated^[12].

Reconstruction may be pursued when the patient has a reasonable chance at weight bearing and functional ambulation. The decision to reconstruct *vs.* amputate also depends on the neurologic and vascular status of the limb, presence of fracture, risk for ongoing wounds or infection as well as the functional goals of the patient. At times, amputation of the limb may provide a better chance at more fully restoring function in the limb than does limb restoration, and vice versa. The number of surgeries and overall time spent actively rehabilitating is greater for limb salvage with reconstruction as compared to amputation^[13]. Despite this initial healthcare utilization, the projected lifetime cost of lower extremity reconstruction is considerably lower than amputation^[6]. The impact of multiple surgeries and subsequent recovery on the overall health of a person should also be considered when deciding between reconstruction *vs.* amputation.

Unlike amputation, which can be divided into categories by level, the reconstruction of the lower limb does not necessarily follow a discrete algorithm in terms of post-reconstruction adaptive devices. Instead, individual defects - their etiology, location, size and depth - must be considered alongside patient factors to determine the need for specific postoperative orthosis. The primary goals of any adaptive device are similarly to improve function, prevent recurrence or ulceration of the defect, and allow for use of conventional footwear and/or clothing.

In this article, we present the surgical considerations of various types of lower extremity amputation and reconstruction, and provide a framework for the role of postoperative adaptive devices including prostheses and orthoses.

LOWER EXTREMITY AMPUTATION

When amputation of the limb is deemed medically appropriate, selection of the correct level is of critical importance for healing potential and for optimal function. The location of amputation and resulting residual length and limb shape help determine function, energy expenditure necessary for ambulation, and prosthetic options for the amputated limb. Generally speaking, a more distal amputation is more functional as it

preserves the greatest number of joints and leaves a longer lever arm, allowing for higher torque generation and less daily energy expenditure for ambulation. However, the distal tissue must also have perfusion sufficient to heal and soft tissue coverage must remain durable over the patient's lifetime. In addition, a more proximal amputation may provide better function if the most proximal joint has limited range of motion or function. Thus, the selection of the amputation level can be complex and the decision ideally should be made through a combined effort by the surgeon performing the amputation, the rehabilitation specialist, the patient, and in more complex cases a reconstructive plastic surgeon.

Data regarding the comparative effectiveness of lower limb prostheses is limited and measurable outcomes are not often standardized. Instead, we often rely on the consensus of prosthetic and rehabilitation experts. A review of amputation levels and considerations regarding outcomes and prosthetic options are presented below.

Transmetatarsal amputation

As its name would suggest, the transmetatarsal amputation (TMA) is performed by transecting between the metatarsal head and base, thus salvaging the mid- and hindfoot^[14]. TMAs are most often performed in the setting of infection, wounds or deformities of the toes or metatarsal heads. A plantar flap including the transected flexor tendons or a fishmouth incision is used to close the surgical site and provide soft tissue coverage to the distal foot. The precise location of amputation through the transmetatarsal is variable. For instance, the amputation may proceed just proximal to the metatarsal head or through the foot distal to the cuboid and cuneiform bones. A longer residual foot provides additional weight-bearing surface and less muscle imbalance, but the quality of the soft tissue coverage should be considered.

The most common biomechanical complication of a TMA (and other midfoot amputations) is an equinovarus deformity - a resultant imbalance between severed dorsiflexors and intact plantarflexors. Achilles tendon lengthening should therefore be performed at the time of a TMA to reduce risk of equinovarus deformity^[15]. Moreover, the shortened foot can be unstable during ambulation and the heel may demonstrate excess movement in the patient's footwear. These postoperative factors predispose to complication - with reported rates of delayed wound healing as high as 43%-54%^[16,17] and ulceration in as many as 27%^[18]. Furthermore, a TMA by definition will reduce the moment arm of the remaining foot, resulting in reduced ankle plantar-flexor torque generation during toe-off. As a result, patients have an inefficient gait without the use of a prosthesis. The appropriate post-operative management of TMAs in terms of dressings (rigid or nonrigid) and weight bearing precautions has not yet been established.

Prosthesis and orthosis for transmetatarsal amputation

After the transmetatarsal amputation has adequately healed and the patient has progressed to weight bearing, a partial foot prosthesis or orthosis may be prescribed. There are currently several different types of devices available to improve ambulation after partial foot amputation. A total contact in-shoe orthotic with a metatarsal pad molded to the contour of the patient's residual foot is used to better distribute compressive forces along the plantar surface. A toe filler contoured to the footwear is also frequently used to prevent excess motion during ambulation and reduce shearing forces to the plantar surface and posterior heel. However, the use of a full-length shoe with insert and rocker bottom sole has been demonstrated to reduce plantar pressure to a greater degree than a regular shoe with toe filler^[19].

The truncated lever arm of the foot after transmetatarsal amputation may be mitigated by using either a carbon-fiber inlay^[20] or steel spring^[21] integrated into the orthotic framework, thus providing additional force during terminal stance and helping propel the limb forward. A partial foot prosthesis that crosses the ankle joint may also be used to produce additional force for push off and provide stability for patients with impaired balance or strength^[22]. Devices range from as simple as an in-shoe orthotic to as complex as a tibial



Figure 1. Carbon fiber partial foot prosthesis after Chopart amputation. The patient has remained active and is able run with this device

tubercle height partial foot prosthesis. The correct adaptive device - for any level - depends on patient factors and goals.

Midfoot amputations - Lisfranc and Chopart

The eponyms Lisfranc and Chopart, both named after their pioneering surgeons, refer to two distinct levels of midfoot amputation. Both of these disarticulations, although less commonly performed, are useful when a paucity of soft tissue in the forefoot prevents successful transmetatarsal amputation or there is significant instability at the respective joint. The Lisfranc amputation disarticulates all five metatarsals from the cuboid or respective cuneiform bone^[23]. Similar to transmetatarsal amputations, the resultant loss of the peroneal brevis and longus and dorsiflexor insertions leads to unopposed plantarflexion with subsequent equinovarus deformity.

The Chopart amputation excises a greater portion of midfoot and disarticulates the talonavicular and calcaneocuboid joints. This amputation has an even greater propensity for equinovarus deformity^[24]. There are several methods for rebalancing the foot after such a procedure^[25,26], which include Achilles tendon lengthening, gastrocnemius resection, and split anterior tibialis tendon transfer. Preservation of the ankle in most instances is not helpful as the lever arm is short. Historically the utility of traditional midfoot amputations is felt to be low given high rates of subsequent proximal revision amputations^[27]. The benefit of this level, however, is that it allows the individual to place their foot on the ground, which may be helpful for short distance ambulation. Advances in dynamic ankle foot orthosis (AFO) style partial foot prosthesis have provided improved options for patients with midfoot amputations.

Prosthesis and orthosis for midfoot amputations

Like transmetatarsal amputations, a custom-fit orthosis and toe filler can be used to stabilize the foot and prevent excess movement of the heel. Mechanisms such as a steel spring or carbon inlay can again be used to counteract the force imbalance between the dorsiflexors and plantarflexors [Figure 1]. Patellar tendon-bearing prostheses have been used to unload the short residual foot, although these devices are bulky and lessen the value the extra length afforded by the chosen amputation level. Novel above-ankle prostheses that adequately protect the amputation site and correct varus deformity, while still utilizing the full length of the amputation, have also been described^[27].

Preservation of the ankle joint in addition to the use of these inlays can cause a limb length discrepancy between the treated and untreated sides. Thinner, “slipper-like” devices designed to minimize this

discrepancy provide protection, but do little to correct the equinovarus deformity. More functional devices often require a contralateral shoe lift to correct the length discrepancy.

At our institution, a carbon fiber AFO with an insert or the Phat Brace style orthosis (Bio-mechanical Composites, Des Moines, IA, USA) is commonly employed to provide improved third phase of gait and generate equal step lengths.

Syme amputation

The Syme amputation, first described by Scottish surgeon James Syme in 1843^[28], is synonymous with an ankle disarticulation procedure for the treatment of various foot pathologies not amenable to a more distal resection. This amputation is also frequently performed in children with congenital foot deformities. Transection proceeds through the ankle joint and includes the medial and lateral malleoli to achieve an even articular surface. The proximal heel pad is used for coverage. This level of amputation is advantageous as compared to a transtibial amputation as it provides superior gait stability and decreased energy expenditure^[29,30]. It also provides a greater lever arm length as compared to a more proximal amputation. Postoperative rigid casting allows for partial weight bearing almost immediately post-procedure and early fitting with a prosthesis is often possible. Patients require less physical therapy gait training than with transtibial amputation^[31]. The retained plantar tissue provides a durable weight-bearing surface and end-limb proprioception remains intact. The residual limb allows for end-bearing so that short distances may be walked without a prosthesis. In patients for whom cognitive or other health factors might preclude prosthesis use, end-bearing can be functionally useful for transfers or standing ADLs. The principle is also true for Chopart and Lisfranc amputations.

Prosthesis and orthosis for Syme amputations

There are several prosthetic considerations unique to a Syme amputation. The socket of the prosthesis must conform to a bulbous distal residual limb and therefore can be bulky. Generally speaking, two primary types of prosthetic options are available: closed or windowed. Closed prostheses have a “stove-pipe” external appearance as they make use of the residual ankle contour to suspend the prosthesis. Windowed variations allow for a more natural external ankle contour, but must be closed with Velcro straps [Figure 2]. The articulation of the residual limb and adaptive prosthetic foot distally is subject to significant stress. This force must be accounted for and subsequently offloaded by the prosthetic foot. Until recently, sophisticated foot componentry was limited for this level amputation. However, a number of prosthetic manufacturers now provide carbon fiber, energy-storing Syme prosthetic feet. It should be noted that a Syme amputation will almost always lead to a limb length discrepancy as the prosthetic foot must be placed under the residual heel. Therefore, orthosis in the contralateral footwear is needed to correct the limb length discrepancy.

Transtibial amputation

A transtibial, or below-knee amputation (BKA), is the most common level of amputation. The vast majority of patients undergoing a transtibial amputation will heal their amputation site without complication^[32]. Patients undergoing a below-knee amputation have a much greater likelihood of ambulating with a prosthesis compared to above-knee amputees, owing to both the mechanical advantages of preserving the knee joint and underlying patient factors predisposing the level of amputation (i.e., often these patients will have greater functional reserve compared to those undergoing above knee amputations). It should be noted, however, that there are situations in which below the knee amputation may not be better than a higher level amputation. For instance, a BKA can predispose to flexion contracture of the knee particularly in patients who are non-ambulatory. Knee flexion contractures can predispose to development of pressure ulcers on the distal residual limb from lying in bed. Patients with spasticity and pre-existing flexion contractures may not be appropriate for BKA, as this may exacerbate the contracture.

The primary surgical consideration of a transtibial amputation relates to the precise anatomic level of bony transection. The ideal length of the residual limb is between 12.5 and 17.5 cm measured from the



Figure 2. Prosthesis for a congenital Syme amputation with patellar tendon bearing proximal cuff and distal build up due to a short limb

medial joint line. It is frequently cited that a minimum of 5 cm is required for acceptable function and prosthesis fitting, though this is not always an absolute requirement. The provider and patient must consider the advantages and disadvantages of a short limb with joint preservation vs. an above knee amputation. Amputation in the distal third of the leg, however, is often complicated by the paucity of soft tissue coverage for the residual limb. A variety of flaps have been described for coverage of transtibial amputations, although a long posterior, musculocutaneous flap is ideal.

In the case of a traumatic BKA with inadequate local soft tissue for coverage of the residual limb and borderline bone length reconstructive plastic surgeons are often consulted for residual limb coverage for length preservation. Goals of reconstruction are to create a soft, pliable, durable interface with a non-adherent incision (i.e., mobile over bone) in a location 2-8 cm superior to anterior edge. Positioning the incision line proximal to the distal anterior tibia will prevent the scar from being at the highest pressure, highest friction location when wearing a prosthesis.

Operative management must take into account the skin and soft tissue, muscles, nerves, and bones. First, skin closure should be without tension but not redundant. The more skin surface area available for contact with the prosthetic socket, the less pressure will be applied to each unit area of skin surface. A cylindrical shaped residual limb with ample muscular padding presents fewer skin problems than the bony, atrophic tapered residual limb.

In modern amputations with improved prosthetic interfaces such as gel liners, it is possible for split thickness skin grafts to withstand forces applied by a prosthesis when not adherent to bone. Thus, application of a skin graft over a vascularized muscle bed is viable method of amputation stump reconstruction. However, without at least a fine layer of subcutaneous fat or muscle to absorb shear force, grafts are not as durable and predictably break down. Skin grafting over granulating bone is therefore not advised.

Maximal preservation of functional muscles is essential to provide the limb with strength, size, shape, circulation, and proprioception. Thus, when native muscle remains but has lost its distal insertion, myodesis or myoplasty are often helpful. Myodesis tends to be preferred unless bone quality is poor.

Care should be taken to identify five nerves intraoperatively: tibial, superficial peroneal, deep peroneal, saphenous, and sural. These should be cut proximally and buried in soft tissue away from the planned incision in order to prevent neuroma formation.

Forces traveling between prosthesis, residual limb, and the remaining body are primarily transmitted through the retained bone in the amputated limb. Managing the edges of severed bone is essential to pain free healing and reduces the chance that bone will erode the overlying skin. The distal corner of tibia should be removed with 45° anterior beveling and edges should be softened with a saw or rasp. The fibula should be 1-2 cm shorter than the tibia and beveled to remove the lateral edge.

Prosthesis and orthosis for below-knee amputations

Below-knee amputation prostheses can be subdivided into the following elements: socket, interface, suspension, shank, and foot/ankle. The prosthetic socket encases the residual limb, and is often classified as either “patellar tendon bearing” - dispersing weight distribution onto several pressure-tolerant areas including patellar tendon - or “total surface bearing,” creating a more equal weight distribution throughout the entirety of the socket. In modern practice, most designs are a hybrid of the two^[33]. The interface describes the material between the socket and the residual limb, which is often a liner. Common interface options include hard-socket with an underlayer of cloth sock, pelite (foam), or silicone. Interface prescriptions take into account maturity and shape of the residual limb, suspension method, patient activity level, patient cognition, upper extremity function, and patient preference.

The mechanical properties of several liner materials - such as tension, compression, shear, and friction - have been well studied^[34]. It has been suggested that stiffer liners are superior for patients with excess soft tissue, while softer, more conformable liners are better for patients with bony prominences^[35]. Furthermore, liners have an effect on stump moisture and heat retention. Liner materials are generally impermeable to moisture^[36] and non-conductive for heat transfer^[37], thus contributing to residual limb maceration, dermatitis, hyperhidrosis, and cellulitis. Generally speaking, modern liners make use of roll-on elastomer materials, a more durable and adhesive alternative to foam liners^[38]. Socks of varying ply are often utilized between the liner and skin and can be added or removed to accommodate for inevitable limb volume changes.

Suspension refers to the method of attachment to the residual limb. Options are numerous and may use anatomic structures to suspend the socket. This may include supracondylar cuffs and brims, may use additional componentry such as neoprene sleeves, thigh corsets, and pin-locks, or utilize pressure differentials as in the case of suction or vacuum assisted suspension. Again, prescriptions take into account anatomical, cognitive, social, and other personal factors. The shank connects the socket to the foot and ankle, and can be categorized as either endo- or exo-skeletal. Endoskeletal pylons are most commonly utilized as they are modular, allowing for modification to height, rotation, and alignment, and also have the potential to be lighter in weight.

There are many prosthetic foot options, which vary in terms of weight, durability, and functionality. Generally, these include solid-ankle cushioned heel, single-axis, multi-axis, and energy-storing/dynamic response, hydraulic, and microprocessor feet. It has been suggested that energy-storing feet provide both vascular and traumatic amputees with a more comfortable stride length and walking speed as compared to traditional solid ankle cushion heel devices^[39-41]. A single-axis foot may be more useful for less active patients, as it provides an early foot-flat stability and timely transfer of weight onto the supporting prosthetic^[42]. The disadvantage of these devices is less restraint of dorsiflexion and therefore less stability in late stance phase^[43,44]. Consequently, there is no single prosthetic foot/ankle that provides superior function to all patients, and instead the prosthetic prescription must be tailored to each patient's baseline, projected functional status, and unique needs.

Knee disarticulation

Knee disarticulation is a less commonly performed level of amputation with advantages and disadvantages compared to the more proximal above-knee amputation (AKA). Early variations of the through-knee amputation used a soft-tissue closure consisting of only skin and subcutaneous tissue, leaving a fragile envelope prone to bone exposure if dehiscence occurred. Knee disarticulation was greatly improved by use of the gastrocnemius muscle bellies to pad the distal end and thus provide vascularity and additional cushioning to the closure and weight-bearing stump, respectively^[45]. The knee disarticulation is capable of end bearing, is muscle-balanced in regards to flexion/extension^[46] and provides an excellent sitting platform and long lever arm for wheelchair transfers in non-ambulatory patients^[47]. Leaving the femoral epiphysis intact is important in children, as it will allow for continued longitudinal growth of the femur. In growing patients, the arrest of longitudinal growth is carefully timed so that the prosthetic knee joint may better approximate the length of the unaffected side.

A through knee amputation may pose challenges in regards to a stable and comfortable fit, though this is not necessarily true if the prosthetist is experienced with creating the appropriate socket. This is particularly problematic at the lateral femoral condyle, which may be prone to unbalanced loading and subsequent skin breakdown.

Prosthesis and orthosis for knee disarticulations

The knee disarticulation results in a bulbous stump end, which is most evident when the femoral condyles are left intact. Choice of liner becomes more important in this circumstance because it has the potential to add even greater bulk to the distal residual limb. Several techniques are available to better accommodate the bulky end - including inner protrusions and medial door openings to allow for passage of the condyles and improved suspension of the prosthetic. The selection of a knee component will be discussed in greater detail below; however, one consideration in knee disarticulation is the position of the prosthetic knee. Analogous to the prosthetic foot/ankle with a Syme amputation, the prosthetic knee center resides more distally than in the contralateral knee following disarticulation, which is more evident when the patient is sitting. Subsequently, the shank portion of the lower leg prosthesis must be shortened to avoid leg-length discrepancy and can cause some challenges in timing of the swing phase of gait on the prosthetic side.

Transfemoral amputation

The transfemoral, or AKA, is a less desirable level of amputation and is reserved for circumstances in which a below- or through-knee amputation would not suffice to resolve the underlying pathology, allow for enough tibial length for prosthetic fitting, or provide adequate tissue for closure of the residual limb. The transfemoral amputation has been well demonstrated to increase the energy expenditure of ambulation due to alteration of gait mechanics^[8]. Loss of contact with the tibia and an unopposed abductor mechanism causes the femur to assume an abducted position, thus decreasing the efficiency of gait^[48].

Ideally the transfemoral amputation is performed no more than 5-7 cm proximal to the knee joint, leaving as long a lever arm as feasible while still allowing room for a prosthetic knee joint. Early techniques of transfemoral amputation sacrificed the hip adductor muscles, which led to unopposed abduction and flexion. Preservation of the adductor magnus and anchoring to the distal femur improves the position of the femur. Overall, the transfemoral amputation tends to heal quickly and the residual femur has ample soft tissue on all sides, especially when myodesis is pursued. This allows for earlier prosthetic fitting compared to more distal amputations. However, there is less successful prosthetic ambulation in patients undergoing above knee amputations^[49].

Prosthesis and orthosis for above knee amputations

As with below-knee prostheses, socket design, interface, and suspension are necessary considerations in

Table 1. Medicare Functional Classification Levels

K-level	Definition
0	Does not have the ability or potential to ambulate or transfer safely with or without assistance, and a prosthesis does not enhance quality of life or mobility
1	Has the ability or potential to use a prosthesis for transfers or ambulation in level surfaces at a fixed cadence. Typical of the limited and unlimited household ambulator
2	Has the ability or potential for ambulation with the ability to transverse low-level environmental barriers such as curbs, stairs, or uneven surfaces. Typical of the limited community ambulator
3	Has the ability or potential for ambulation with variable cadence. Typical of the community ambulator who has the ability to transverse most environmental barriers and may have vocational, therapeutic, or exercise activity that demands prosthetic use beyond simple locomotion
4	Has the ability or potential for prosthetic ambulation that exceeds basic ambulation skills, exhibiting high impact, stress, or energy levels. Typical of the prosthetic demands of the child, active adult, or athlete

above-knee prosthetic prescriptions. Modern socket designs typically have a narrow mediolateral dimension and should encompass the ischium - thus the term “ischial containment” socket. They promote femoral adduction and improve gait efficiency as compared to the more historical “quadrilateral”, narrow anterior-posterior design, which did not house the ischium^[50]. Suspension methods are similar to those with BKAs, and most commonly include suction, pin-locks, or belts/straps.

The primary challenge to the transfemoral amputee prosthetic user is relying on two insensate prosthetic joints during ambulation. Several versions of prosthetic knees exist. The locking knee represents the most simple and stable joint for the wearer, though results in the worst gait efficiency. It is occasionally used early in physical therapy for gait training, for long-term use in patients with high risk of falls, and in minimal ambulators. The knee essentially remains locked in an extended position during all phases of the gait cycle, but can be unlocked to allow transfer between seated and standing positions, and vice versa. A constant friction, single axis knee with stance control is also a relatively stable knee joint, allowing for locked extension when weight bearing and flexing when weight is shifted off the prosthetic. A constant friction, single-axis knee without stance control allows for fixed cadence of gait along a single axis and grants the wearer more control of leg positioning; it is light, durable, and inexpensive, but the user must have adequate hip extensor strength and positional awareness to prevent knee buckling. Four-bar polycentric knees provide no stance control but are inherently more stable than single-axis knees. Additionally, the knee unit is relatively short which may be advantageous for patients with knee disarticulations. Fluid controlled knees allow for a variable cadence of gait via either a hydraulics or pneumatics. These devices are typically prescribed for more active patients with higher-level mobility goals, including variable speeds and/or uneven terrain. Similarly, microprocessor knees utilize hydraulics but with the added feature of computer-programmed custom settings to regulate knee function. They do not provide active flexion or extension of the knee, but rather finely tune knee stability up to 50-times per second depending on ground forces and joint angle. This is useful to optimize gait efficiency and reduce the amount of falls for the amputee. Obvious disadvantages of microprocessor knees include increased weight and cost, frequent maintenance, and need for daily charging.

The Medicare Functional Classification Levels is a rating system for stratifying an amputee’s ability to ambulate. Insurance coverage criteria for knee prostheses were adapted from this system and still remain in effect^[51]. Levels span K0, or non-ambulatory, through K4, or high-impact [Table 1]. Constant friction, manual locking, stance-control, and polycentric knees are generally prescribed for K1 and K2 users - those able to ambulate within their own home and those who can overcome minor environmental barriers outside the household. Fluid controlled and microprocessor prosthetics are covered by insurance for those who can exceed the demands of routine locomotion, though there may be utility of these devices for preventing falls in those with lesser levels of ambulation as well.

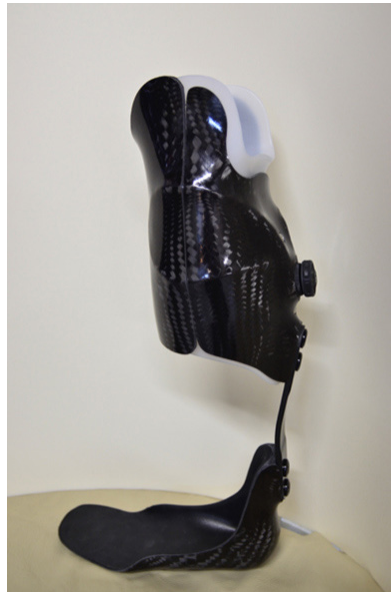


Figure 3. Dynamic ankle foot orthosis with a pretibial shell that allows for offloading of the foot and ankle

LOWER EXTREMITY RECONSTRUCTION

Goals of reconstruction

The term “lower extremity reconstruction” consists of a heterogeneous grouping of procedures that aim to restore function, bony support, and adjacent soft tissues of a lower extremity defect or deformity. As previously mentioned, reconstruction of the lower extremity attempts to achieve functional weight bearing and independent ambulation. Several scoring systems have been created to predict the potential for limb salvage after traumatic injury^[52-57]. These systems, however, are unable to accurately predict which patients will eventually undergo an amputation because of their low sensitivities, limiting their usefulness in the clinical setting^[58]. The decision to perform a lower limb reconstruction is therefore determined based on the specific patient factors and needs, ultimate cost, and social support for rehabilitation.

Orthoses after lower extremity reconstruction

The primary goal of orthosis in this context is to protect the both remaining and reconstructed soft tissue. One illustrative area of this concept is following reconstruction of the plantar surface of the foot. The heel pad and distal plantar region are characterized by distinct microarchitectural anatomy that withstand compressive and shear forces during the gait cycle. Reconstructed soft tissue with skin grafts, locoregional flaps, and free tissue transfer must also resist these forces. The result of inadequately redistributed pressure is altered gait mechanics, pain in sensitive tissue, and recurrent ulceration^[59,60]. The use of total contact insoles after hindfoot reconstruction has been shown to reduce maximal forces in the heel and improve walking speed^[61].

Over the last 10 years, there have been significant advances in offloading ankle/foot orthosis designs that have allowed people with significant lower extremity trauma to participate in higher-level activities. Dynamic AFOs are passive devices that control ankle motion and limit weight bearing through the ankle to address pain, weakness and limitations in range of motion^[62-64]. Dynamic AFOs are typically made of carbon fiber with a pretibial shell that allows for offloading of the foot and ankle with posterior struts of variable stiffness [Figure 3]. The device stores energy during the stance phase and uses it to generate a more forceful push-off.

One such device, the Intrepid Dynamic Exoskeletal Orthosis (IDEO), was designed to optimize biomechanics and power after salvage of severely traumatized lower extremities in soldiers^[65,66]. A systematic review of the IDEO device found that it improved agility, power, and speed compared with non-custom bracing and brace-less rehabilitation^[64]. Dynamic AFOs can potentially change the post-reconstruction function in pre-morbidly fit patients and provide a rationale for foregoing amputation.

ADVANCEMENTS AND FUTURE DIRECTIONS IN LOWER EXTREMITY PROSTHESIS

Tremendous improvements in the care and rehabilitation of amputee patients have been made in recent decades. One such advancement is the development of the externally-powered or so-called “bionic” devices. Activation can be microprocessor-controlled (MPC) or driven by myoelectric inputs, whereas function is described as either passive or active. All commercially available lower extremity prosthetic joints are microprocessor-controlled. For these systems, an integrated computer adjusts movement based on real-time calculations of gait-cycle interpretation. The majority of bionic prostheses function passively by means of modulating friction through the joint. For instance, MPC knees increase resistance during stance to mimic eccentric knee extension and decrease resistance during perceived swing to aid toe clearance. MPC knee components may enhance safety and confidence by rapidly adjusting resistance during perceived falls, and may decrease reliance on compensatory gait strategies^[67-69].

Myoelectric control systems, which are investigatory for lower extremity prostheses currently, require viable muscle tissue for electrode placement. Signal noise remains a notable challenge with myoelectric devices, compounded by that fact that closed chain kinetics may alter the electrode-residuum contact within the socket. Numerous approaches are being investigated to overcome this, including EMG pattern recognition, intramuscular EMG electrodes, and decomposition of EMG signals^[70].

Another limitation of myoelectric devices, especially for lower extremity use, is the unidirectional nature of control; specifically, these systems lack proprioceptive afferent information critical for reflexive and volitional control. This issue has been addressed by surgically creating an agonist-antagonist myoneural interface. This technique involves coaptation of antagonistic lower limb muscle groups within the residual limb, allowing antagonist stretch receptors to better communicate proprioceptive information to the central nervous system. Animal models have demonstrated the potential to communicate graded afferent signals in a manner similar to native muscle architecture^[71]. A subsequent trial of this method in a single human subject demonstrated objectively improved control over the prosthesis and provided a subjective sense of embodiment of the limb^[72].

Notable drawbacks to bionic componentry include increased costs and complexity, as well as the need for charging. Unreliable durability and increased weight are also problematic with myoelectric upper extremity componentry. When considering any prosthetic prescription, one must consider the patient’s functional expectations and goals, in addition to their aptitude for complex technology.

CONCLUSION

Determining whether to pursue amputation or reconstruction of a lower extremity is challenging for patients and practitioners alike - and is dependent on the patient’s premorbid health and function, functional goals and preferences in addition to the viability of the limb. The decision to undergo limb reconstruction or amputation is best made with input from surgeon, physical medicine and rehabilitation specialist, and patient in order to achieve the best long-term outcomes. Understanding the functional potential that can be achieved with different levels of amputation and types of and the available prosthetic and orthotic devices is critical to ensure that patients are well-informed of their options [Table 2]. Recent advances in prosthetic and orthotic devices have provided a wider range of options to achieve optimal outcomes. Integration of

Table 2. Surgical and prosthetic considerations by amputation level

	Surgical considerations	Prosthetic and orthotic considerations
Transmetatarsal amputation	Exact location of transection variable Closure via plantar flap or fishmouth incision Consider Achilles lengthening to reduce the risk of equinovarus deformity	Partial foot prosthesis with toe filler Carbon-fiber inlay or spring to provide additional force during terminal stance
Midfoot amputation (e.g., Lisfranc and Chopart)	Level of amputation dependent on joint space transected Useful when midfoot joint instability is present Greater propensity for equinovarus deformity and may require a balancing procedure	Similar prosthetic considerations to transmetatarsal amputation Consider contralateral shoe lift if orthotic causes limb length discrepancy
Syme amputation	Provides greater lever arm as compared to transtibial amputation Proximal heel pad used for coverage Partial weight bearing may proceed in early postoperative period	Limb length discrepancy almost always present Device must accommodate bulbous distal limb Prosthetic foot must offload compressive force on residual limb
Transtibial amputation	Location of transection important for both lever arm, prosthetic accommodation, and soft tissue coverage Myodesis is preferable if bone quality adequate Traction neurectomies should be performed in such a way to prevent neuroma formation	Consider componentry of prosthetic prescription individually Ankle joint axis should be chosen based on patient's level of functionality
Knee disarticulation	Generally preferable compared to transfemoral amputation Gastrocnemius muscle belly may be used to pad distal end Femoral epiphysis may be left intact in children to allow for growth	Choice of liner important to accommodate bulbous residual limb Position of prosthetic knee lies distal to contralateral knee, necessitating shortening of lower leg prosthesis
Transfemoral amputation	Soft-tissue envelope generally adequate Ideally transection occurs no more than 7 cm proximal to knee joint Preservation and anchoring of adductor magnus improves position of femur	Socket narrow in mediolateral dimension and incorporate ischium to promote femoral adduction Choice of prosthetic joints highly dependent on patient's ambulatory status

processing systems within prosthetic devices and the advent of myoelectric devices represent promising advancements in the field of prosthetic restoration. Limitations regarding sensibility and proprioception remain a hurdle for emulation of the native limb.

DECLARATIONS

Authors' contributions

Literature review: Crowe CS, Impastato KA, Donaghy AC, Earl C
 Primary manuscript drafting: Crowe CS, Impastato KA, Donaghy AC
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 Substantial manuscript revision: Earl C, Friedly JL, Keys KA

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REFERENCES

1. MacKenzie EJ, Bosse MJ, Kellam JF, Burgess AR, Webb LX, et al. Factors influencing the decision to amputate or reconstruct after high-energy lower extremity trauma. *J Trauma* 2002;52:641-9.
2. Bosse MJ, MacKenzie EJ, Kellam JF, Burgess AR, Webb LX, et al. An analysis of outcomes of reconstruction or amputation after leg-threatening injuries. *N Engl J Med* 2002;347:1924-31.
3. Russell Esposito E, Stinner DJ, Ferguson JR, Wilken JM. Gait biomechanics following lower extremity trauma: amputation vs. reconstruction. *Gait Posture* 2017;54:167-73.
4. Saddawi-Konefka D, Kim HM, Chung KC. A systematic review of outcomes and complications of reconstruction and amputation for type IIIB and IIIC fractures of the tibia. *Plast Reconstr Surg* 2002;122:1796-805.
5. Pinzur MS, Pinto MA, Saltzman M, Batista F, Gottschalk F, et al. Health-related quality of life in patients with transtibial amputation and reconstruction with bone bridging of the distal tibia and fibula. *Foot Ankle Int* 2006;27:907-12.
6. MacKenzie EJ, Jones AS, Bosse MJ, Castillo RC, Pollak AN, et al. Health-care costs associated with amputation or reconstruction of a limb-threatening injury. *J Bone Joint Surg Am* 2007;89:1685-92.
7. Chung KC, Saddawi-Konefka D, Haase SC, Kaul G. A cost-utility analysis of amputation versus salvage for Gustilo IIIB and IIIC open tibial fractures. *Plast Reconstr Surg* 2009;124:1965-73.
8. Waters RL, Mulroy S. The energy expenditure of normal and pathologic gait. *Gait Posture* 1999;9:207-31.
9. Schmalz T, Blumentritt S, Jarasch R. Energy expenditure and biomechanical characteristics of lower limb amputee gait: the influence of prosthetic alignment and different prosthetic components. *Gait Posture* 2002;16:255-63.
10. Buckley JG, Spence WD, Solomonidis SE. Energy cost of walking: comparison of "intelligent prosthesis" with conventional mechanism. *Arch Phys Med Rehabil* 1997;78:330-3.
11. Zhang M, Turner-Smith AR, Roberts VS, Tanner A. Frictional action at lower limb/prosthetic socket interface. *Med Eng Phys* 1996;18:207-14.
12. Asano M, Rushton P, Miller WC, Deathe BA. Predictors of quality of life among individuals who have a lower limb amputation. *Prosthet Orthot Int* 2008;32:231-43.
13. Hertel R, Strebel N, Ganz R. Amputation versus reconstruction in traumatic defects of the leg: outcome and costs. *J Orthop Trauma* 1996;10:223-9.
14. McKittrick LS, McKittrick JB, Risley TS. Transmetatarsal amputation for infection or gangrene in patients with diabetes mellitus. *Ann Surg* 1949;130:826-40.
15. Garwood CS, Steinberg JS. Soft tissue balancing after partial foot amputations. *Clin Podiatr Med Surg* 2016;33:99-111.
16. Mueller MJ, Allen BT, Sinacore DR. Incidence of skin breakdown and higher amputation after transmetatarsal amputation: implications for rehabilitation. *Arch Phys Med Rehabil* 1995;76:50-4.
17. Thomas SR, Perkins JM, Magee TR, Galland RB. Transmetatarsal amputation: an 8-year experience. *Ann R Coll Surg Engl* 2001;83:164-6.
18. Pollard J, Hamilton GA, Rush SM, Ford LA. Mortality and morbidity after transmetatarsal amputation: retrospective review of 101 cases. *J Foot Ankle Surg* 2006;45:91-7.
19. Mueller MJ, Strube MJ, Allen BT. Therapeutic footwear can reduce plantar pressures in patients with diabetes and transmetatarsal amputation. *Diabetes Care* 1997;20:637-41.
20. Tang SF, Chen CP, Chen MJ, Chen WP, Leong CP, et al. Transmetatarsal amputation prosthesis with carbon-fiber plate: enhanced gait function. *Am J Phys Med Rehabil* 2004;83:124-30.
21. Rommers GM, Diepstraten HJ, Bakker E, Lindeman E. Shoe adaptation after amputation of the II - V phalangeal bones of the foot. *Prosthet Orthot Int* 2006;30:324-9.
22. Spaulding SE, Chen T, Chou LS. Selection of an above or below-ankle orthosis for individuals with neuropathic partial foot amputation: a pilot study. *Prosthet Orthot Int* 2012;36:217-24.
23. Lis Franc J. Nouvelle methode operateire pour l'amputation partielle dans so articulation tarsometatarsienne. Paris, France; 1815. Available from: <https://play.google.com/books/reader?id=emJtsrU3Sv8C&hl=en&pg=GBS.PA3>. [Last accessed on 22 Feb 2019]
24. DeCotiis MA. Lisfranc and Chopart amputations. *Clin Podiatr Med Surg* 2005;22:385-93.
25. Schweinberger MH, Roukis TS. Surgical correction of soft-tissue ankle equinus contracture. *Clin Podiatr Med Surg* 2008;25:571-85.
26. Schweinberger MH, Roukis TS. Soft-tissue and osseous techniques to balance forefoot and midfoot amputations. *Clin Podiatr Med Surg* 2008;4:623-39.
27. Krause FG, Aebi H, Lehmann O, Weber M. The "flap-shaft" prosthesis for insensate feet with Chopart or Lisfranc amputations. *Foot Ankle Int* 2007;28:255-62.
28. Syme J. Amputation at the ankle joint. *J Med Sci* 1843;2:93.
29. Pinzur MS, Gold J, Schwartz D, Gross N. Energy demands for walking in dysvascular amputees as related to the level of amputation. *Orthopedics* 1992;15:1033-6; discussion 1036-7.
30. Pinzur MS, Gottschalk F, Smith D, Shanfield S, de Andrade R, et al. Functional outcome of below-knee amputation in peripheral vascular insufficiency. *Clin Orthop Relat Res* 1993;286:247-9.
31. Pinzur MS. Restoration of walking ability with Syme's ankle disarticulation. *Clin Orthop Relat Res* 1999;361:71-5.
32. Smith DG. Amputation: Preoperative assessment and lower extremity surgical techniques. *Foot Ankle Clin* 2001;6:271-96.
33. Cifu DX. Braddom's physical medicine & rehabilitation, 5th ed. Philadelphia, PA: Elsevier Mosby; 2006.
34. Klute GK, Glaister BC, Berge JS. Prosthetic liners for lower limb amputees: a review of the literature. *Prosthet Orthot Int* 2010;34:146-53.

35. Sanders JE, Greve JM, Mitchell SB, Zachariah SG. Material properties of commonly-used interface materials and their static coefficients of friction with skin and socks. *J Rehabil Res Dev* 1998;35:161-76.
36. Hachisuka K, Matsushima Y, Ohmine S, Shitama H, Shinkoda K. Moisture permeability of the total surface bearing prosthetic socket with a silicone liner: is it superior to the patella-tendon bearing prosthetic socket? *J UOEH* 2001;23:225-32.
37. Klute GK, Rowe GI, Mamishev AV, Ledoux WR. The thermal conductivity of prosthetic sockets and liners. *Prosthet Orthot Int* 2007;31:292-9.
38. Sanders JE, Nicholson BS, Zachariah SG, Cassisi DV, Karchin A, et al. Testing of elastomeric liners used in limb prosthetics: classification of 25 products by mechanical performance. *J Rehabil Res Dev* 2004;41:175-86.
39. Powers CM, Torburn L, Perry J, Ayyappa E. Influence of prosthetic foot design on sound limb loading in adults with unilateral below-knee amputations. *Arch Phys Med Rehabil* 1994;75:825-9.
40. Casillas JM, Dulieu V, Cohen M, Marcer I, Didier JP. Bioenergetic comparison of a new energy-storing foot and SACH foot in traumatic below-knee vascular amputations. *Arch Phys Med Rehabil* 1995;76:39-44.
41. Snyder RD, Powers CM, Fontaine C, Perry J. The effect of five prosthetic feet on the gait and loading of the sound limb in dysvascular below-knee amputees. *J Rehabil Res Dev* 1995;32:309-15.
42. Postema K, Hermens HJ, de Vries J, Koopman HF, Eisma WH. Energy storage and release of prosthetic feet. Part 1: biomechanical analysis related to user benefits. *Prosthet Orthot Int* 1997;21:17-27.
43. Perry J, Boyd LA, Rao SS, Mulroy SJ. Prosthetic weight acceptance mechanics in transtibial amputees wearing the Single Axis, Seattle Lite, and Flex-Foot. *IEEE Trans Rehabil Eng* 1997;5:283-9.
44. Huang GF, Chou YL, Su FC. Gait analysis and energy consumption of below-knee amputees wearing three different prosthetic feet. *Gait Posture* 2000;12:162-8.
45. Wagner FW. Management of the diabetic neurotrophic foot. Part II. A classification and treatment program for diabetic, neuropathic, and dysvascular foot problems. *Instructional course lectures* 1979;28:143-65.
46. Pinzur MS, Bowker JH. Knee disarticulation. *Clin Orthop Relat Res* 1999;361:23-28.
47. Pinzur MS, Smith DG, Daluga DJ, Osterman H. Selection of patients for through-the-knee amputation. *J Bone Joint Surg Am* 1988;70:746-50.
48. Gottschalk F. Transfemoral amputation. Biomechanics and surgery. *Clin Orthop Relat Res* 1999;361:15-22.
49. Volpicelli LJ, Chambers RB, Wagner FW. Ambulation levels of bilateral lower-extremity amputees. Analysis of one hundred and three cases. *J Bone Joint Surg Am* 1983;65:599-605.
50. Tan J. Practical manual of physical medicine and rehabilitation, 2nd ed. Philadelphia, PA: Elsevier Mosby; 2006. pp. 257-9.
51. Hafner BJ, Smith DG. Differences in function and safety between Medicare Functional Classification Level-2 and -3 transfemoral amputees and influence of prosthetic knee joint control. *J Rehabil Res Dev* 2009;46:417-33.
52. Helfet DL, Howey T, Sanders R, Johansen K. Limb salvage versus amputation: Preliminary results of Mangled Extremity Severity Score. *Clin Orthop* 1990;256:80-6.
53. Howe HR Jr, Poole GV Jr, Hansen KJ, Clark T, Plonk GW, Koman LA, Pennell TC. Salvage of lower extremities following combined orthopedic and vascular trauma. A predictive salvage index. *Am Surg* 1987;53:205-8.
54. Russell WL, Sailors DM, Whittle TB, Fisher DF Jr, Burns RP. Limb salvage versus traumatic amputation: A decision based on a seven-part predictive index. *Ann Surg* 1991;213:473-81.
55. McNamara MG, Heckman JD, Corley EG. Severe open fracture of the lower extremity: a retrospective evaluation of Mangled Extremity Severity Score. *J Orthop Trauma* 1994;8:81-7.
56. Tschern H, Oestern HJ. A new classification of soft tissue damage in open and closed fractures. *Unfallheilkunde* 1982;85:111-5.
57. Johansen K, Daines M, Howey T, Helfet D, Hansen ST Jr. Objective criteria accurately predict amputation following extremity trauma. *J Trauma* 1990;30:568-73.
58. Ong YS, Levin LS. Lower limb salvage in trauma. *Plast Reconstr Surg* 2010;125:582-8.
59. Chen WP, Ju CW, Tang FT. Effects of total contact insoles on the plantar stress redistribution: a finite element analysis. *Clin Biomech* 2003;18:S17-24.
60. Tang SF, Chen CP, Hong WH, Chen HT, Chu NK, et al. Improvement of gait by using orthotic insoles in patients with heel injury who received reconstructive flap operations. *Am J Phys Med Rehabil* 2003;82:350-6.
61. Chen JT, Tang AC, Hong WH, Tang SF. The effects of heel-elevated total contact insole on rearfoot pressure reduction in heel injury patients who had neurosensory impairment after receiving reconstructive flap operations. *Clin Neurol Neurosurg*. 2015;129 Suppl 1:S47-52.
62. Koller C, Arch ES. State of the prescription process for dynamic ankle-foot orthoses. *Curr Phys Med Rehabil Rep* 2018;6:55-61.
63. Wach A, McGrady L, Wang M, Silver-Thorn B. Assessment of mechanical characteristics of ankle-foot orthoses. *J Biomech Eng* 2018;140.
64. Highsmith MJ, Nelson LM, Carbone NT, Klenow TD, Kahle JT, et al. Outcomes associated with the intrepid dynamic exoskeletal orthosis (IDEO): a systematic review of the literature. *Mil Med* 2016;181:69-76.
65. Patzkowski JC, Blanck RV, Owens JG, Wilken JM, Blair JA, et al. Can an ankle-foot orthosis change hearts and minds? *J Surg Orthop Adv* 2011;20:8-18.
66. Blair JA, Patzkowski JC, Blanck RV, Owens JG, Hsu JR, et al. Return to duty after integrated orthotic and rehabilitation initiative. *J Orthop Trauma* 2014;28:e70-4.
67. Kannenberg A, Zacharias B, Pröbsting E. Benefits of microprocessor prosthetic knees to limited community ambulators: a systematic review. *J Rehabil Res Dev* 2014;51:1469-95.
68. Sawers AB, Hafner BJ. Outcomes associated with the use of microprocessor-controlled prosthetic knees among individuals with unilateral transfemoral limb loss: a systematic review. *J Rehab Res Dev* 2013;50:273-314.
69. Fuenzalida Squella SA, Kannenberg A, Brandão Benetti Â. Enhancement of a prosthetic knee with a microprocessor-controlled gait phase

switch reduces falls and improves balance confidence and gait speed in community ambulators with unilateral transfemoral amputation. *Prosthet Orthot Int* 2018;42:228-35.

70. Kapelner T, Negro F, Aszmann OC, Farina D. Decoding motor unit activity from forearm muscles: perspectives for myoelectric control. *IEEE Trans Neural Syst Rehabil Eng* 2018;26:244-51.
71. Clites TR, Carty MJ, Srinivasan S, Zorzos AN, Herr HM. A murine model of a novel surgical architecture for proprioceptive muscle feedback and its potential application to control of advanced limb prostheses. *J Neural Eng* 2017;14:036002.
72. Clites TR, Carty MJ, Ullauri JB, Carney ME, Mooney LM, et al. Proprioception from a neurally controlled lower-extremity prosthesis. *Sci Transl Med* 2018;10:eaap8373.

Technical Note

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An updated diced cartilage fascia technique for dorsal augmentation in rhinoplasty

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Abstract

The aim of this paper is to discuss an updated technique for dorsal augmentation during rhinoplasty using diced cartilage wrapped in fascia. The usage of diced cartilage has been variously described in the literature with consistently satisfactory results. Herein, we present our experience with patients undergoing dorsal augmentation during rhinoplasty using an updated method of diced cartilage wrapped in fascia. Diced cartilage fascia techniques have become the technique of choice for dorsal augmentation for an ever-increasing number of rhinoplasty surgeons. The term is broadly descriptive and there remains a wide-range of ways to execute. Updating and enhancing the technique with greater attention to precision, and creating an aesthetically optimal and predictable result, may result in even improved outcomes for future patients.

Keywords: Rhinoplasty, revision rhinoplasty, dorsal augmentation, costal cartilage, diced cartilage, asian rhinoplasty, DCF, diced cartilage fascia

INTRODUCTION

In the practice of medicine, the concept of the “gold standard” refers to the best available test or treatment under reasonable conditions. Given the relative lack of purely objective experimentation and testing in



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rhinoplasty, no such criterion standard yet exists for dorsal augmentation. In the ongoing pursuit of the optimal technique for augmenting the dorsum during primary and revision rhinoplasty, surgeons have continuously sought to increase precision, safety, and permanence.

The history of dorsal augmentation during rhinoplasty emulates in many ways the progression of increasingly higher standards of care in medicine driven by technological advances and rapidly evolving therapies. Early attempts were decidedly crude, with a wide assortment of everyday materials including ivory^[1] and jade used to increase the height of the nose. Through the years surgeons have attempted to improve outcomes by utilizing a variety of autologous and alloplastic materials, including: cartilage, bone^[2-4], fascia^[5] diced cartilage and fascia^[6-9], silicone^[10-12], medpore^[13], polytetrafluorethylene^[14,15], supramid^[16], proplast^[17], vicryl^[18], and mersilene^[19]. All with mixed results.

While many contemporary surgeons favor autologous grafts in an onlay configuration for mild to moderate amounts of dorsal augmentations^[2,10,20], cases demanding a larger volume of graft materials have prompted surgeons to explore alloplastic (silicone, Goretex, *etc.*) and homoplastic (irradiated costal cartilage) options in addition to autologous options given the ease of obtaining grafts, and the absence of any donor site morbidity^[2-5]. However, a primary downside of these grafts has proven to be the relatively high risk of complications compared to autologous graft techniques, driving other surgeons to pursue this avenue more intently.

The use of diced cartilage in dorsal augmentation has been periodically documented in the English-language literature as early as 1943 by Peer, in 1951 by Cottle, and in 1968 by Burian, though it did not gain wide-spread acceptance at the time^[21-23]. Guerrerosantos revisited this concept in the 1990s^[8], refining the technique by wrapping fragmented cartilage in fascia, while Erol brought a larger audience with his description of wrapping diced cartilage in Surgicel in 2000^[24], then Daniel subsequently brought a renewed interest in wrapping diced cartilage in fascia^[6,7]. Modifications of the concept of using diced cartilage as the building block for dorsal augmentation have been variously described, primarily adding assorted tissue adhesives to ease shaping of the graft, altering the material wrapping the cartilage, or foregoing an encasement altogether^[9,25-30]. The manifold existing descriptions in the literature notwithstanding, a systematic approach refining the surgical technique to achieve greater precision and consistency using diced cartilage with fascia has not been previously delineated.

Diced cartilage with fascia represents a potentially ideal graft for dorsal augmentation as it makes use of the lower complication rates associated with autologous grafts, while also providing a graft that has the ability to recreate dorsal aesthetic lines in a natural and predictable manner. The usage of diced cartilage has been variously described in the literature, with consistently satisfactory results reported. Herein, we present our experience, with patients undergoing dorsal augmentation during rhinoplasty, using an updated method of diced cartilage wrapped in fascia.

SURGICAL TECHNIQUE

Proper surgical planning and preparation for dorsal augmentation begins with the consultation and pre-operative visit, wherein the nasal anatomy should be thoroughly assessed, and the aesthetic goals of surgery defined, with particular attention directed at the dorsum, established with the patient.

The primary consideration with regards to the pre-operative nasal anatomy is the shape and integrity of the platform created by the confluence of the upper lateral cartilages along the dorsal septum. The presence of significant contour irregularities such as a dorsal hump or inverted-V deformities, indicate the need for proper preparation and modification of the dorsum to support a diced cartilage wrapped in fascia (DCF)

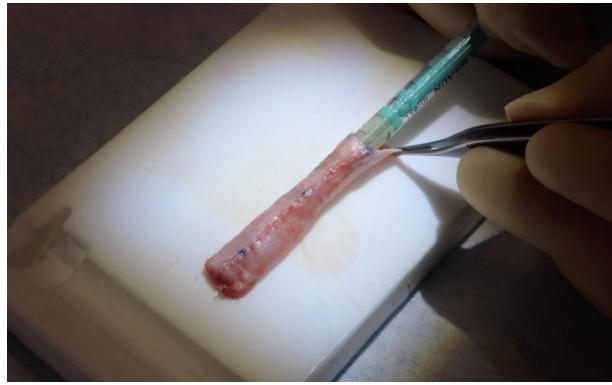


Figure 1. Care is taken to ensure the diced cartilage flows freely through the hub of the syringe

graft. Physical exam findings in conjunction with the patient's aesthetic desires dictate the most appropriate source of graft material.

Computer-imaging is also a beneficial communication tool between surgeon and patient as it allows a focused discussion of the patient's anticipated results with the realities and limitations of surgery, as well as the types and degrees of potential changes. This provides the surgeon an opportunity to more accurately gauge the desired shape of the nose and dorsum with regards to nasofrontal angle, radix height, dorsal height, length, and supratip break, which become important considerations in shaping the DCF.

Pre-operatively, the patient is marked in the upright position. The anticipated nasal starting point, dorsal convexity - if present, desired supratip break, and the midline of the face should be marked, as well as the inframammary/infrapectoral crease and xiphoid in the case of costal cartilage harvest.

Cartilage may be harvested from the septum, ears, or rib, depending on the volume requirements of the dorsal augmentation. The physical characteristics of the cartilage sources do vary, with softer cartilage allowing for finer dicing and greater pliability once placed within fascia. Dicing of the cartilage to < 0.5 mm pieces is recommended to minimize the risk of contour irregularities, as shown in [Figure 1](#).

While fascia may be obtained from multiple sources, deep temporalis fascia is the thinnest of commonly used options, and produces minimal donor site morbidity. Once healed, the diced cartilage within the DCF provides the lasting volume, while the fascia simply acts as a temporary vehicle to place and shape the cartilage. For this reason, thinner fascia is preferable for more precise titration of graft size and shape. Care should be taken during fascia harvest to ensure adequate surface area (> 5 cm × 3.5 cm) and that all extraneous fat and muscle is meticulously removed to create the thinnest and most uniform layer of tissue, as shown in [Figures 2 and 3](#).

Once the deep temporalis fascia has been thinned, it is sutured longitudinally into a cylindrical shape with a running-locking 5-0 vicryl to avoid any escape of diced cartilage from the construct. The width of the cylinder is determined by the desired width as well as height of the patient's bridge, generally in a range between 3.2-3.5 cm of fascia diameter. One end of the fascia is then closed and filled with an estimated volume of diced cartilage, then placed along the nasal dorsum.

The DCF will contract and dehydrate when healed, so every effort is made to remove fluid from the DCF prior to making measurements for its final dimensions. The cephalic end of the DCF is placed at the previously marked nasal starting point, and the supratip break marked caudally. The fascia is then closed

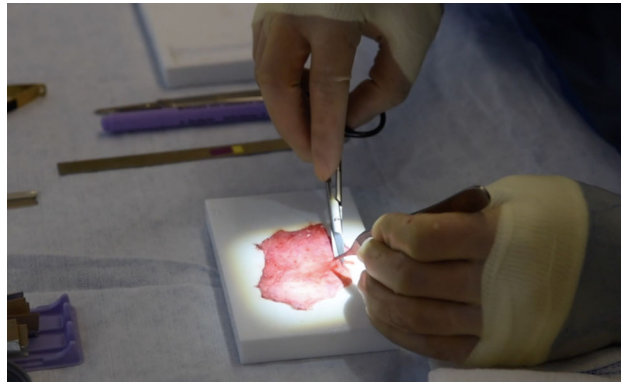


Figure 2. Removal of all excess fat, muscle, and adherent superficial fascia to preserve only the deep temporalis fascia



Figure 3. Demonstrating adequate fascia surface area (> 5 cm × 3.5 cm)

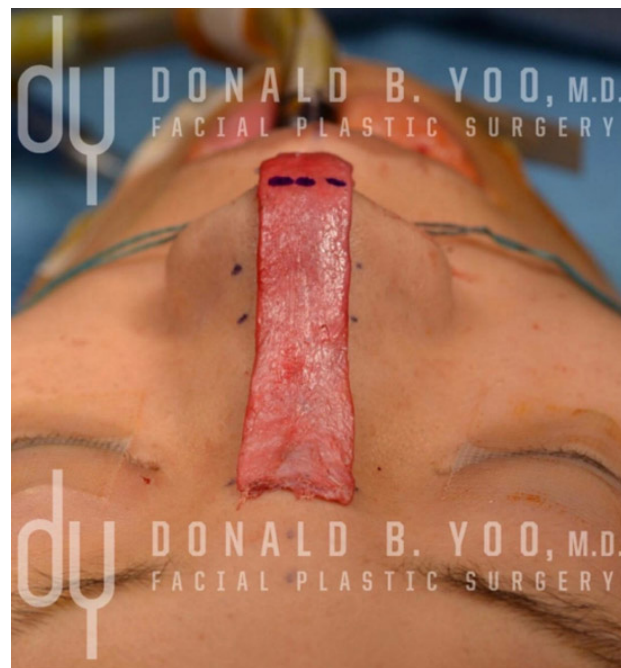


Figure 4. The dimensions of the diced cartilage wrapped in fascia are determined by placement on top of the patient's dorsum



Figure 5. The diced cartilage wrapped in fascia is adjusted to account for the nasal starting point, dorsal aesthetic line, and supratip break

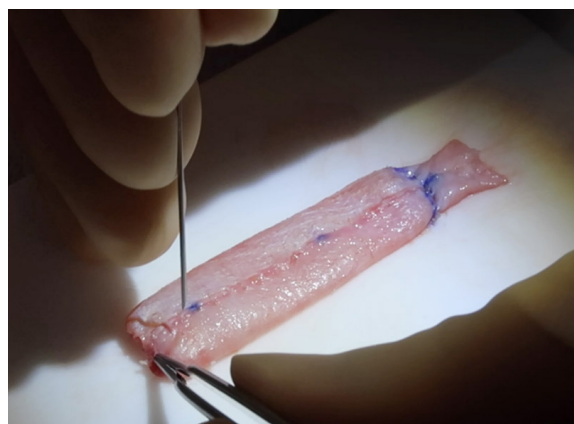


Figure 6. Fenestrations are created throughout the diced cartilage fascia to allow for free effusion of any remaining fluid to promote earlier vascular and fibrous ingrowth

along the supratip break with a 5-0 vicryl, creating a portion of the construct filled with diced cartilage, and a tab of fascia without cartilage used to secure the complex to the supratip and tip complex, as shown in [Figures 4 and 5](#).

A needle is used to create fenestrations throughout the DCF, to allow for free effusion of any remaining fluid within the construct, and to promote quicker fibrous and vascular ingrowth into the graft [\[Figure 6\]](#). Corset sutures are placed to taper the graft from a cylindrical shape to a more parabolic shape, consistent with the appearance of the desired dorsal aesthetic lines [\[Figure 7\]](#). These corset sutures may be used to great effect to finely calibrate the proportions and dimensions of the graft.

When the final shape has been achieved, the DCF may be placed again along the dorsum of the nose to evaluate the size and shape one final time prior to placement. Deficiency or excess volume and height may be adjusted by making a small incision along the DCF and removing or adding diced cartilage as deemed necessary.

The DCF is secured along its cephalic and caudal ends, and its body shaped by casting. A percutaneous suture is placed through the marked starting point, and secured to the cephalic end of DCF. In cases of excessively wide skin dissection and a resultant large dorsal pocket - such as in removal of a previous implant or graft, multiple percutaneous sutures may be placed to allow for more secure fixation. Along the caudal aspect of the construct, the fascia is secured to the supratip and over the tip complex. The nasal skin envelope may then be re-draped and the shape of the dorsum evaluated.

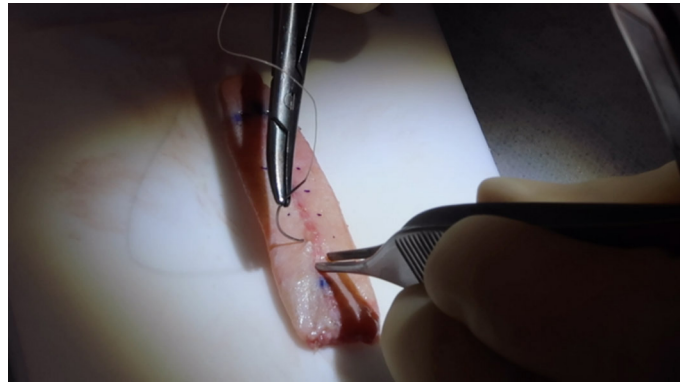


Figure 7. Precise placement of corset sutures allows for the creation of dorsal aesthetic lines



Figure 8. (A, C) Frontal, oblique and (B, D) lateral views of Patient 1 before and 2.5 years after primary rhinoplasty with rib cartilage and diced cartilage fascia

Casting is the last step and is critical for a successful result. The shape and position of the mid-portion of the graft relies heavily on precise molding and contouring of the cast to shape the coagulum of diced cartilage within the DCF. For this reason, casting with a thermoplastic splint is recommended to allow for precise shaping. Once the ideal shape has been obtained, ice-cold water is poured liberally on the cast to lock in the final shape. The cast and percutaneous sutures are removed 1 week post-operatively. Case examples of primary and revision rhinoplasties using the updated dice cartilage technique are demonstrated in [Figures 8-10](#), respectively. The dorsum will initially be much wider and taller, but the majority of the swelling will resolve in 3-6 months with the final results in 1-2 years.



Figure 9. (A, C) Frontal, oblique and (B, D) lateral views of Patient 2 before and 8 months after revision rhinoplasty with rib cartilage and diced cartilage fascia. Previous over-aggressive rhinoplasty resulted in low dorsum

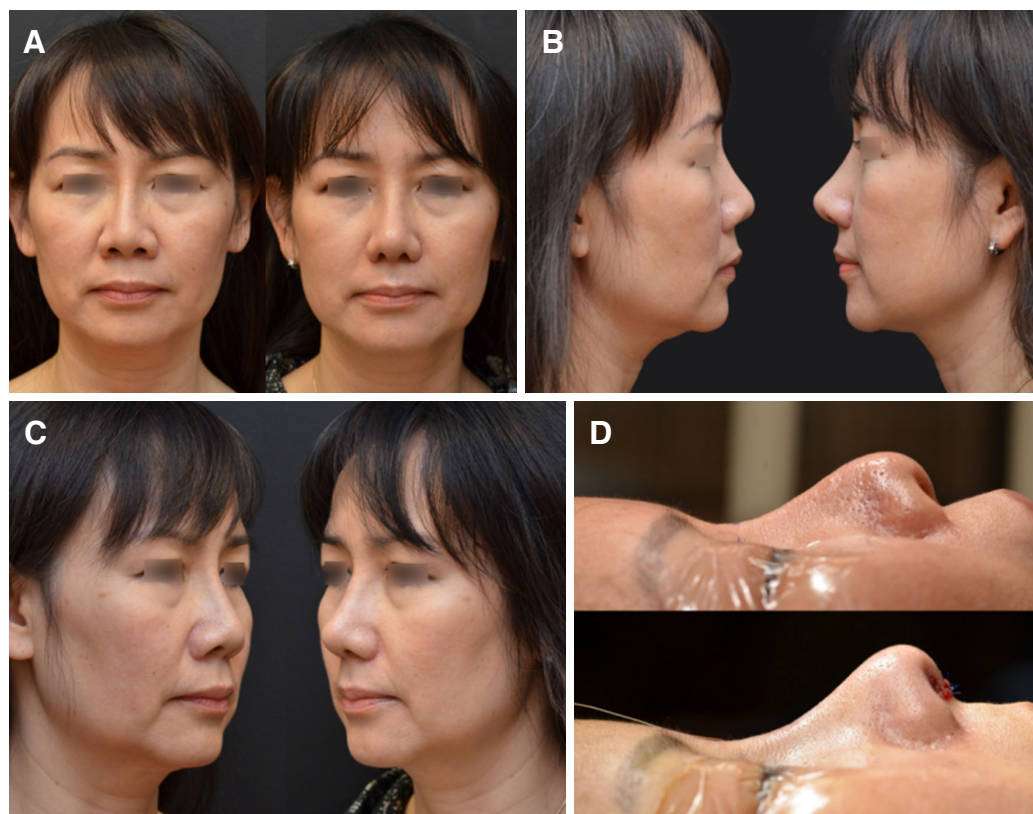


Figure 10. (A, C) Frontal, oblique and (B, D) lateral views of Patient 3 before and 1 year after revision Asian rhinoplasty with rib cartilage and diced cartilage fascia. Previous rhinoplasty with silicone implant

DISCUSSION

Given the contemporary focus of minimizing complications and creating a life-long result, many rhinoplasty surgeons have shifted towards exclusively using autologous grafts during dorsal augmentation. Diced cartilage fascia techniques have proven attractive for a number of reasons, including their relative pliability, wide availability of materials needed for the construct, and the perceived forgiving nature with regards to contour irregularities.

Diced cartilage fascia techniques for dorsal augmentation in rhinoplasty and revision rhinoplasty have been variously utilized and described for over half a century. Despite producing satisfactory results in many cases, it has received criticism at times for creating a “sausage-like” appearance or an otherwise unnatural look to the dorsum. Also despite its perception as forgiving, it does have a somewhat large inter-surgeon variance with regards to aesthetic outcomes. The term is broadly descriptive, and there remains a wide-range of ways to execute it.

Contour irregularities remain the most common reason for surgeon and patient dissatisfaction after dorsal augmentation using diced cartilage with fascia. Sub-optimal contours may manifest in the form of convexities and concavities, over or under augmentation, deviation, asymmetries, and unnatural dorsal aesthetic lines. Occasionally, natural variations in nasal skin envelope thickness and sebaceous qualities between the dorsum, supratip, tip, infratip and columella, as well as scarring from previous surgeries, may result in a less than ideal appearance to the nasal starting point, radix, dorsum, supratip break, nasal tip, infratip lobule, and columella. Conservative management of minor contour irregularities with nasal exercises (especially within the first month following surgery), and directed injections of kenalog and 5-fluorouracil, will successfully address many of the irregularities observed in the early post-operative period. Persistent contour irregularities beyond post-operative edema involving coalesced diced cartilage will infrequently warrant revision surgery to address.

This updated diced cartilage fascia technique seeks to eliminate variance and enhance precision to create more predictable and consistently beautiful results. Placing greater emphasis on precision and a more algorithmic approach to constructing the DCF graft may result in even improved outcomes for future patients.

DECLARATIONS

Authors' contributions

The authors contributed solely to the article.

Availability of data and materials

Not applicable.

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Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Written informed consent was obtained for all patients.

Consent for publication

Written informed consent was obtained for all patient images.

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REFERENCES

1. Vilar-Sancho B. An old story: an ivory nasal implant. *Aesthetic Plast Surg* 1987;11:157-61.
2. Krause CJ. Augmentation rhinoplasty. *Otolaryngol Clin North Am* 1975;8:743-52.
3. Wheeler ES, Kawamoto HK, Zarem HA. Bone grafts for nasal reconstruction. *Plast Reconstr Surg* 1982;69:9-18.
4. Romo T 3rd, Jablonski RD. Nasal reconstruction using split calvarial grafts. *Otolaryngol Head Neck Surg* 1992;107:622-30.
5. Leaf N. SMAS autografts for the nasal dorsum. *Plast Reconstr Surg* 1996;97:1249-52.
6. Daniel RK. *Rhinoplasty: an atlas of surgical techniques*. New York: Springer; 2002. pp. 11-2.
7. Daniel RK, Calvert JW. Diced cartilage grafts in rhinoplasty surgery. *Plast Reconstr Surg* 2004;113:2156-71.
8. Guerrerosantos J, Trabanino C, Guerrerosantos F. Multifragmented cartilage wrapped with fascia in augmentation rhinoplasty. *Plast Reconstr Surg* 2006;117:804-12; discussion 13-6.
9. Cerkas N, Basaran K. Diced cartilage grafts wrapped in rectus abdominis fascia for nasal dorsum augmentation. *Plast Reconstr Surg* 2016;137:43-51.
10. Regnault P. Nasal augmentation in the problem nose. *Aesthetic Plast Surg* 1987;11:1-5.
11. Khoo BC. Augmentation rhinoplasty in the orientals. *Plast Reconstr Surg* 1964;34:81-8.
12. Beekhuis GJ. Silastic alar-columellar prosthesis in conjunction with rhinoplasty. *Arch Otolaryngol* 1982;108:429-32.
13. Wellisz T. Clinical experience with the Medpor porous polyethylene implant. *Aesthetic Plast Surg* 1993;17:339-44.
14. Godin MS, Waldman SR, Johnson CM Jr. The use of expanded polytetrafluoroethylene (Gore-Tex) in rhinoplasty. A 6-year experience. *Arch Otolaryngol Head Neck Surg* 1995;121:1131-6.
15. Queen TA, Palmer FR 3rd. Gore-tex for nasal augmentation: a recent series and a review of the literature. *Ann Otol Rhinol Laryngol* 1995;104:850-2.
16. Adams JS. Grafts and implants in nasal and chin augmentation. A rational approach to material selection. *Otolaryngol Clin North Am* 1987;20:913-20.
17. Juraha LZ. Experience with alternative material for nasal augmentation. *Aesthetic Plast Surg* 1992;16:133-40.
18. Gilmore J. Use of vicryl mesh in prevention of postrhinoplasty dorsal irregularities. *Ann Plast Surg* 1989;22:105-7.
19. Fanous N. Mersilene tip implants in rhinoplasty: a review of 98 cases. *Plast Reconstr Surg* 1991;87:662-71; discussion 72-3.
20. Gunter JP, Rohrich RJ. Augmentation rhinoplasty: dorsal onlay grafting using shaped autogenous septal cartilage. *Plast Reconstr Surg* 1990;86:39-45.
21. Peer LA. Diced cartilage grafts: new method for repair of skull defects, mastoid fistula and other deformities. *Arch Otolaryngol* 1943;38:156-65.
22. Cottle MH. Nasal surgery in children. *Eye Ear Nose Throat Mon* 1951;30:32-8.
23. Burian F. *The plastic surgery atlas*. New York: Macmillan; 1968.
24. Erol OO. The Turkish delight: a pliable graft for rhinoplasty. *Plast Reconstr Surg* 2000;105:2229-41; discussion 42-3.
25. Berghaus A, San Nicolo M, Jacobi C. Use of a fibrinogen-thrombin sponge in rhinoplasty. *Hno* 2018;66:103-10.
26. Hoehne J, Gubisch W, Kreutzer C, Haack S. Refining the nasal dorsum with free diced cartilage. *Facial Plast Surg* 2016;32:345-50.
27. Erol OO. Injection of compressed diced cartilage in the correction of secondary and primary rhinoplasty: a new technique with 12 years' experience. *Plast Reconstr Surg* 2017;140:673e-85.
28. Tasman AJ. Advances in nasal dorsal augmentation with diced cartilage. *Curr Opin Otolaryngol Head Neck Surg* 2013;21:365-71.
29. Tasman AJ. Dorsal augmentation-diced cartilage techniques: the diced cartilage glue graft. *Facial Plast Surg* 2017;33:179-88.
30. Kovacevic M, Riedel F, Wurm J, Bran GM. Cartilage scales embedded in fibrin gel. *Facial Plast Surg* 2017;33:225-32.

Review

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Revision rhinoplasty using autologous rib cartilage in Asians

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Abstract

A considerable part of revision rhinoplasty in Asians is associated with problems arising from the use of alloplastic implants. Revising alloplast associated problems of the nose mostly requires the use of autogenous grafting material to minimize complications and maximize favorable outcomes. Although remnant septal cartilage and/or conchal cartilage can be used, as the deformity becomes more severe, adequate revision requires more volume and strength of grafting materials. Autogenous rib cartilage may be the most practical choice in these circumstances. In this review, common causes of revision rhinoplasty in Asians are discussed together with operative techniques with emphasis on the use of autologous rib cartilage.

Keywords: Rhinoplasty, Asian, revision, rib cartilage

INTRODUCTION

The increasing number of primary rhinoplasties coupled with heightened patient expectations, has led to an increase of revision surgery. In a recent study of revision rhinoplasty in Asians, we have shown that most revision rhinoplasties were associated with problems arising from the use of alloplastic implants, reflecting the trend of using alloplastic implants in many Asian countries^[1]. Although studies and years of clinical experience have proven that these implants can be used safely, incorrect surgical techniques coupled with inappropriate patient selection, can cause an array of complications.



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Table 1. Causes of revision rhinoplasty in Asians^[1]

Main etiology for revision rhinoplasty (n = 52)	
Alloplast related (n = 33)	33 (63%)
Deviation	12
Foreign body	5
Extrusion	5
Infection	4
Unnatural look	4
Contracture (short nose)	3
Alloplast unrelated (n = 19)	19 (37%)
Mainly upper two-thirds problem (n = 12)	
Residual deviation	7
Dorsal irregularity or depression	4
Residual hump	1
Mainly tip problem (n = 7)	
Tip underprojection (loss of projection)	2
Upturned, overrotated tip	2
Visible graft	2
Tip deviation	1
Nasal obstruction	4

Like other revision surgeries, the difficulty of revision rhinoplasty arises not only from the effort it takes to correct the specific deformities and scars left by the primary surgery, but also from the psychological stress experienced by both the patient and the surgeon. An in-depth understanding and sufficient experience in various rhinoplasty techniques together with familiarity with the alloplasts' characteristics and related complications become necessary with dealing with the highly variable cases of Asian revision rhinoplasty^[2-7].

Remnant septal cartilage and/or conchal cartilage can be used for the revision procedure. However, as the deformities become more severe, adequate revision requires more volume and strength of grafting materials. This usually far exceeds available septal cartilage and the need for adequate strength precludes the use of conchal cartilage. Autogenous costal cartilage is a favorable grafting material and may be the only practical choice in these circumstances.

In this review, common causes of revision rhinoplasty in Asians are discussed as well as operative techniques that focus on the use of autologous costal cartilage are presented.

REVISION RHINOPLASTY IN ASIANS

The main reasons for revision rhinoplasty in Asians often involve issues with alloplastic implants. Common indications for revision rhinoplasty that we have encountered are as follows and are summarized in Table 1^[1].

Alloplast-related complications such as deviation, extrusion, infection, short and contracted nose after multiple surgeries involving alloplastic implants, dorsal deviation and/or irregularity and tip problems related to septal extension graft.

Alloplast related complications

Even though trends change silastic implants remain the single most commonly used alloplastic implant in Asia^[7-9]. Despite the fact that they can be better tolerated by the thicker skin and soft tissue envelope (SSTE) of the Asian nose^[10], silicone implants have been heavily criticized for their association with various complications^[11]. Typical examples of alloplast-related complications include unnatural or operated appearance, deviation, extrusion of the implant, infection, foreign body reaction and compromised SSTE. Proper selection of patients, adherence to proper surgical techniques and acquiring the necessary techniques to manage complications when they occur are important^[1,7].



Figure 1. Infection of an alloplastic implant used for dorsal augmentation showing pus coming out from the nasal tip



Figure 2. Short and contracted nose after multiple rhinoplasties

Infection with alloplastic implants can occur immediately or years after surgery [Figure 1]^[12-15]. Although aggressive antibiotic therapy can be undertaken, the chances of implant salvage are low, especially in cases where e-PTFE has been used^[13,15]. There is no consensus on the timing of the definitive revision rhinoplasty after implant removal. Currently, the mainstay of treatment is a staged approach with removal of the alloplast and subsequent revision operation after infection control. Although it can provide a more sterile environment, the delay in surgery can result in contracture of the overlying SSTE not to mention the added frustration of the patient^[16]. In recent years, we have performed many reconstruction using autologous cartilage, especially rib cartilage, after removal of an infected alloplast. We have found that the result is favorable with minimal chances of infection and resorption^[17].

Short, contracted nose

A short, contracted nose is a devastating complication usually associated with repeated surgery using alloplastic grafting material^[17-19]. The distorted anatomy lies not only in the structural support but also in the overlying SSTE. The exact pathogenesis is yet unknown but possible etiologies include capsular contraction around the implant, lower lateral cartilage necrosis by long term pressure from implants and chronic inflammation that eventually leads to progressive scar contracture^[20]. As the contracture progresses, the so-called snub nose deformity develops [Figure 2]. Therefore, caudal rotation of the tip together with superior movement of the nasion to elongate the nose are necessary. Building a firm foundation with autologous grafting material that can counteract the contractile forces of the skin is the key and rib

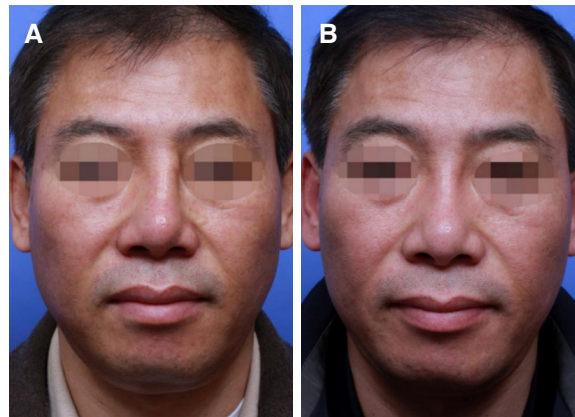


Figure 3. Pre and postoperative 1 year frontal photograph of a 52-year-old male patient with deviation of the silicone implant (A, B). The implant was removed together with the surrounding capsule and dorsal augmentation was performed using autogenous rib cartilage. Tip projection and rotation was achieved using a septal extension graft

cartilage is often used to fulfill this purpose. Often conchal composite grafts are needed to correct the deficient vestibular mucosa. A non-alloplast dorsal onlay graft that fills the dorsal defect after removal of the previous alloplast is also preferred.

Dorsal deviation/irregularity

Residual dorsal deviation is most often caused by failure to recognize or correct the pre-existing deviation. Improper osteotomies with or without adequate correction of the septum is the main cause. Deviation of the dorsal graft/implant and warping of the costal cartilage graft can be other reasons. Complete realignment employing restorative measures to straighten the bone and cartilaginous structures are required. If residual deviation persists after adequate structural realignment, camouflage grafts need to be applied [Figure 3].

A supratip depression or fullness after dorsal augmentation is not uncommon. Careful design of the implant and fine adjustment with additional grafts at the supratip is often necessary during primary rhinoplasty. Radix irregularity is more common when the radix is augmented with cartilage. To avoid this, the radix graft should be morcelized and inserted under a layer of soft tissue. Mastoid periosteum provides a good grafting source to smoothly elevate the radix area.

Tip problems related with septal extension graft

The recent trend of using septal extension graft for tip surgery in Asian rhinoplasty has created an array of complications such as overly aggressive tip projection (Pinocchio nose), deviated, asymmetric tip, pain and nasal obstruction. Aggressive tip projection using septal bone or Medpor is a common reason for tip pain and tenderness [Figure 4]. Removing stiff materials and restoring adequate projection with autologous cartilage is the best solution in these patients.

Inadequate midline stabilization of the septal extension graft is a common reason for tip deviation, nostril asymmetry, and nasal obstruction due to caudal septal deviation. This can often be avoided by securely suturing the graft to the anterior nasal spine and positioning the end into the midline in the overlapping type of septal extension graft. In the end to end type septal extension graft, reinforcement can be achieved with extended spreader grafts.

GRAFTING MATERIAL IN REVISION RHINOPLASTY

Revision rhinoplasty requires a large quantity of implants for grafting, supporting, and reconstruction. We prefer autologous cartilage for revision rhinoplasty in order to avoid further infection and soft

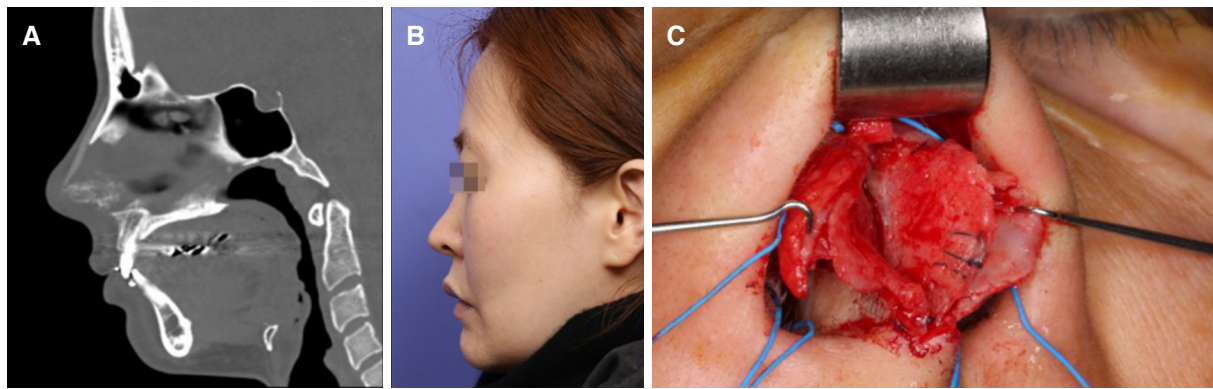


Figure 4. Sagittal CT scan of a 36-year-old female patient who underwent a rhinoplasty 6 years ago complaining of nasal tip pain, tenderness, and overly projected tip. Dorsal silicone implant and suspicious bone at the caudal septal area used as a septal extension graft (A, B); Intraoperative photos show an L-shaped Medpor implant used as septal extension graft (C). After implant removal and reconstructing of the tip without over projection using autologous cartilage, the pain disappeared

tissue contraction. Remnant septal and ear cartilage are the first choice of grafting materials in revision rhinoplasty cases with minor deformities. However, secondary rhinoplasty more often than not requires a larger amount of tissue that requires a robust source of grafting material. This usually exceeds the available septal cartilage and the need for adequate strength precludes the use of conchal cartilage. Autogenous costal cartilage may be the only practical choice in these circumstances. Common scenarios that frequently require the use of rib cartilage include the following: contracted short nose, significant loss of dorsal volume and/or septal support and/or tip support that is usually associated with removal of the alloplast.

We rarely use homologous rib cartilage because we believe that it is unpredictable in terms of long-term resorption. In cases with problems of the skin-soft tissue envelope, temporalis fascia, costal perichondrium, mastoid periosteum, or autologous dermis is used to reinforce the skin that may have been overly-thinned or weakened. Homologous fascia or dermis (Alloderm®, Surederm®) can be feasible alternatives. Lastly, although not common in our hands, alloplastic implants can be used again for revision, if the patient recognizes and agrees to the risks of complication, when there is no demonstrable infection, and in the presence of relatively thick skin.

COSTAL CARTILAGE HARVESTING

Before harvesting, it is prudent to check the rib series X-ray to look for possible calcifications. Even young patients can have severe calcification of the costal cartilage, which is more common in females. Calcification makes harvesting and carving of the cartilage more difficult and if totally calcified, it cannot be used as a grafting material.

The costal cartilage is commonly harvested from the sixth or the seventh rib. The incision is made directly over the chosen rib in male patients and just above the infra-mammary crease in female patients to conceal the chest scar [Figure 5]. The size of the incision may vary and is usually 2 cm in length in thin skinned patient and 2-2.5 cm in the thick skinned patient. The costochondral junction is confirmed by serial puncture with a 26-gauge needle for precise placement of the incision. The skin and subcutaneous tissue are incised with a no.10 blade and the subcutaneous tissue is retracted using retractors until exposing the external oblique muscles. Instead of cutting them with a Bovie, the muscle fibers are separated with Kelly forceps and retracted with an Army-Navy retractor which can minimize postoperative pain. After adequate exposure, two parallel incisions are made along the superior and inferior borders of the rib cartilage, leaving an intact central strip of perichondrium on the anterior surface. Several small incisions are made perpendicular to the longitudinal incision to facilitate reflection of the perichondrium [Figure 6].

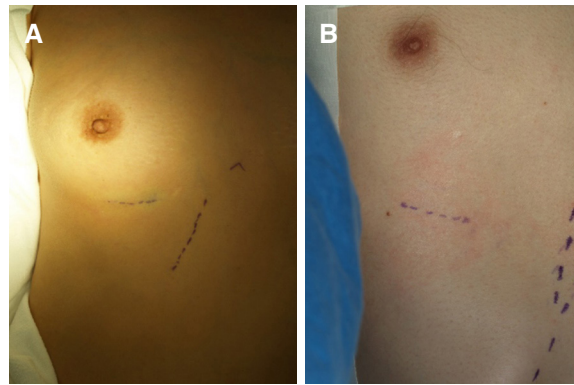


Figure 5. Incision for costal cartilage harvest in women (A) and men (B)

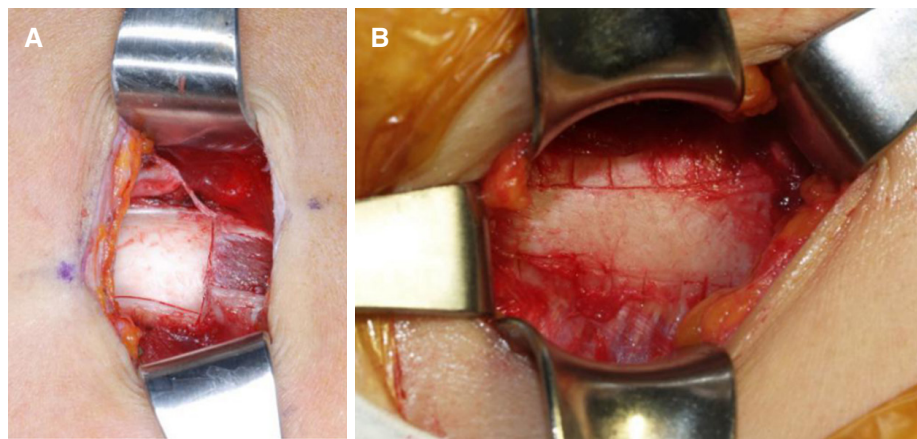


Figure 6. Bone cartilage junction (A); multiple small perichondrial incisions are made perpendicular to the longitudinal one to facilitate circumferential reflection of the perichondrium (B)

Harvesting can be facilitated by performing a medial cut before completing the dissection of the posterior surface of the costal cartilage. The initial incision is made with a blade and the cartilage cut is completed with a Freer elevator to avoid inadvertent pleural injury. After the lateral cut, small two-prong retractors are used to pull the costal cartilage exposing the posterior surface. The perichondrium of the posterior surface is dissected with a curved elevator and delivered. Typically, a 3-4 cm length of costal cartilage can be harvested together with the central strip of perichondrium [Figure 7]. When necessary, the cartilaginous cut can be extended up to the synchondrosis portion to obtain a longer graft.

Testing for air leakage is performed by filling the dissection pocket with saline and performing positive-pressure hyperventilation. If no air leakage is confirmed, the donor site is packed with antibiotic-soaked gauze until the end of the operation. Extra cartilage can be harvested during the operation or remnant cartilage can be reinserted for future use. If air leakage is noted, a nelaton catheter is inserted at the leakage site and repaired in a purse-string manner. The nelaton catheter is removed while exerting positive-pressure ventilation. The separated muscles are approximated to diminish postoperative pain and the wound is closed layer by layer using 4-0 vicryl. A drain is usually not necessary. If the skin margins are macerated, they should be trimmed before suturing with a 6-0 nylon which is removed on the seventh to tenth postoperative day. A routine chest X-ray to check for pneumothorax is not mandatory if the surgeon is confident that there was no pleural injury. However it should be performed if the patient develops chest signs and symptoms. Rarely, pneumothorax can occur even though leakage was not evident during surgery, in which case, a chest tube is inserted to expand the collapsed lung.



Figure 7. Harvested costal cartilage together with the central strip of perichondrium



Figure 8. Section through the costal cartilage reveals a yellowish core region and a whitish peripheral region

TAILORED USE OF COSTAL CARTILAGE

Harvested autologous costal cartilage is designed into various shapes and sizes depending on the purpose of the graft.

Costal cartilage for dorsal implant

There are various ways of using the costal cartilage for dorsal augmentation, these include, dorsal augmentation as a single piece, stacked layered pieces, and diced cartilage wrapped with fascia.

Dorsal augmentation in one piece

Costal cartilage consists of a central core and a peripheral region surrounding the core [Figure 8]. A balance within the cartilage is maintained by the internal stress created by the two competing regions. The peripherally cut cartilage warps more than the centrally cut segment^[21,22]. Side-to-side warping is clinically more evident due to diminished soft tissue resistance in this dimension [Figure 9].

To design an implant for dorsal augmentation, the periphery is symmetrically cut away, leaving a central core. The central part is carved with a No.10 blade. The cartilage is periodically soaked in saline for 10-20 min to carefully monitor signs of warping. Once warping is evident, the remaining peripheral concave portion of the cartilage is cut out keeping the central core. Making additional cuts in the graft can further minimize warping. The final dorsal graft is a canoe-shaped graft when seen from above. When seen from the lateral view, it has a slightly concave side that comes into contact with the nasal dorsum, and the skin side is slightly convex [Figure 10]. Perichondrium placement on the undersurface of the radix portion and suture fixation of the graft to the upper lateral cartilage can reduce movability and decrease the chances

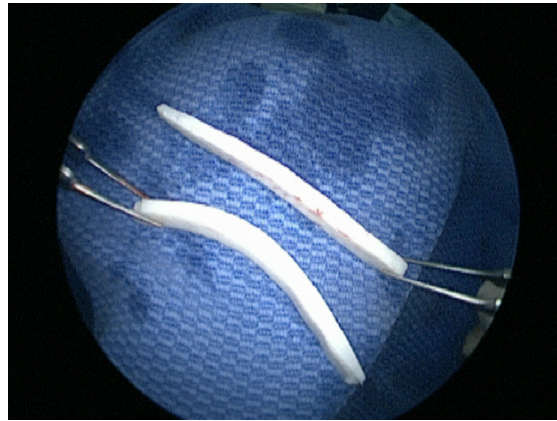


Figure 9. Warping of the costal cartilage

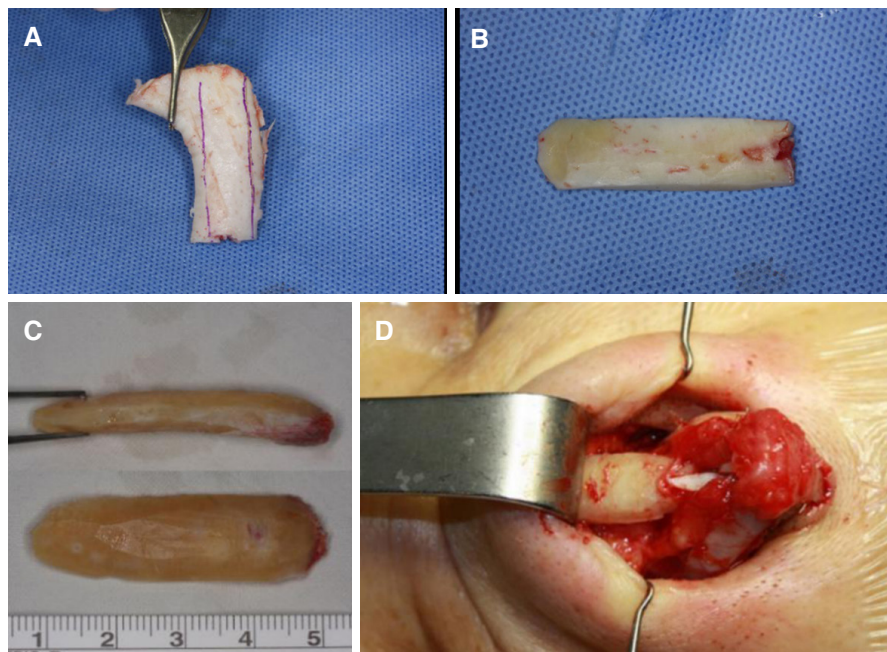


Figure 10. A dorsal onlay graft carved from a rib cartilage. A straight portion of the harvested rib cartilage is selected (A); the peripheral portion is excised leaving a central portion for additional carving (B); the final graft has a canoe-like shape from the frontal view and a slightly convexity in the dorsal side when seen from the lateral view (C); insertion of the dorsal graft (D)

of migration [Figure 11]. When wide dissection of the dorsal skin is necessary, fixation of the carved rib cartilage needs additional procedures. A K-wire fixation for two weeks or transcutaneous suture fixation of the graft to the nasal bony pyramid helps to stabilize the graft [Figure 12].

Dorsal augmentation with layered costal cartilage

Alternatively, the costal cartilage can be cut in layers or long strips which can be stacked to be used as the dorsal graft. Usually strips of 1.0-1.5 cm by 3-4 cm with 1mm thickness are used. Obtaining strips with consistent thickness is not easy. Using a dermatome blade is helpful to achieve this goal [Figure 13]. The number of strips to stack depends on the desired dorsal height and are sutured with 5-0 PDS or nylon. More often than not, the strips bend or warp. By stacking the warped strips in a way that can counteract the forces of one another can succeed in obtaining a straight dorsal graft. Special care is taken to bevel all the edges. Fascia or perichondrium is used to cover and camouflage the graft.



Figure 11. Perichondrium on the undersurface of the radix portion of the graft with slight rasping of the bone can reduce mobility and decrease the chances of migration

Dorsal augmentation with diced costal cartilage wrapped in fascia

The use of diced cartilage for dorsal augmentation has been previously published. Although similar in concept, there have been differences in the source of cartilage and the way they are prepared before insertion. The most common source of cartilage is the septum and ear if the needed volume is not small. Superiority of one versus another has not been clearly shown. The diced cartilage is usually wrapped before being inserted into the dorsal pocket so that it can conform to the desired shape and height of the dorsum. There are also a wide range of materials to wrap the diced cartilage in, with temporalis fascia being the most popular [Figure 14]. To avoid dorsal irregularities, costal cartilage is diced into fine pieces (usually 0.5-1 mm). Wrapping them with thicker fascia lata also helps to avoid palpable protuberances. The radix and supratip portions need extra attention in order to avoid slight depression in the long-term follow up.

Costal cartilage for structural support: SEG and extended spreader grafts

For structural grafts, the costal cartilage is designed into flat, straight pieces of thin cartilage. To minimize warping, the cartilage is cut longitudinally or tangentially, leaving symmetric peripheral portions on both sides of the central core portion. However, when warping occurs, affected fragments can be split in half and used as bilateral extended spreader grafts, compensating for the curvature [Figure 15]. If a thin straight piece of septal cartilage remains, it can be used as septal extension graft and costal cartilage can be used as extended spreader grafts to fix it.

Costal cartilage used for tip modifications

Examples are lateral crural strut grafts, lateral crural onlay grafts and tip onlay grafts. Usually thin, beveled slices of costal cartilage are carved with a 10 blade [Figure 16]. Grafts should be symmetrical when applied bilaterally and not thick in thin skinned patients. Cap graft can also be fashioned from the rib cartilage. The authors prefer an elliptical shaped, well beveled cartilage graft for the cap graft. The perichondrium can be draped over the cap graft for smooth transition from the dome to the soft tissue triangle.

Use of rib cartilage perichondrium

The rib perichondrium is a valuable grafting material in revision rhinoplasty. Usually the anterior perichondrium of the harvested rib cartilage is used but additional perichondrium can be harvested from the adjacent ribs (superior or inferior). Applications include the following: placement in the undersurface of the dorsal graft to increase friction and avoid mobility of the dorsal graft, on the dorsum for a radix graft or to camouflage any dorsal irregularities, on the tip to conceal graft edges and in any other areas of thinned/damaged skin. When harvesting the rib, the authors prefer harvesting periosteum of the rib bone near the costochondral junction together with the perichondrium. Periosteum is thicker than perichondrium and helps to camouflage more especially when used at the radix portion.

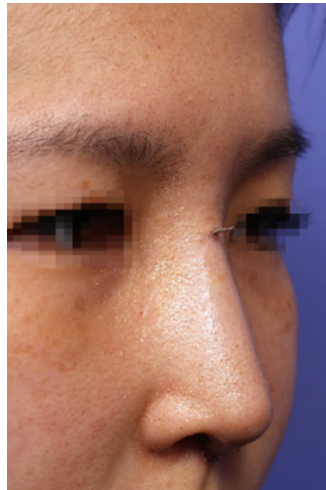


Figure 12. Fixation of the dorsal graft with K-wire

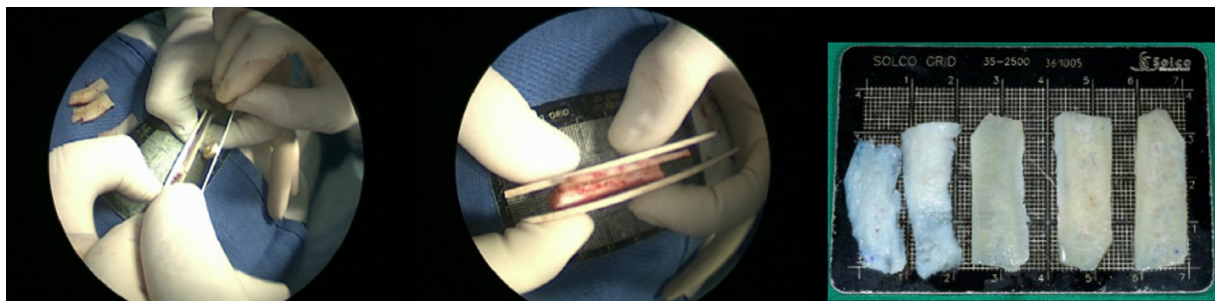


Figure 13. Layers of costal cartilage cut with a dermatome blade can be stacked for dorsal augmentation

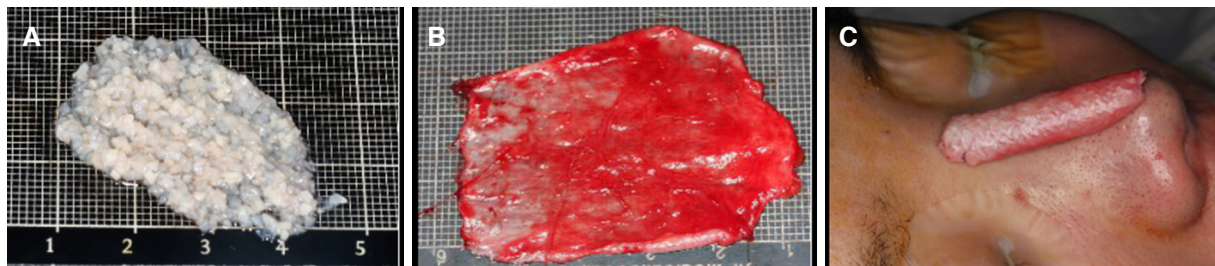


Figure 14. Dorsal augmentation with diced costal cartilage (A) wrapped in temporalis fascia (B); Final dorsal implant before insertion (C)

COMPLICATIONS OF RIB CARTILAGE AND ITS MANAGEMENT

Complications associated with using rib cartilage in rhinoplasty include warping, migration, infection, operated look and donor site morbidity such as pain, pneumothorax, and chest scar. We hereby introduce ways to deal with some of them.

Even with every preventive measure such as using the core of the rib cartilage, balanced carving, repeated immersion and checking for warping, creation of a tight pocket for insertion, and suture fixation on the dorsum, warping of the dorsal graft can occur [Figure 17]. When warping occurs postoperatively, we take out the curved rib graft and reinsert it after carving it again into a straighter piece which is possible in most instances. If that is not possible, we dice the rib graft and insert it after wrapping in temporalis fascia. In our experience, autogenous rib cartilage is able to maintain its original volume years after surgery. If

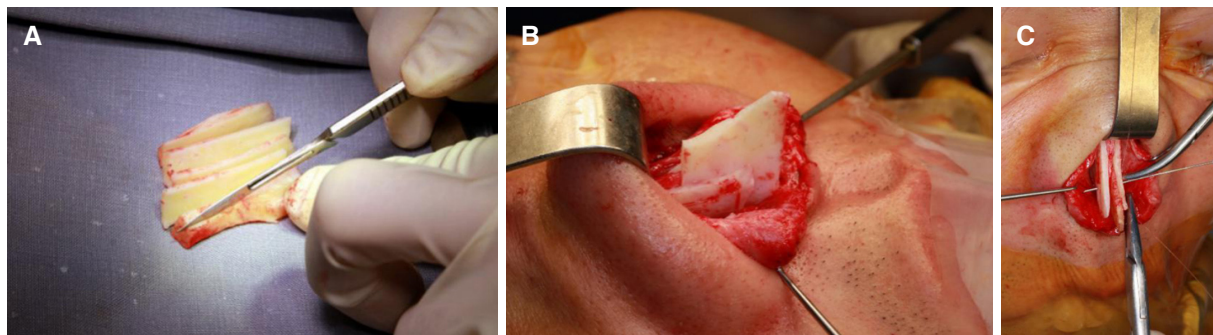


Figure 15. Costal cartilage is cut in straight layered strips(A); septal extension graft with bilateral extended spreader grafts carved from layers of costal cartilage (B, C)

slight volume loss occurs while taking out or recarving the rib cartilage, adding some soft tissue such as the mastoid periosteum or temporalis fascia may help in keeping the original volume or camouflaging the junction area such as radix or supratip.

Although not frequent, infection can occur after use of autologous rib cartilage. The use of autogenous material is not completely without the risk of infection, especially when rib cartilage is used for multiply revised cases. With the use of IV antibiotics, adequate drainage and proper local dressing, the costal cartilage graft can be salvaged without the need of removal. When managing the infection, early detection and aggressive intervention are important. With delayed detection and timid intervention, infection cannot be controlled completely and may end up with complete debridement of the already infected, resorbed, fragmented rib cartilage^[16].

Migration of the costal cartilage graft is rare. Possible reasons include, an excessive wide pocket around the radix area, inappropriate fixation of the costal cartilage and remnant capsule. To prevent migration, complete removal of the underlying capsule, roughening of the radix with rasps, and placement of perichondrium on the undersurface of the carved graft at the radix area are techniques to consider. Occasionally, a K-wire fixation of the graft to the underlying nasal bone at the radix can be performed.

To avoid the unnatural operated look, the authors do the following: (1) avoid over-augmentation, especially at the radix area and try to set the starting point of the dorsum to the interpupillary line; (2) fill the radix with soft tissue such as perichondrium to avoid an interrupted look from the forehead to the nose; (3) when augmenting the dorsum, narrowing the bony base with osteotomies is avoided; (4) the width of dorsal graft is kept adequately wide and the edges are beveled/carved so that transition from the sidewall to the dorsum is smooth; (5) the dorsal graft is covered with soft tissue such as temporalis fascia or mastoid periosteum especially when the skin is thin or damaged.

REVISION RHINOPLASTY CASES WITH COSTAL CARTILAGE

Case 1: contracted nose after previous rhinoplasty

A 28-year-old male present with short nose and nasal obstruction. He had only had one previous rhinoplasty using silicone implant and it was removed due to infection. He had a typical post-surgical short, contracted nose showing exaggerated nostril show in the frontal view and severely cephalically rotated nasal tip with low-set nasion in the lateral view [Figure 18A-C].

The first step of his surgical procedure consisted of a wide dissection of the skin-soft tissue envelope. The silicone capsule and thick scars were excised and the lower lateral cartilage was released from the upper lateral cartilage and pyriform aperture.

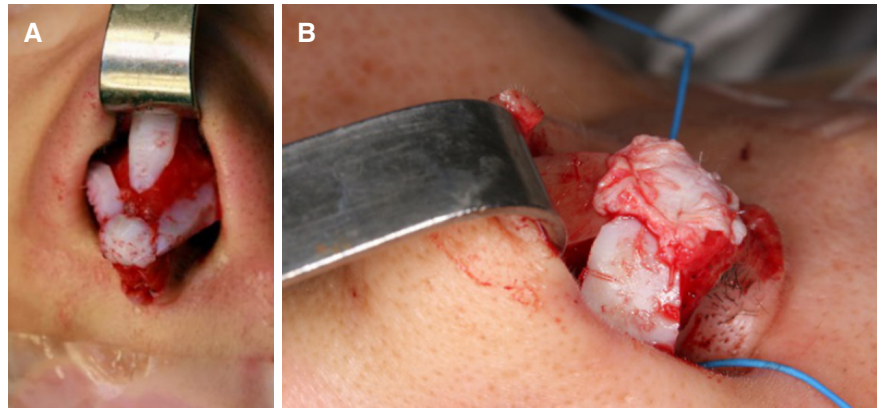


Figure 16. Costal cartilage used for tip-plasty. A dorsal graft, cap graft and bilateral lateral crural onlay grafts are shown (A); perichondrium covered over the cap graft can conceal irregularities (B)

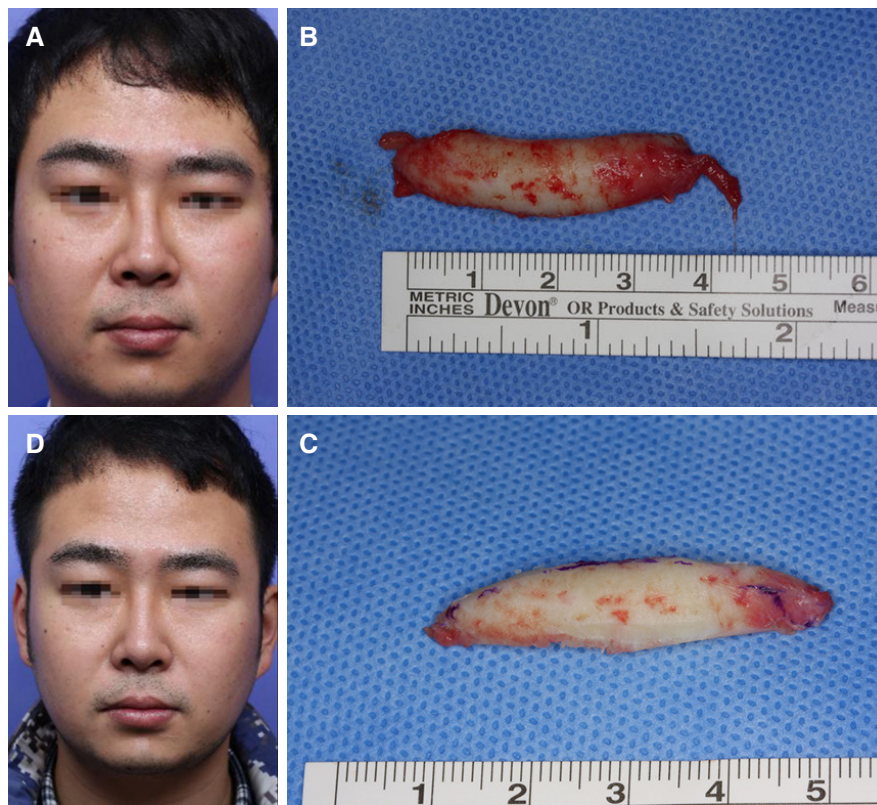


Figure 17. Warping of dorsal onlay rib graft. A 25-year-old man who had revision rhinoplasty with rib cartilage developed warping of the dorsal implant (A); during the revision surgery, the warped costal cartilage graft was removed, recarved, and reinserted with mastoid periosteum reinforcement over the radix (B, C); frontal view 6 months after surgery shows a straightened dorsum (D)

Flat and straight pieces of cartilage were carved from his 6th costal cartilage using a No. 10 blade. After dividing the lower lateral cartilages and elevating the septal mucosa, a septal extension graft was designed from the rib cartilage to reach the anterior nasal spine inferiorly and to extend the nasal tip anteriorly while rotating it caudally. The septal extension graft was reinforced with a septal batten graft and an extended spreader graft to prevent twisting forces.

Afterwards, extended lateral crural strut grafts were employed to strengthen the lateral compartment and match the elongated central compartment [Figure 18D-F]. After completely separating the lateral crus from

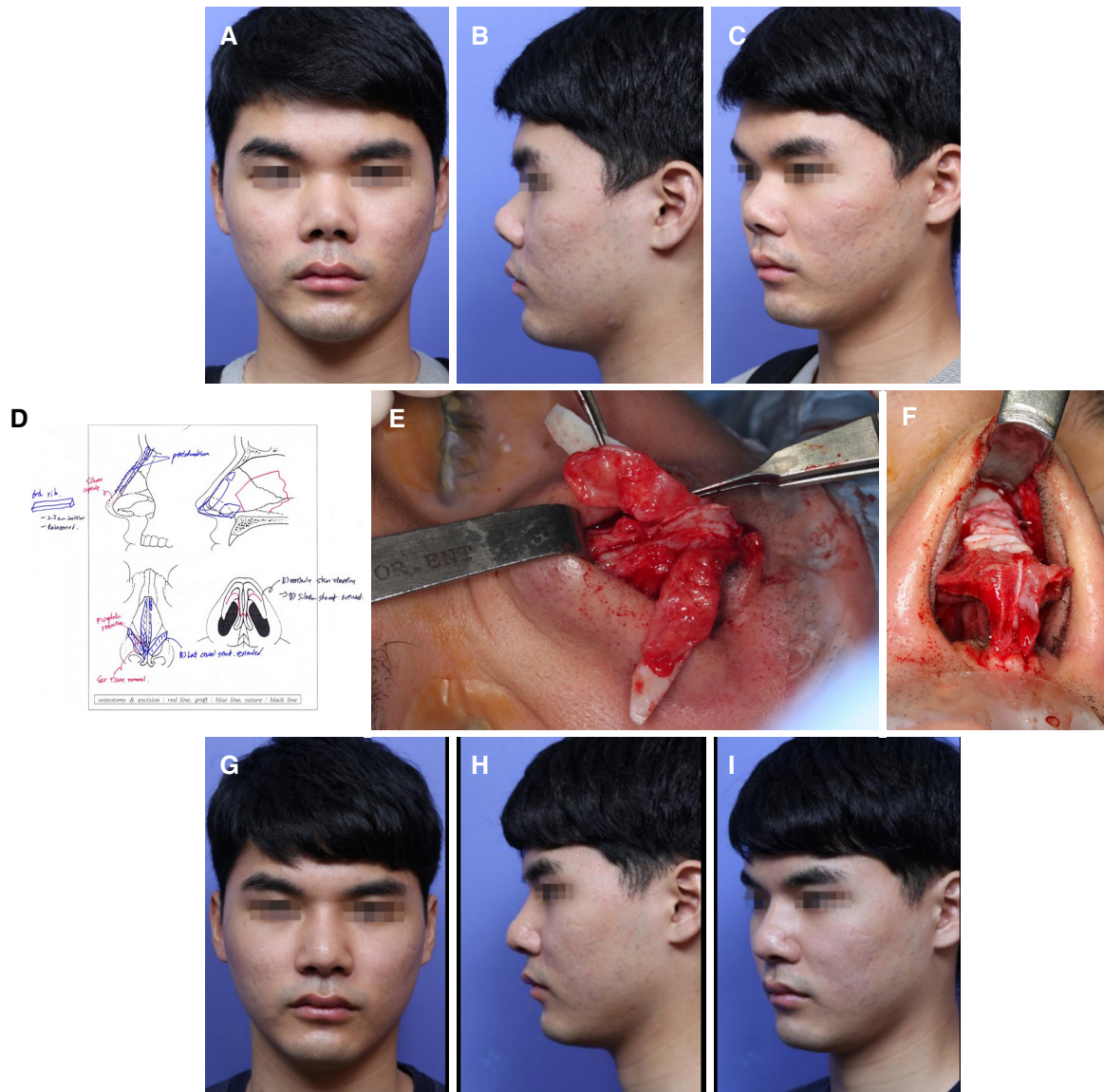


Figure 18. Correction of the short nose due to contracture after multiple rhinoplasties. A short and contracted nose, developed after infected dorsal silicone implant removal is evident from the preop photos (A, B, C); The surgical diagram shows septal extension graft, dorsal onlay graft, bilateral extended spreader grafts, lateral crural onlay grafts, shield graft and cap graft were placed using irradiated homologous costal cartilage (D); After wide release of the skin envelope, a septal extension graft is placed and reinforced with extended spreader grafts. The released lower lateral cartilages and reinforced with extended lateral crural strut grafts. Perichondrium is added for camouflage (E, F). One year after revision surgery using rib cartilage, the nose looks much better than before. His dorsum is well elevated and the tip is caudally rotated (G, H, I)

the vestibular mucosa, a long, straight piece of cartilage fashioned from the rib cartilage was sutured to the undersurface of the lateral crus with their cephalic ends extending to the pyriform aperture so that they held the skin tension applied on the tip and lateral crus. In this way, lateral crural strut grafts strengthen the lateral compartment and help to stabilize the dome in a more favorable position. Because the vestibular skin is dissected off the lateral crus, it helps to reposition the vestibular mucosa more caudally.

Finally, the dorsum was elevated using a dorsal graft carved from the rib. A strip of perichondrium over the costal cartilage was used as a dorsal onlay graft making a smooth transition from bony dorsum to cartilaginous dorsum. The dorsal onlay graft was extended to include the nasion to elongate the nose.



Figure 19. Case of a 19-year old female who presented with implant infection after nasal augmentation. Preoperative pictures show evident signs of infection (A, B, C). The implant was removed, and the dorsum was subsequently augmented with autogenous rib cartilage (D, E) in the same setting. Tip-surgery was done using septal extension graft. One-year post-operative photos show a well restored dorsal height with appropriate tip projection and rotation of the tip (F, G, H)

Appearance one year after the operation shows improved nasal appearance. Caudal rotation of the nasal tip, a decreased nasolabial angle, and increased height of nasal dorsum make the nose appear significantly longer than before [Figure 18G-I].

Case 2: infection after primary rhinoplasty using silicone implant. Removal and immediate reconstruction with autologous rib cartilage graft

A 19-year-old female presented with implant infection after nasal augmentation with silicone a year before. Exudate and frank pus is noted coming from the skin of the nasal sidewall near the left medial canthus with a polly beak deformity on the lateral view [Figure 19A-C]. The implant and the surrounding granulation tissue were removed, followed by irrigation with betadine solution. The dorsum was subsequently augmented with autogenous rib cartilage [Figure 19D and E] in the same setting. Tip-surgery was done using septal extension graft. One-year post-operative photos show a well restored dorsal height with appropriate tip projection and rotation of the tip [Figure 19F-H].

CONCLUSION

The use of autogenous grafting material, especially the rib cartilage, is frequently needed when dealing with revision rhinoplasty cases associated with alloplast complications. Wise use of costal cartilage in revision rhinoplasty involves mastering intricacies that can decrease complications and improve results. Safe harvesting minimizing the complications, appropriate designing and carving to maximize the results and avoid warping, and appropriate postoperative care are all important. The rhinoplasty surgeon should be familiar with the common scenarios in which the rib cartilage is necessary as well as with the various technical aspects necessary to reduce complications.

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Authors' contributions

Wrote the paper: Won TB, Jin HR

Availability of data and materials

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None.

Conflicts of interest

Both authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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REFERENCES

1. Won TB, Jin HR. Revision rhinoplasty in Asians. *Ann Plast Surg* 2010;65:379-84.
2. Toriumi DM, Swartzout B. Asian rhinoplasty. *Facial Plast Surg Clin North Am* 2007;15:293-307.
3. Jin HR, Won TB. Nasal hump removal in Asians. *Acta Otolaryngol Suppl* 2007;558:95-101.
4. Jin HR, Won TB. Nasal tip augmentation in Asians using autogenous cartilage. *Otolaryngol Head Neck Surg* 2009;140:526-30.
5. Won TB, Jin HR. Nuances with the Asian tip. *Facial Plast Surg* 2012;28:187-93.
6. Jin HR, Won TB. Recent advances in Asian rhinoplasty. *Auris Nasus Larynx* 2011;38:157-64.
7. Jin HR, Won TB. Rhinoplasty in the Asian Patient. *Clin Plast Surg* 2016;43:265-79.
8. Zeng Y, Wu W, Yu H, Yang J, Chen G, et al. Silicone implant in augmentation rhinoplasty. *Ann Plast Surg* 2002;49:495-9.
9. Ahn JM, Honrado C, Horn C. Combined silicone and cartilage implants: augmentation rhinoplasty in Asian patients. *Arch Facial Plast Surg* 2004;6:120-3.
10. Deva AK, Merten S, Chang L. Silicone in nasal augmentation rhinoplasty: a decade of clinical experience. *Plast Reconstr Surg* 1998;102:1230-7.
11. Tham C, Lai YL, Weng CJ, Chen YR. Silicone augmentation rhinoplasty in an Oriental population. *Ann Plast Surg* 2005;54:1-5.
12. Endo T, Nakayama Y, Ito Y. Augmentation rhinoplasty: observations on 1,200 cases. *Plast Reconstr Surg* 1991;87:54-9.
13. Mendelsohn M, Dunlop G. Gore-Tex augmentation grafting in rhinoplasty-is it safe? *J Otolaryngol* 1998;27:337-41.
14. Rothstein SG, Jacobs JB. The use of Gore-Tex implants in nasal augmentation operations. *Entechnology* 1989;68:40-5.
15. Jin HR, Lee JY, Yeon JY, Rhee CS. A multicenter evaluation of the safety of Gore-Tex as an implant in Asian rhinoplasty. *Am J Rhinol* 2006;20:615-9.
16. Jung DH, Moon HJ, Choi SH, Lam SM. Secondary rhinoplasty of the Asian nose: correction of the contracted nose. *Aesthetic Plast Surg* 2004;28:1-7.

17. Won TB, Jin HR. Immediate reconstruction with autologous cartilage after removal of infected alloplast in revision rhinoplasty. *Otolaryngol Head Neck Surg* 2012;147:1054-9.
18. Jin HR. Correction of the short, contracted nose. In: Jin HR, editor. *Aesthetic Plastic Surgery of the East Asian Face* 1st ed. New York: Thieme Medical Publishers; 2016. pp. 93-113.
19. Park JH, Mangoba DC, Mun SJ, Kim DW, Jin HR. Lengthening the short nose in asians: key maneuvers and surgical results. *JAMA Facial Plast Surg* 2013;15:439-47.
20. Sunwoo W, Jung H, Kim DW, Jin HR. Immunohistochemical analysis of capsular contracture in silicone implant rhinoplasty. *JAMA Facial Plast Surg* 2017;19:436-7.
21. Harris S, Pan Y, Peterson R, Stal S, Spira M. Cartilage warping: an experimental model. *Plast Reconstr Surg* 1993;92:912-5.
22. Kim DW, Shah AR, Toriumi DM. Concentric and eccentric carved costal cartilage: a comparison of warping. *Arch Facial Plast Surg* 2006;8:42-6.

Review

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Preoperative considerations, operative preparation, and postoperative care for rib cartilage use in rhinoplasty

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Abstract

Rib cartilage is the most reliable material for structural support and dorsal augmentation in Asian rhinoplasty with its robust strength and bountiful amount. Its value is incomparable especially in complex, cartilage-depleted revision surgery or major reconstruction. There are many articles regarding harvesting and carving of rib cartilage in rhinoplasty, however, only few has focused on preoperative and postoperative issues. Preoperatively, evaluating cartilage availability, assessing quality and quantity of cartilage, and choosing the cartilage to harvest are necessary. Although easily overlooked, proper postoperative management of rib cartilage rhinoplasty patients is key to prevent infection and heighten patient satisfaction. Here in, I would like to introduce how I evaluate rib cartilage rhinoplasty patients preoperatively and manage them postoperatively to maximize the surgical results.

Keywords: Rib cartilage, rhinoplasty, autologous graft, preoperative evaluation, postoperative management

INTRODUCTION

Cartilage grafts are widely used in nasal surgery. Although septal and auricular cartilage are easy to harvest, they often lack the amount necessary for many situations like revision rhinoplasty, severe deformity or trauma. As such, a surgeon is often compelled to use other sources^[1,2]. Rib cartilage is the most reliable material for structural support and augmentation with its robust strength and bountiful amount. It can



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provide all of the necessary grafts from a single donor site with fewer complications^[1]. However, many novice surgeons in rhinoplasty who are not familiar with chest anatomy, have difficulty in initiating the use of rib cartilage. The essential guidelines for use of rib cartilage in rhinoplasty are safe harvesting, and effective and appropriate carving of the rib cartilage. There are also several important factors to consider in a preoperative consultation for rib cartilage rhinoplasty. These considerations include an assessment of cartilage availability, and the choice of cartilage for harvesting. In addition, postoperative management is also important for optimal results. Herein, we introduce preoperative evaluation for assessment of proper rib cartilage and postoperative care.

PREOPERATIVE EVALUATIONS

Decision to use a rib: consideration factors

When the decision is made that rib cartilage is required, the first step is to check its availability. According to previous studies, sex and age are best related to the quality of rib cartilage^[1-5]. In general, younger patients have more flexible and softer cartilage than older persons^[1-5]. Contrary to our expectations, however, surgeons often encounter severely calcified rib cartilage, especially in young females. Sunwoo *et al.*^[6] reported that 22.5% of teenage female patients showed calcification, and as early as 14 years old in some, which can suggest that the onset of rib cartilage calcification is earlier in women than in men^[6,7]. Calcification makes it difficult not only to perform the graft manipulation, but also makes it more difficult to predict outcome because of its irregular absorption^[7]. In addition, the risk of donor site morbidity may increase if the rib cartilage is severely calcified^[6]. Therefore, preoperative assessment of the calcification degree by obtaining a series of radiographs of the rib or by pricking the rib cartilage with a fine needle are necessary regardless of a patient's sex or age [Figure 1]. Computed tomographic (CT) scans of chest are best used to specify calcification pattern with overall features of rib in many previous studies^[5-8]. However, CT is more expansive and the radiation exposure is higher than simple X-ray. In my practice, simple rib X-ray provides enough information regarding the degree of calcification and size and shape of cartilage, thus, enables me to judge its availability in rhinoplasty safely with relatively low cost. Luckily, not all calcified cartilages are contraindication for harvest. Grades of cartilage calcification can be classified by the percentage of calcified lesion, and more than 25% can be regarded as meaningful calcification^[6]. A mild degree (< 25%), marginal type calcification (calcification along the periphery of rib cartilage) is often acceptable, but a central/granular type with moderate calcification (> 25%) is not suitable in most cases^[6].

In selection of an appropriate amount of rib cartilage, costal cartilage is harvested from the sixth through eighth ribs according to its shape and purposes^[1,6,8]. Right side cartilages are commonly preferred than the left to avoid injury to the pericardium and confusion of postoperative chest pain from angina^[1-9]. Interestingly, however, a study revealed that the greatest amount of costal cartilage from the sixth, seventh, and eighth rib was identified on the left side than right on CT scan data^[10]. Therefore, rib cartilage harvesting from the left side can be a viable option in those patients who have had previous rib surgery, radiotherapy, or trauma with destruction of costal cartilage on the right side^[10].

The sixth rib is usually at an ideal depth and the width is wide. But the straight piece is shorter than the seventh rib and has slight genu. Furthermore, if the patient has a history of breast implant, care should be taken not to injure implant material since the sixth rib is typically directly located under an implant^[1,6,8]. Seventh rib cartilage has been known as the safest anatomically. It is situated over the abdominal cavity and thus can lessen the chance of pneumothorax since the parietal pleura of the lung runs down to reach the lower edge of the sixth rib at the xyphoid-chondral junction to the upper edge of the ninth rib cartilage laterally. The internal thoracic artery and vein also descend medial to the ribs from the seventh rib and therefore vascular injury is rare^[8]. Its contour is also suitable for any rhinoplasty grafts because of an appropriate length and width. Thus, the seventh rib from the right side appears to be most advisable for

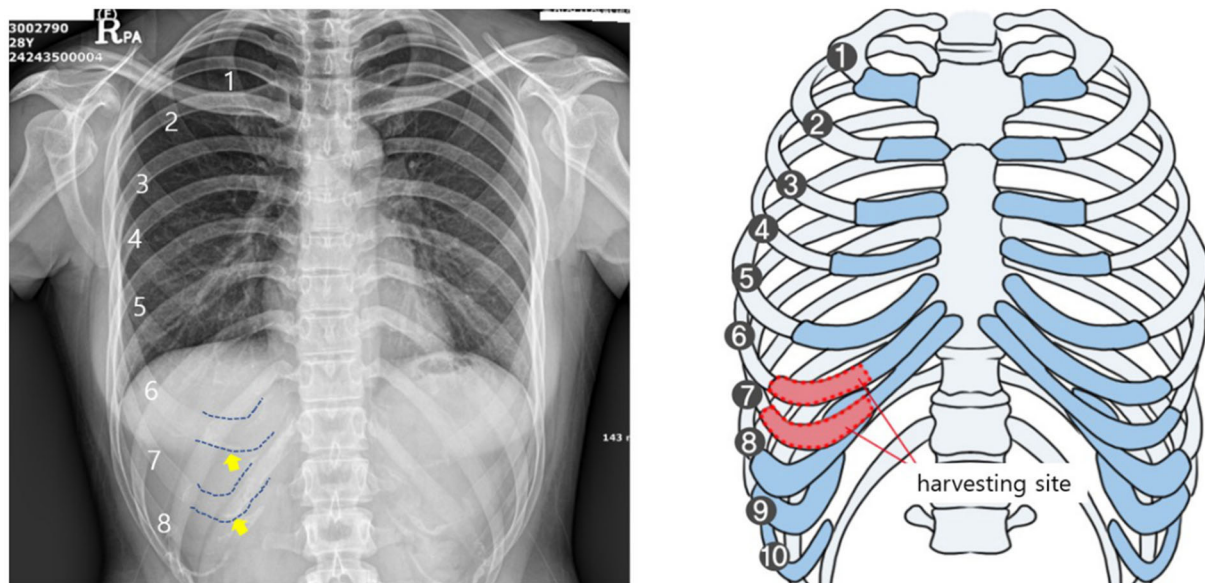


Figure 1. Appropriate number of rib cartilages are assessed on a simple rib series X-ray. Shape, curvature, width and calcification can be reviewed. Dotted lines show curvature, shape, and width of rib cartilages. Yellow arrow shows linear marginal calcification on the 6th rib while granular type on the 7th

rhinoplasty in general^[10]. The eighth rib has a significant connection with the adjacent rib and the width is narrow, which is inadequate for a dorsal graft^[1,6,8,11]. Also, some senior physicians prefer the eleventh and twelfth free-floating ribs as graft material because they are naturally straight, require less carving and undergo less warping. Moreover, they are thin and easily accessible^[12].

Diced cartilage in temporalis fascia is an alternative choice when using rib cartilage if the length of the rib cartilage is insufficient as a one block dorsal graft or if the patient has very thin skin. In a case with a spotty calcified rib, it would be also better to dice for major dorsal augmentation to prevent unpredictable absorption^[13].

OPERATIVE PREPARATION

Identify selected rib cartilage from surface anatomy: stepwise approach

After selecting an ideal rib from a rib series or CT scan, the next step is to find an exact rib from the chest surface with manual palpation. Fortunately, prior studies from cadaver and CT scans show that sex, age and ethnic background had little effect on determining costal cartilage anatomy^[1,11]. For this process, the clavicle and xyphoid process are first marked on the skin in a supine position, and then the number of ribs is counted serially along the lateral rib cage [Figure 2]. The first palpable rib cartilage just below the clavicle is usually the second rib. In patients with a breast implant or that are obese, it is more helpful to count the ribs at the medial side rather than lateral. In a very difficult patient, the eighth rib can be found from the transverse plane passing through spinous process of the T12 vertebra in a lateral position^[11].

Over the chosen rib cartilage, the osseocartilagenous junction can be localized by pricking the rib using a 26-27 gauge needle considering its contour^[1,2,6]. Harvesting rib cartilage from the osseocartilagenous junction can provide a maximal straight piece and volume with limited incision^[11]. While pricking, great caution should be taken not to poke the pleura or lung parenchyma, resulting in a closed tension pneumothorax. For novices, it is recommendable to grab the superior and inferior margin of the selected rib with the other index and middle fingers to assure a midline [Figure 3]. After marking the osseocartilagenous junction, a horizontal skin incision is started from the marking and moving medially along the skin crease [Figure 4].



Figure 2. Rib cartilages are identified on supine position. The clavicle and xiphoid process is a key landmark and the first rib below the clavicle is the second rib



Figure 3. While needle pricking, keeping a midline is crucial to avoid tension pneumothorax. Grabbing selected ribs with two fingers from the other hand are helpful to guide the right direction

POSTOPERATIVE CARE

After wound closure, routine postoperative chest X-ray can be recommended until the surgeon is familiar with the procedure^[1]. The chest wound is compressed lightly with a bandage and kept for 3 days to prevent hematoma. Drain is unnecessary in most cases. Pain is the most common complaint after costal cartilage harvest, regardless of purpose or extent. Many authors reported that donor site pain usually peaked in the first week and diminished slowly over 3 months^[13-19]. In the past, local application of a long-lasting anesthetic substance close to the intercostal nerve was used to reduce extensive postoperative pain^[15,16]. Anantanarayanan *et al.*^[16] reported that the use of catheter-based ropivacaine provided an earlier return to normal function with significant long duration, hence, decreasing the need for rescue analgesics. Recently, however, other studies have proven that severe pain can be minimized with modification of rib harvest techniques. For example, after superior and inferior perichondrium elevation, special precaution is taken not to injure the inferior line neurovascular bundle. Rib harvesting can also be limited to the outer lamellar while preserving the internal costal arch. By preserving the inner lamellar of the rib, postoperative morbidities, including pain, splinting and pneumothorax, can be reduced^[17]. Recently, a muscle sparing

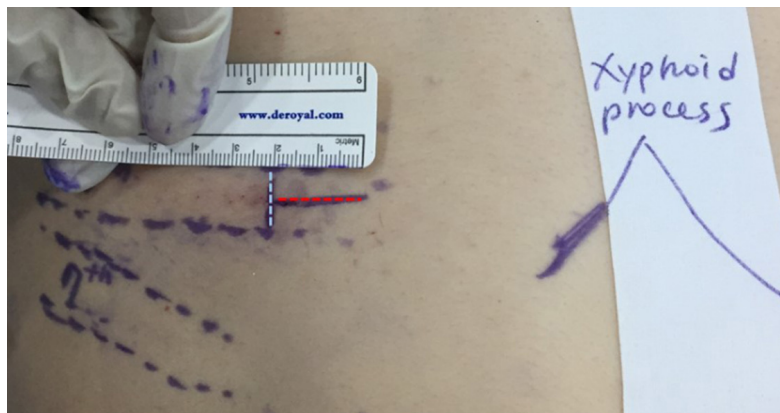


Figure 4. About a 2 cm transverse incision is made along the skin crease. The incision line (red dotted line) starts from the osseocartilaginous junction (blue dotted line) to obtain a maximal length in the piece of harvested cartilage

technique has been increasingly applied to reduce donor site discomfort^[19,20]. Instead of transection, a blunt dissection of the external oblique muscle can significantly reduce pain during rest and movement. Thus, some authors recommend routine use of a muscle-sparing technique in autologous costal cartilage harvesting^[20]. With these procedures, regular pain pills are sufficient to control postoperative chest pain. The author usually prescribes routine antibiotics and oral pain pills for a week after surgery with this muscle sparing technique. The pain tends to be peaked in 3-4 days and diminishes slowly over a week. Long lasting chest pain is a rare entity after rib cartilage harvest, however, long-lasting pain even months after surgery is possible especially when multiple rib cartilages were harvested. Even with a little pain after harvest of rib cartilage, restriction of activity is not recommended and rather light daily activities like walking, sitting are recommended from the day after surgery. However, more heavy activities like running, weight training, or playing with instruments are recommended to resume in 3 weeks.

Scar management is also an important part of postoperative care. To minimize unwanted skin abrasion, unidirectional skin retraction is helpful during harvest to prevent skin margin abrasion. The wound is closed in 4 layers; muscle, fascia, subcutaneous tissue and skin. Multilayered sutures are helpful to reduce vertical tension from stretch of upper body. Antibiotic ointment is put to incision scar once a daily for a week. A patient with a history of keloids or hypertrophic scar, triamcinolone can be injected at the costal cartilage harvest site as a preventative measure^[1]. Wound stitch-out is performed in a week and then silicone scar sheets can be applied for two months to reduce visible scars. The author experienced elevated scar flattening after triamcinolone injection twice at two weeks interval at the donor site scar and the results were often acceptable in most patients. Yang *et al.*^[21] compared a VAS cosmetic score of costal cartilage harvest site scar from a retroauricular skin incision scar and reported that there was no significant difference at 6 months post operation.

Infection prevention needs special attention when heavy amount of rib cartilage was used in multiply revised patients. They tend to have poor blood supply, often the skin is stretched more, and the septum is also explored which all contribute to raise the infection chance. In this case, I give them IV antibiotics for a few more days after surgery and pay special attention to the intranasal hygiene to prevent retrograde infection from the nasal cavity. Everyday dressing of the nasal cavity and the wound with betadine solution and antibiotic ointment for a week is recommended. I teach patients to soak the nasal cavity often with betadine gauze for a week at home. After casting and stitch at one week postoperatively, I see them once again after a week to check any sign of infection and tell them to pay special attention to any sign of swelling, redness, and pain of the nose till follow-up time.

CONCLUSION

To get optimal result in using rib cartilage, thorough preoperative evaluation and proper postoperative care should be achieved. The author introduced how to seek and select appropriate rib cartilage from chest surface and radiographic images. Pain control, scar management, and infection prevention are three major consideration factors in postoperative care and can be managed well with advanced techniques.

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The author contributed solely to the article.

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The author declared that there are no conflicts of interest.

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Not applicable.

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REFERENCES

1. Chung V, Toriumi DM. The use of costal cartilage for dorsal augmentation and tip grafting. *Aesthetic Plastic Surgery of the East Asian Face*. Thieme Medical Publishers; 2016. pp. 26-47.
2. Park JH, Jin HR. Use of autologous costal cartilage in Asian rhinoplasty. *Plast Reconstr Surg* 2012;130:1338-48.
3. McCormick WF, Stewart JH. Ossification patterns of costal cartilages as an indicator of sex. *Arch Pathol Lab Med* 1983;107:206-10.
4. Navani S, Shah JR, Levy PS. Determination of sex by costal cartilage calcification. *Am J Roentgenol Radium Ther Nucl Med* 1970;108:771-4.
5. Sanders CF. Sexing by costal cartilage calcification. *Br J Radiol* 1966;39:233.
6. Sunwoo WS, Choi HG, Kim DW, Jin HR. Characteristics of rib cartilage calcification in Asian patients. *JAMA Facial Plast Surg* 2014;16:102-6.
7. Elkeles A. Sex differences in the calcification of the costal cartilages. *J Am Geriatr Soc* 1966;14:456-62.
8. Jung DH, Choi SH, Moon HJ, Chung IH, Im JH, et al. A cadaveric analysis of the ideal costal cartilage graft for Asian rhinoplasty. *Plast Reconstr Surg* 2004;114:545-50.
9. Wustrow TP, Kastenbauer E. Surgery of the internal nasal valve. *Facial Plast Surg* 1995;11:213-27.
10. JP Windfuhr, Chen YS, Güldner C, Neukirch D. Rib cartilage harvesting in rhinoplasty procedures based on CT radiological data. *Acta Otolaryngol* 2011;131:67-71.
11. Lepage D, Tatu L, Loisel F, Rey PB, Obert L, et al. Anatomical and computed tomography study of the eight costochondral junctions: topography for costochondral graft harvesting. *Surg Radiol Anat* 2016;38:809-15.
12. Moretti A, Sciuto S. Rib grafts in septorhinoplasty. *Acta Otorhinolaryngol Ital* 2013;33:190-5.
13. Park P, Jin HR. Diced cartilage in fascia for major nasal dorsal augmentation in Asians: a review of 15 consecutive cases. *Aesthet Plast Surg* 2016;40:832-9.
14. Uppal RS, Sabbagh W, Chana J, Gault DT. Donor-site morbidity after autologous costal cartilage harvest in ear reconstruction and approaches to reducing donor-site contour deformity. *Plast Reconstr Surg* 2008;121:1949-55.
15. Rasp G, Staudenmaier R, Ledderose H, Kastenbauer E. Autologous rib cartilage harvesting: operative procedure and postoperative pain reduction. *Laryngorhinootologie* 2000;79:155-9.

16. Anantanarayanan P, Raja DK, Kumar JN, Sneha P, Christabel A, et al. Catheter-based donor site analgesia after rib grafting: a prospective, randomized, double-blinded clinical trial comparing ropivacaine and bupivacaine. *J Oral Maxillofac Surg* 2013;71:29-34.
17. Yilmaz M, Vayvada H, Menderes A, Mola F, Atabey A. Dorsal nasal augmentation with rib cartilage graft: long-term results and patient satisfaction. *J Craniofac Surg* 2007;18:1457-62.
18. Nelson M, Gaball C. Technique to reduce time, pain, and risk costal cartilage harvest. *JAMA Facial Plast Surg* 2017;19:333-4.
19. Fedok FG. Costal cartilage grafts in rhinoplasty. *Clin Plast Surg* 2016;43:201-12.
20. Özücer B, Dinç ME, Paltura C, Koçak I, Dizdar D, et al. Association of autologous costal cartilage harvesting technique with donor-site pain in patients undergoing rhinoplasty. *JAMA Facial Plast Surg* 2018;20:136-40.
21. Yang HC, Cho HH, Jo JY, Jang CH, Cho YB. Donor-site morbidity following minimally invasive costal cartilage harvest technique. *Clin Exp Otolaryngol* 2015;8:13-9.

Technical Note

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Costal cartilage graft in Asian rhinoplasty: surgical techniques

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Abstract

Asian rhinoplasty is a very common cosmetic procedure. Many Asians desire a higher nasal bridge, for which they undergo several procedures, including filler injections, implantations and insertion of threads. Surgeons encounter many patients who have had several procedures done on them previously. In this paper, we introduce the use of autologous grafts for Asian rhinoplasty (primary and secondary), and discuss the rib carving techniques and difficulties encountered during harvesting, carving and placements of grafts and how to overcome these problems and prevent complications.

Keywords: Rhinoplasty, costal cartilage, Asians, warping

INTRODUCTION

Surgeons who perform Asian rhinoplasty often have to treat patients who have had rhinoplasty (or several rhinoplasties) previously. Revision rhinoplasty is one of the most difficult and challenging surgeries in facial plastic surgery.

For treating complications in rhinoplasty, a considerable quantity of cartilage is required to correct both nasal contour deformities and functional problems caused by previous surgeries. Revision Asian rhinoplasty tends to be a more complicated procedure than primary rhinoplasty, especially due to framework deficiency, that needs further reconstruction. For consistent long-term results, surgeons should use grafts with low



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resorption rates and sufficient strength for framework support. Autologous tissue is always preferred as the use of alloplastic material increases the rate of infection, wound contracture and extrusion^[1].

For achieving successful results in Asian rhinoplasty, an appreciation of the Asian patient's anatomical characteristics, a conceptual approach as well as an appreciation of recent trends of beauty should be fully understood^[2]. Asian patients generally seek a high dorsum and nasal tip refinement. Silastic implants were used traditionally (and are still in use), but they cause a high incidence of early and late complications. Minimally invasive rhinoplasty, such as threads insertion rhinoplasty and injectable filler rhinoplasty have recently become popular, but repeated procedures may result in complications.

The ideal material for grafting or implantation in rhinoplasty must have the characteristics of low complication rates and high long-term patient satisfaction^[3]. Thus, autografts are considered as better alternatives for augmentation in Asian rhinoplasties. Costal cartilage is commonly used for augmentation of the nasal dorsum and for infrastructure reconstruction as it provides an ample amount of autogenous cartilage, but is frequently associated with warping^[4]. When an autologous rib cartilage rhinoplasty is performed properly by an experienced surgeon for complicated cases or for a short nose, it will provide excellent, reliable, and long-lasting results with low risk^[5]. Warping rate of costal cartilage and unpredictable cosmetic results are topics of concern for both patients and surgeons. In this paper, we will discuss how to minimize complications and improve the surgical results.

SURGICAL TECHNIQUE

Harvesting the rib cartilage

We usually harvest the rib cartilage from the right sixth or seventh rib, with a short linear inframammary incision [Figure 1A]. In women, we place an oblique incision carefully on the inframammary fold, to conceal the scar. The incision is around 2-3 cm in length. If a female patient wishes to opt for a breast implant in the future, we make the inframammary fold incision 7.5-8.0 cm below the nipple, so that the scar is hidden within the anticipated, future inframammary fold after breast implantation. If the patient has had a previous breast implant, the incision is made a little lower and we are careful not to rupture the capsule and prevent chances of breast implant infection.

We make an incision with a No. 10 or 15 blade and perform meticulous dissection of the subcutaneous tissue after infiltration of local anesthesia. Once we reach and divide the muscle fascia, the extra-costal muscle is divided directly over the rib. We identify the underlying rib and a syringe needle is stabbed on the costal cartilage to check for calcification. The medial dissection is near the junction of the rib cartilage and the sternum, while the lateral dissection is up to the osteochondral junction. We further carry out sub-perichondrium dissection underneath, along the longitudinal axis of the rib. Since we also aim to harvest some amount of perichondrium from the superior aspect of the rib, we make a rectangular incision on its superior aspect. Dissection is carried out carefully, with patience and accuracy, to leave the perichondrium on the lower aspect intact. We often use a curved or a right angled elevator to lift the rib off its underlying perichondrium. A blade is used to make an incision halfway through the rib and the costal cartilage is severed laterally near the osteo-chondral junction. The harvested rib measures 4.5-6.5 cm in length [Figure 1B]; we tend to harvest more costal cartilage in revision cases. The perichondrium on the superior aspect of the harvested rib [Figure 2] is preserved and kept aside. A sharp, curved Freer's elevator is used to make an incision at the medial end and sever the rib. A drill may be used to cut through the rib cartilage in cases of ossification, which is often seen in individuals over 40 years of age. Hence, we ask patients older than 40 years old to have a CT scan of the chest wall, for evaluation of costal cartilage calcification. But in our experience, rib calcification in younger individuals has also been noticed. In some patients, where there is

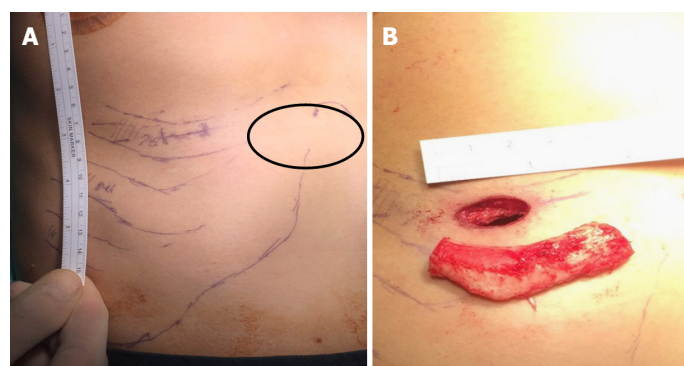


Figure 1. A: Incision site for harvesting the seventh rib; B: an approximately 5 cm rib harvested from a 2 cm incision



Figure 2. Harvested 7th rib cartilage with intact overlying perichondrium and two pieces of conchal cartilage

a considerable amount of calcification and if we suspect deficient septal cartilage, a short segment of the adjacent rib is also harvested, to use as splinting grafts or as a caudal septal extension graft.

The next crucial step is performing a Valsalva maneuver to check for injury to the lung pleura. The donor site is irrigated with thermal saline and positive pressure ventilation is applied to see the presence of bubbles. After ensuring that there is no pneumothorax, the wound is carefully closed in layers. The most important step is proper closure of fascia over the muscle with interrupted sutures. This will facilitate drainage of blood and avoidance of hematoma. Proper closure of this layer will also reduce postoperative pain over the chest area by a great extent. We generally use a 3-0 vicryl suture for closure of fascia over the muscle, 4-0 vicryl for subcutaneous closure and 6-0 nylon for interrupted closure of the skin. In female patients, we prefer to use 5-0 PDS or vicryl suture for subcutaneous closure instead of 6-0 nylon for skin closure; to avoid suture removal [Figure 3]. We then apply dressing over the wound to keep it dry and clean. The graft is put in normal saline with gentamycin solution and observed for warping.

Carving the rib cartilage

Carving and smoothening of the rib cartilage is crucial to get an even and aesthetically favorable outcome. Whilst carving a graft, we consider the patient's skin thickness. Asians have a thick skin, compared to that of Caucasians. This quality of skin comes with both an advantage and disadvantage. Minor irregularities on the nose may not be as obvious as it would be in the thinner Caucasian skin. But, for a patient requiring minimal changes, the final outcome may not be apparent and the patient might not be completely satisfied. It is difficult to achieve the desired level of definition and refinement because sharp lines and angles of the graft can appear blunted under a thick skin.

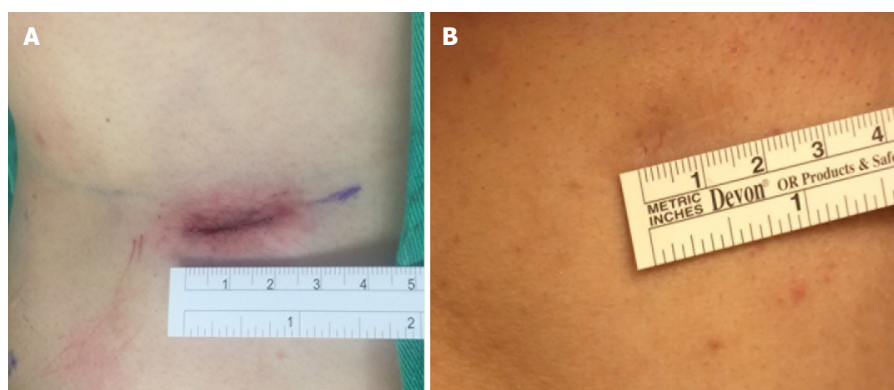


Figure 3. A: Oblique linear sutured wound about 2 cm over right inframammary fold after rib cartilage harvesting; B: a linear scar, appearing almost invisible, one year after surgery

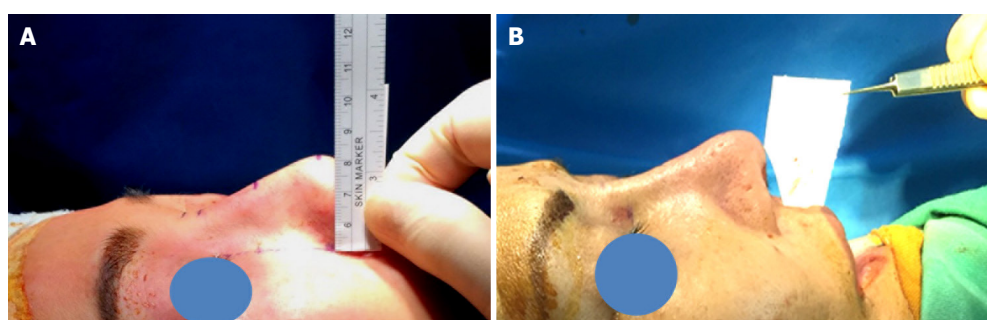


Figure 4. A: Intraoperative measurement of profile heights at nasion, bridge at mid-pupil level, rhinion and nasal tip; B: a paper is cut to check the nasolabial angle before and after surgery



Figure 5. Fusiform shaped carved rib cartilage, perichondrium is placed on the cephalic end of the onlay graft to smoothen the radix contour

INTRAOPERATIVE MEASUREMENT

Before we carve the rib, we measure the height of the nose at 4 points in order to monitor the profile change during the operation [Figure 4] and check the contour change: (1) nasion height from the medial canthus; (2) bridge height at mid-pupil level; (3) rhinion; (4) nasal tip.

The shape we carve the rib graft into can be best described as a “fusiform” shape. It is tapered off on both ends and has a wider mid region [Figures 5-9]. We use the longer portion of the harvested costal cartilage for dorsal augmentation and the remaining shorter portion for other grafts (splint grafts, lateral crura strut



Figure 6. Powered instrument with cutting burr is used to carve the costal cartilage if it is calcified



Figure 7. Partially calcified costal cartilage is sculptured according to the silicone implant

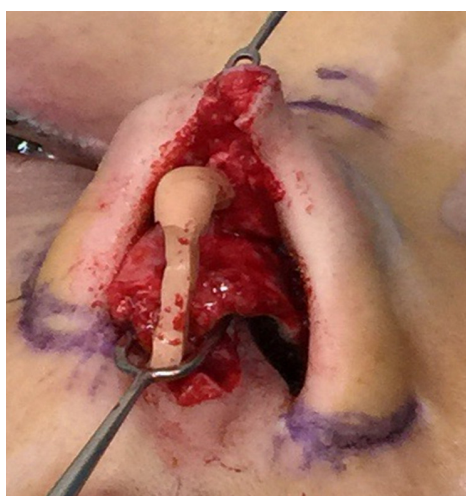


Figure 8. Intra-operatively, an L-shaped silicone implant is seen after opening the fibrotic capsule

grafts, caudal septal extension graft). The posterior aspect of the rib lies over the nasal area (over the nasal bones and cartilaginous dorsum) and is carved to blend with the underlying nasal framework. Asians have a rather low radix height. To ameliorate this, we carve the superior aspect of the graft in an uphill-converging manner, which rests effortlessly over the underlying bone, forming a new, enhanced radix. The undersurface of the graft is carved with a No. 10 blade in an inverted, flattened out “U” fashion, along the natural contour



Figure 9. Intraoperative picture showing graft placement for dorsal augmentation



Figure 10. A: Medial portion of harvested rib cartilage carved into a dorsal onlay graft and the remaining lateral portion; B: the lateral portion of the harvested rib is split into three pieces which are used as caudal septal extension graft and splint grafts

of the harvested rib, for better fixation of the onlay graft over the underlying nasal framework. If the patient requires or wishes for a higher dorsum, we can assemble an additional rib cartilage underneath the onlay graft, carved to mingle with the underlying nasal framework and raise the overlying harvested rib for dorsal augmentation. Carving is done carefully to taper the margins of the rib so as not to make the graft too obvious or visible postoperatively. The caudal end of the rib graft is narrowed which harmonizes with the nasal bridge. While carving, we make sure that the end result is not a very narrow looking nose, nor is it too broad. We always keep in mind that a graft that is too narrow might not be in tone with the rest of the Asian facial features. We seldom use diced cartilage for dorsal augmentation as its absorption rate is very unpredictable and the nasal skin surface may appear irregular.

Splint grafts are carved either from the remaining septum or the harvested rib. The lateral or shorter part of the L-shaped harvested rib, is split into three identical grafts. The grafts are sliced in a longitudinal direction. The central part of the sliced rib is generally used as a caudal septal extension graft (CSEG) to minimize warping. The CSEG is carved into an approximately 2 mm thick graft. The length and height of the rib graft to be carved into a CSEG can be manipulated according to the requirements of the patient. The peripheral sliced grafts are further carved into spreader grafts or splint grafts [Figure 10]. The splint grafts are shaped as a trapezoid - the key point is that they need to support the septal cartilage along with the CSEG and form a strong platform. The remaining cartilage from the medial rib, after carving out the required amount needed

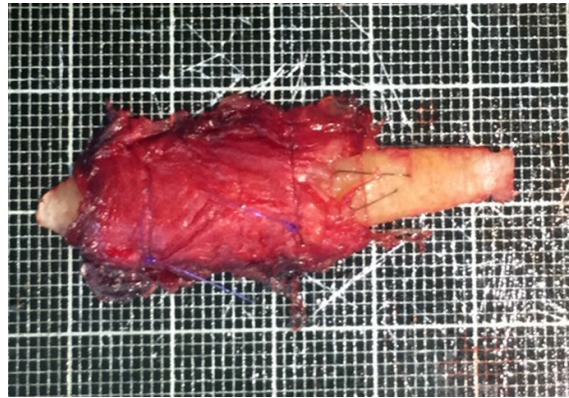


Figure 11. Rib graft covered with deep temporal fascia on the convexity

for the dorsal augmentation, can be carved into spreader grafts. We use spreader grafts only when the patient undergoes extensive osteotomy, if there is evidence of internal valve collapse or if there is deviation of the cartilaginous dorsum.

Owing to its curvature and elasticity, we prefer using conchal cartilage as lateral crura strut grafts (LCSG). If conchal cartilage is deficient or if we decide to use the rib as a LCSG, a small part of the rib is carved into a rectangular graft tapered on both sides.

Graft placements and osteotomy

After placing the rib onlay graft, we secure it in position by applying two or three fixation sutures with 5.0 PDS around the graft and through bilateral upper lateral cartilages (ULC). If a capsule is present due to a previous silicone implant, it is preserved and wrapped gently around the rib cartilage graft to minimize irregularity and thinning of the skin soft tissue envelope. Perichondrium of costal cartilage or deep temporal fascia can also be harvested and wrapped around the rib graft to hide any irregularities [Figure 11].

The caudal septal extension graft is fashioned from the septal cartilage or the rib graft in a trapezoidal shape. We place it in the midline, between bilateral medial crura and fixed to the caudal septum in an end-to-end fashion or overlapped over the caudal end of the septum (depending on the strength and resilience of the remaining septal cartilage). End-to-end fixation of CSEG can prevent deviation. Splint grafts are used on either side over the dorsal septum to secure the CSEG at the midline and the lower end of CSEG is fixed near the anterior nasal spine (ANS). We are careful not to fix it too close to the ANS, to avoid any postoperative discomfort, columellar tilt or upper philtrum crease, which may be apparent on smiling and could be cosmetically unappealing. It is also paramount for bilateral medial LLC to be sutured in symmetry to prevent tip deformity.

According to the desired nasal shape and skin thickness, we insert other grafts such as lateral crura struts, batten grafts or tip-shield grafts. We rarely perform osteotomies on Asian patients because augmentation itself can improve a broad bridge. If the patient has a crooked bony dorsum, we perform intranasal medial and lateral osteotomies. Medial osteotomy begins at the junction of ULC and nasal bone at a paramedian position, preserving optimal width of the bony dorsum to prevent inverted V deformity or other deformities. We curve the cut of the medial osteotomy gently outwards (approximately 10°-15°) as we proceed upwards, ensuring that osteotomy is complete and does not move too far cephalically into the frontal bone. It is then connected with the lateral osteotomy. This is how we avoid “rocker” deformity. We use the low-low-high fashion for lateral osteotomy as opposed to the high-low-high osteotomy performed in Caucasians. To circumvent narrowing of the nasal valve area, we start the lateral osteotomy at the level of the inferior

turbinate. This can avoid step-like deformity, nasal block or collapse with preservation of periosteum along the osteotomy route.

Other steps such as alar flare reduction and rim strut grafts are performed as needed. We make sure to preserve as much tissue as possible to avoid scarring (which could be a result of multiple rhinoplasties).

DISCUSSION

Rib grafting has several advantages in revision rhinoplasty, especially for complications from filler injection rhinoplasty or artificial nasal implantation, which is very common in Asian patients. It offers an abundant supply of cartilage for use and rigid support. The chances of infection, skin necrosis and shrinkage are minimized. Many surgeons prefer harvesting the sixth, seventh or occasionally the eighth rib^[6]. We harvest the sixth rib cartilage in females because the oblique incision scar can usually be hidden over the infra-mammary fold, and the seventh rib cartilage in males because the seventh rib cartilage is usually the longest one. If the patient is older than 40 years, a CT scan of chest wall may be needed to evaluate calcification of cartilage.

Complications such as warping can be overcome by balanced carving and allowing 15 min for maximal warping to occur^[7]. We harvest the rib perichondrium as it can serve as an extra graft material. It can be used to camouflage skin thinning of the nasal tip and can also be used over the rib onlay graft to minimize noticeable graft contour. The incision for harvesting a rib graft may vary from 1.0-5 cm, depending on the patient's anterior chest wall thickness and surgeon's skill. Rib carving requires a lot of experience and versatility on the surgeon's part. The edges of the dorsal onlay graft may show irregularities even after fine trimming. Infection is not uncommon in secondary rhinoplasty. Meticulous dissection during surgery, effective antibiotics and appropriate postoperative care are very important. Cigarette is absolutely prohibited at least two weeks before and 1-2 months after surgery. The pre and post operative pictures of a few of our cases are listed below [Figures 12 and 13]. In cases of wound infection, the patients are treated with wound debridement, removal of inflamed cartilage and intravenous antibiotics. The reasons for infection could be the mass effect of harvested graft that affect the skin tension and disturb the nutrient/waste exchange diffusion process and also due to the poor blood supply in the recipient area in revision cases^[7].

To obtain aesthetically pleasing results, ensure patient satisfaction and minimize complications, the rhinoplasty surgeon must possess a thorough knowledge of nasal anatomy and ideal facial aesthetic proportions^[8]. Many Asian patients undergo more than three revision surgeries to correct or offset improperly performed surgeries, the improper use of implants or surgical complications^[9]. In a study by Park and Jin^[10], 47 percent were revision cases of rhinoplasty and four of five infection cases occurred in their revision operations.

The current best evidence for techniques and complication rates in costal cartilage associated with rhinoplasty are based on case series^[11]. Hence, complication rates depend on the surgeon's surgical skills as well as the patient's compliance.

In conclusion, revision rhinoplasty in Asians is a challenging surgery. Most of the revision cases require previous graft removal or reshaping, harvesting of a new graft, creating a clean plane and facing the scar tissues formed by previous surgeries. When a large amount of grafting is required, the costal cartilage can provide an ample amount of cartilage graft material. As the possibilities of complications should also be anticipated in revision rhinoplasty, rhinoplasty surgeons need more experience and learning from follow-up patients.

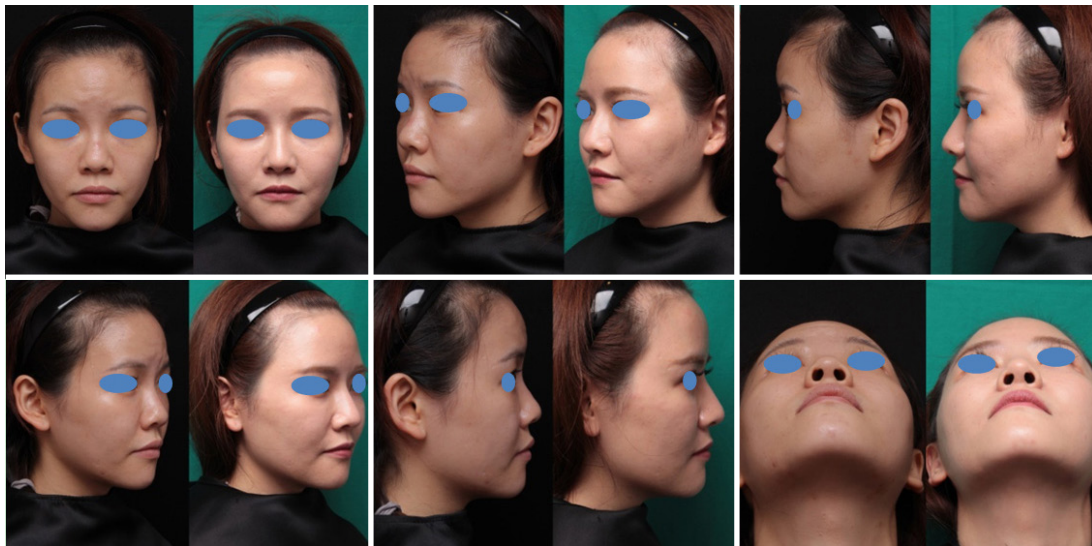


Figure 12. A 25-year-old female had filler injectable rhinoplasty thrice previously, as well as threads insertion. She underwent open rhinoplasty with autogenous costal cartilage grafting and ear cartilage grafting for tip refinement. These pictures show before and one year after surgery

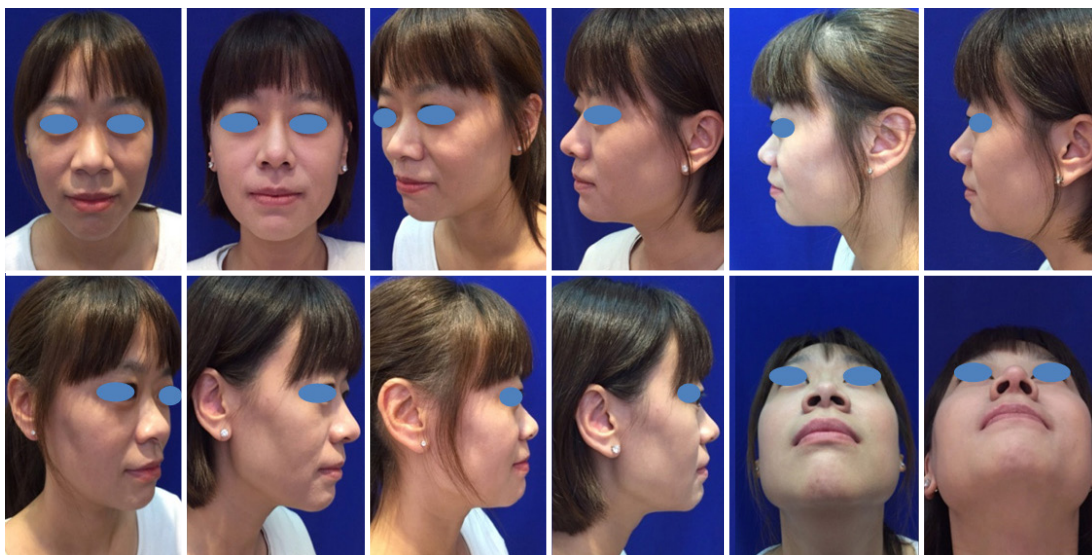


Figure 13. This female underwent open rhinoplasty with autogenous costal cartilage grafting and ear cartilage grafting for tip refinement. These pictures show before and three months after surgery

DECLARATIONS

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Authors' contributions

Made contribution to the conception and design of the study and provided cases and material for the study:
Kao CH

Made contribution to the presentation of the text and concept of the study: Rajbhandari S

Availability of data and materials

Not applicable.

Financial support and sponsorship

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Both authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Written informed consent was obtained.

Consent for publication

Written informed consent was obtained for all patient images.

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REFERENCES

1. Marin VP, Landecker A, Gunter JP. Harvesting rib cartilage grafts for secondary rhinoplasty. *Plast Reconstr Surg* 2008;121:1442-8.
2. Lee MJ, Song HM. Asian rhinoplasty with rib cartilage. *Semin Plast Surg* 2015;29:262-8.
3. Kao CH, Hsu CH, Lee JC, Wang HW, Tsai KK. Customized material choice for Asian rhinoplasty: how we do it. *Clin Otolaryngol* 2011;36:165-70.
4. Bussi M, Palonta F, Toma S. Grafting in revision rhinoplasty. *Acta Otorhinolaryngol Ital* 2013;33:183-9.
5. Toriumi DM, Pero CD. Asian rhinoplasty. *Clin Plast Surg* 2010;37:335-52.
6. Gunter JP, Cochran CS. Dorsal augmentation with autogenous rib cartilage. *Semin Plast Surg* 2008;22:74-89.
7. Moon BJ, Lee HJ, KJang YJ. Outcome following rhinoplasty using autologous costal cartilage. *Arch Facial Plast Surg* 2012;14:175-80.
8. Lagura EMA, Yap EC, Garcia AVG. Augmentation rhinoplasty with rib cartilage graft. *Philipp J Otolaryngol Head Neck Surg* 2015;30:29-33.
9. Suh MK, Ahn ES, Kim HR, Dhong ES. A 2-year follow-up of irradiated homologous costal cartilage used as a septal extension graft for the correction of contracted nose in Asians. *Ann Plast Surg* 2013;71:45-9.
10. Park JH, Jin HR. Use of autologous costal cartilage in Asian rhinoplasty. *Plast Reconstr Surg* 2012;130:1338-48.
11. Varadharajan K, Sethkumar P, Anwar M, Patel K. Complications associated with the use of autologous costal cartilage in rhinoplasty: a systematic review. *Aesthet Surg J* 2015;35:644-52.

Technical Note

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Oblique split technique: a game changer in costal cartilage sculpting

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Abstract

Oblique split method is a technique used to carve the costal cartilage. Its main advantages are the high number of grafts that can be obtained, the ability to obtain grafts of various thicknesses and lengths, no risk of warping, less chance of desorption, preservation of the straight forms of grafts although they can be carved in different shapes.

Keywords: Oblique split method, saddle nose, structural rhinoplasty, revision rhinoplasty, septal reconstruction

INTRODUCTION

Costal cartilage is one of the main sources for grafts in the reconstruction of saddle nose deformities and revision rhinoplasty cases. However, its handling and carving methods have always created a challenge for the surgeon. In 1958, Gibson and Davis published a technique called as “principle of the balanced cross-section” which could be used to overcome warping, the major disadvantage of the use of carved/sculpted costal cartilage^[1]. They stated that if the distorting forces were balanced along a cartilage graft, the grafts would not be distorted (warp). In total 46 balanced cross-section grafts were followed for over a three-year period. The oblique split method after Taştan *et al.*^[2] describes the angle to the long axis of the rib cartilage upon which the costal cartilage is cut/sectioned. In this original description there was no clinical observation of graft warping in the follow-up period. It was also stated that although the grafts obtained could be modified into different shapes, they preserved their straight shape.



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Figure 1. In the reconstruction of a crooked nose, a subtotal reconstruction was done by L-strut obtained from the 6th rib. It had warped and a revision was needed

METHODS

Costal cartilage sculpting methods

The principle of the balanced cross-section

This principle is still the fundamental technique when costal cartilage use comes into consideration in saddle noses corrections or revision rhinoplasties^[1]. The sculpted cartilage grafts are used as structural grafts and augmentation grafts. Besides, the integrated dorsal graft/columellar strut has been used in many cases where the caudal septal support was poor^[3]. It has been reported that careful symmetric carving of costal cartilage could minimize the chance of cartilage warping over time^[3]. Our experience has shown us that costal cartilage warping can still occur despite careful symmetric carving, especially while using structural grafts [Figure 1]. The one-piece L-strut graft obtained from the costal cartilage was described by Rettinger and its use has been effective for decades^[4]. Our experience of dorsal onlay grafts is that they rarely have clinically apparent warping. However, warping has remained the primary concern with the use of costal cartilage grafts. Many cutting and additional techniques have been developed to overcome this issue. For the last 19 years we have been utilizing balanced cross-sectional carving and although warping was rarely seen, concerns always remained. The use of thicker grafts employed by us and other experienced rhinoplasty surgeons to minimize warping resulted in stiffer noses, which was undesirable to some patients.

Freehand carving/sculpting of costal cartilage with a scalpel has historically been the technique of choice for fashioning grafts. The creation of thin grafts using the technique is however technically challenging and carries a higher risk of warping. Dermotome blades overcome the technical challenges of producing thin grafts, the unfavorable warping characteristics however remains^[5].

An observed major limitation was the paucity of grafts that can be obtained by this method.

The central portion of the rib is utilized as a graft, with the remaining peripheral cartilages portions/shavings often unusable due to the unfavorable warping characteristics. Typically in the correction of saddle nose deformity, we use the central rib portion for caudal septal graft and the one outer layer/shaving for dorsal onlay graft. However, in revision rhinoplasties variation in graft type, size and amount graft material required limit the use of balanced cross-section carving rib carving.

Oblique split method

I have learned this technique during a meeting from Dr. Taştan in 2008, several years prior to its publication^[2]. Impressed with the simple logical solution to this common and difficult problem I adopted his technique. My preferred ribs have been the 5th and the 6th due to the ease of access through the infra-mammary incision in females. After harvesting the 4 to 6 cm long rib, the cutting angles, direction and the length of the implants are calculated dependent on the requirements. The idea is to obtain the longest possible implants depending on the shape of the harvested cartilage [Figure 2].



Figure 2. The sixth costal cartilage is obtained and markings performed to decide on the best way for oblique cuts (A); The Chef's knife is used for precise cuts (B); As seen in the picture, about 12 implants of various thicknesses with the preserved outer cortex are obtained and more implants can be sculpted from the remaining cartilage (C)

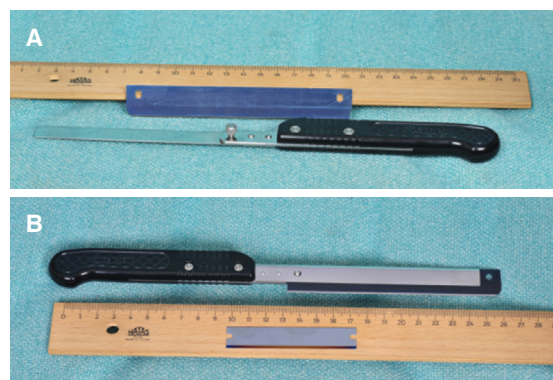


Figure 3. The Chef's knife is composed of two parts: a 26 cm blade holder and a 13 cm blade (A). The blade is inserted in the housing of the holder and a bolt is used to fix the blade in place. The microtome blade is put on the ruler for comparing the dimensions of both blades (B)

What kind of instruments have I used throughout the past 10 years? I started using the microtomes of the pathologists. They were longer than a scalpel and very helpful to make clean long cuts and obtain smooth grafts. After cutting my fingers a few times, I found a microtome handle which kept my fingers on the safe side. Then I used dermatome blades which further improved sectioning the rib cartilage. Almost four years ago, I found the ideal blade which I call as Chef's knife^[6]. While working with the costal cartilage, I always looked for a knife with the cutting height of at least 7-8 mm which is usually the height of the rib. The blades are 13 cm in length and 14 mm in height. When placed in the blade holder, its cutting height becomes 8 mm [Figure 3]. With the help of this knife, the cuts can be done more precisely with improved control, and 0.5, 1, 2 and 3 mm thick grafts can be obtained. In the majority of the cases, the outer cortex is left intact which helps stability and prevents warping and absorption.

Clinical situations to use costal cartilage

Nasal septum

Nasal septum can be severely deviated, or partially absent especially in saddle nose, congenital disorders such as Binder's syndrome or cleft lip nose. The severe deviation can be traumatic or iatrogenic due to previous surgery. In these situations, there is a need for straight implants to reconstruct the nasal septum. The nasal septum can be divided into imaginary sections, and these grafts can be used to reinforce or replace each of the segments (dorsal and or caudal) to obtain a straight L-strut. In cases of previous septal abscess where all the septal cartilage is deficient, it is possible to reconstruct the entire septal cartilage by using the grafts obtained with an oblique cutting technique. Instead of using a template such as PDS foil, these implants of 1-2 mm in thickness can be sutured on 0.5 mm thick implants. The dorsal segment can be supported from both sides by splinting spreader grafts, then they can be coupled with a caudal septal extension or replacement grafts [Figure 4].

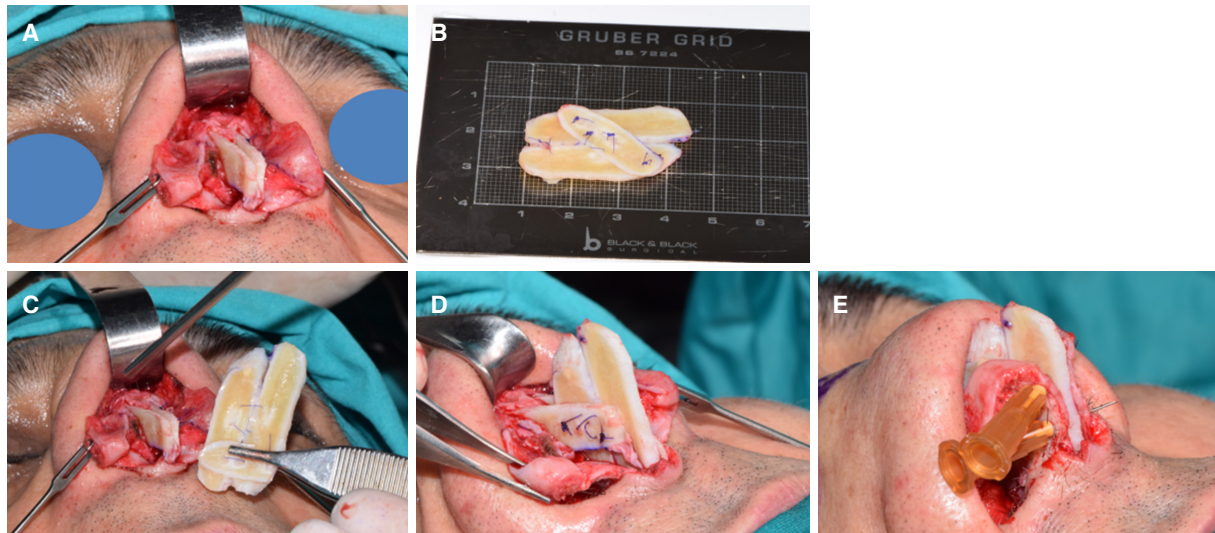


Figure 4. Two splinting spreader grafts are sutured to the small piece of septal cartilage at the key area (A); a new septum is constructed by bringing two 2 mm thick implants sutured to each other by 0.5 mm thick graft (B, C); the new septum is sutured to the spreader grafts to rebuild the L-strut (D); the medial crura are sutured to the new septum as a tongue-in-groove (E)

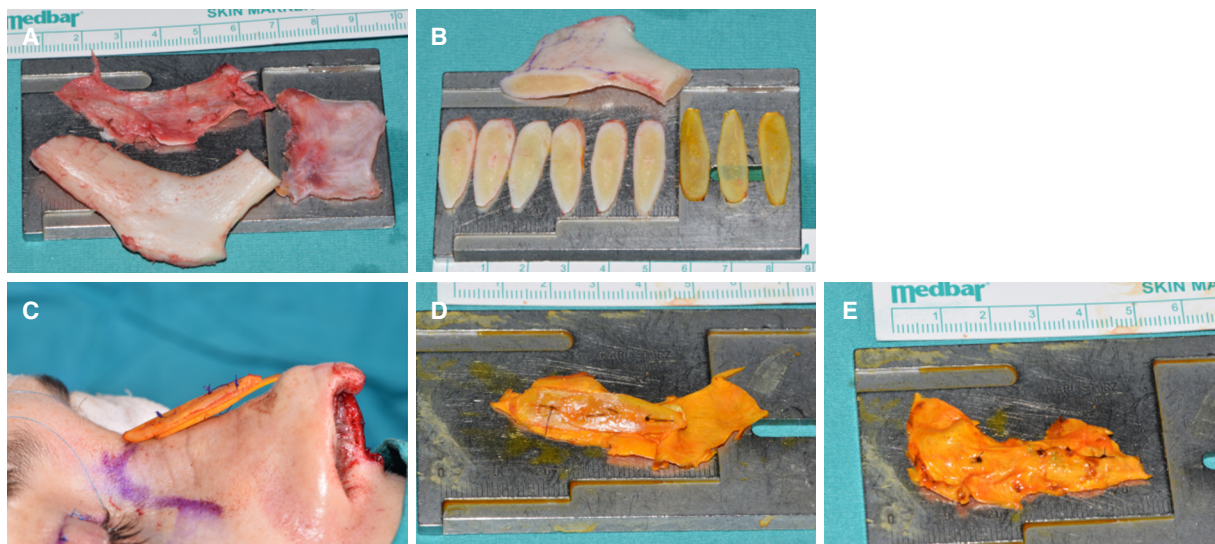


Figure 5. The sixth rib harvested with rectus abdominis fascia and the outer perichondrium (A); multiple implants of various thicknesses are cut by oblique split (B); two laminas are sutured together for augmentation (C); the dorsal surface and the lateral parts of the implants are covered by perichondrium for camouflage (D, E)

Saddle nose

In saddle noses, there are two main issues to address: the nasal septum and the need for augmentation. Regarding the septum, the techniques are described above. For dorsal augmentation, I have been using the following techniques: (1) Solid onlay grafting; (2) Laminated grafts; (3) Diced cartilage in fascia^[7,8]; (4) Cartilage chips in fascia.

The Laminated graft technique involves the combining of two or more obliquely cut grafts by suturing. They are tailored to the needs of the augmentation by partial shaving. I like covering the upper part by means of perichondrium obtained from the outer surface of the rib [Figure 5]. The advantage of this technique is that many oblique cut grafts can be brought together to get the desired dimensions with no risk of warping and resorption.

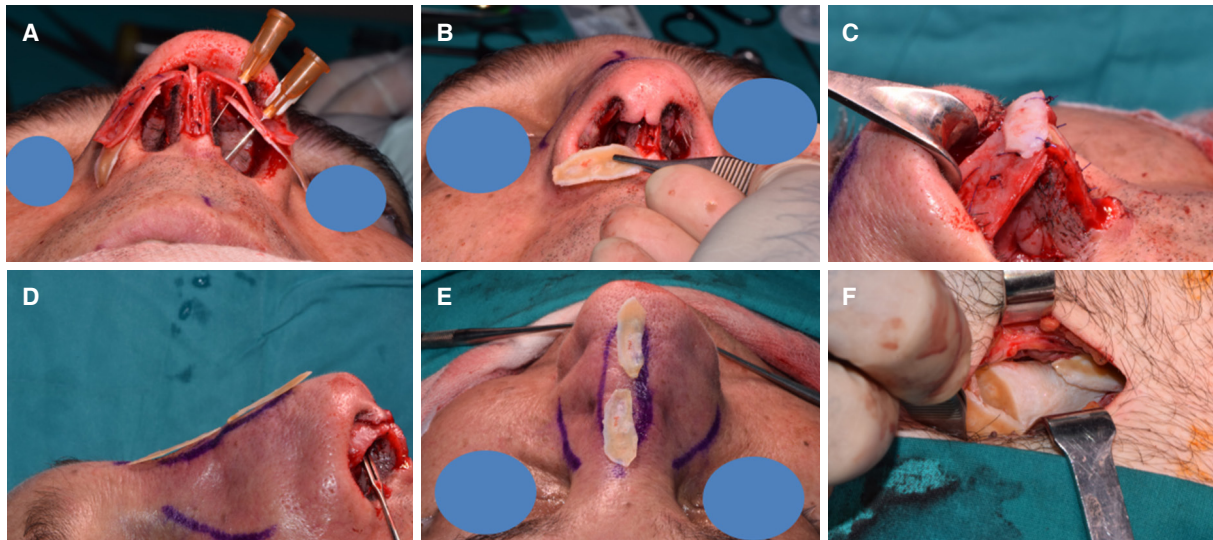


Figure 6. When thinner implants are used as lateral crural strut grafts, the patients do not palpate them from the inside (A); a similar situation is valid for alar batten grafts as well (B); tip grafts can easily be carved from rib cartilage (C); paper thin implants can be used for camouflage purposes (D, E); the remaining cartilages can be inserted into the recipient bed for support (F)

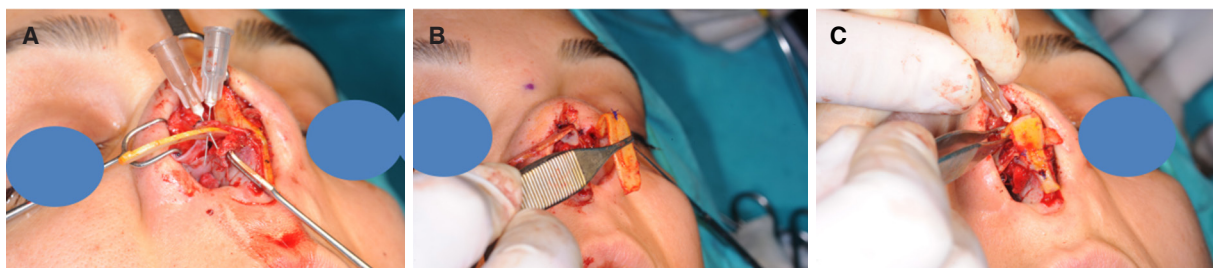


Figure 7. In younger patients, the thin implants are flexible enough to reconstruct the missing lower lateral cartilages partially or totally. In this case, the lateral crura and the domes are reconstructed by thin rib implants (A, B); then a shield graft is sculpted for a better tip definition and projection (C)

Revision rhinoplasty

The patients usually seek revision surgery due to over resection, under resection or persistent nasal deviation. In cases of over resection, graft requirements can often exceed the amounts of cartilage that can be harvested from conchal cartilages. In these situations, the oblique split technique has provided large amounts of straight grafts of various thicknesses and lengths from a single rib, while avoiding technically complicated and time consuming carving techniques. The volume and the variability grafts that can be produced combined with the speed of the oblique split method affords the surgeon greater flexibility than other methods. I have had a chance to cut paper thin implants to use as lateral crural strut grafts and camouflage grafts [Figure 6]. In younger patients, the thinner implants can easily be bent to reconstruct the lower lateral cartilages [Figure 7]. These thinner grafts avoid rigidity and stiffness associated with the use of the thicker grafts.

In revision rhinoplasties and saddle noses, a very useful technique that I have used over the last 5 years is to put paper-thin slices of cartilage, called as cartilage chips, within rectus abdominis fascia or temporalis fascia. In my experience, this is a superior technique than diced cartilage in fascia (a technique which I have used for 8 years), because although very similar in purpose, it stays much firmer on the dorsum than diced cartilage, so the patient is not able to make any changes with the shape of the dorsum [Figure 8].

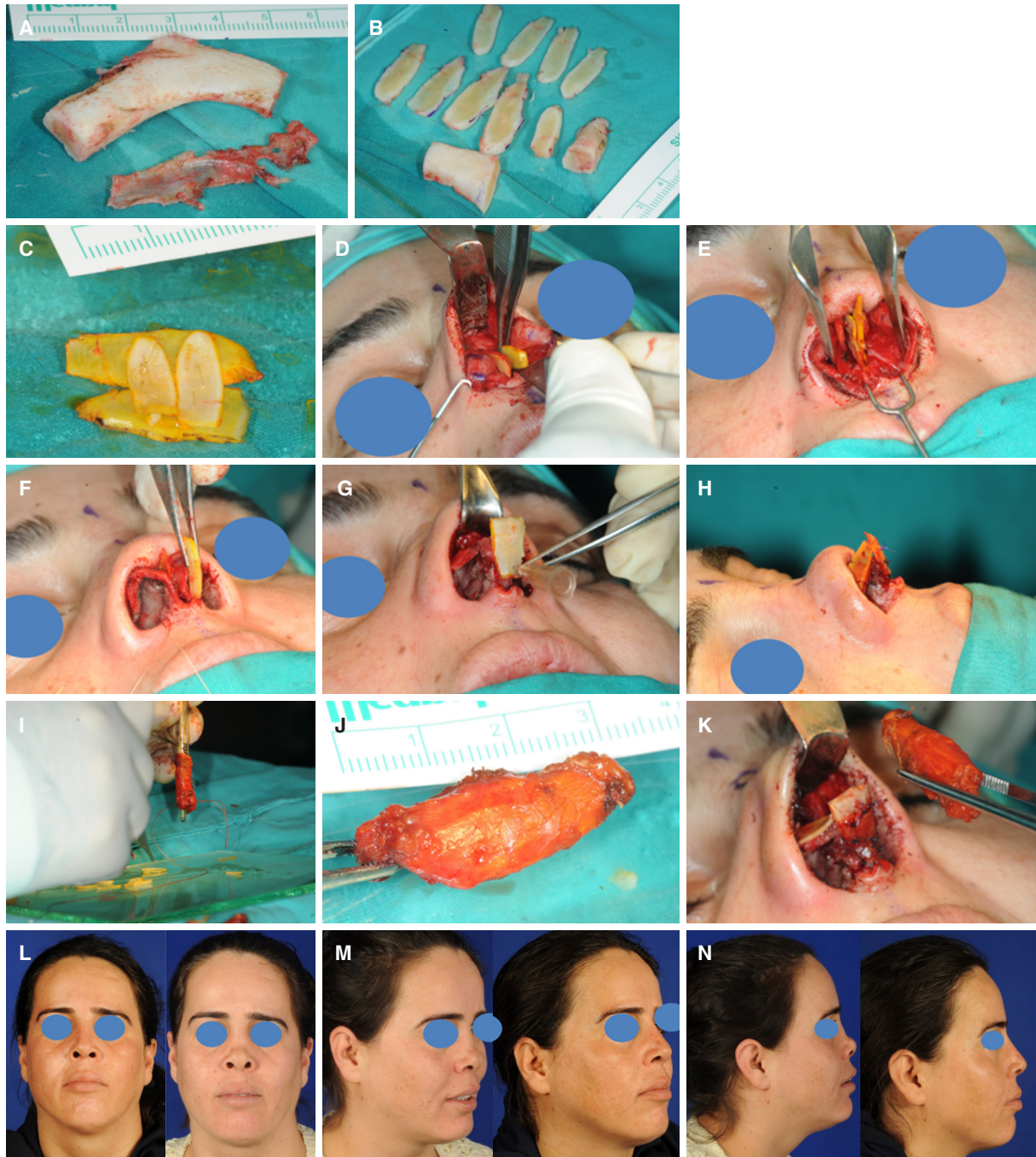


Figure 8. A 28-old female patient had nasal trauma followed by a septal abscess four years ago. She has ended with a short saddle nose. During examination, the septal cartilage was missing. The sixth rib was harvested and obliquely cut (A, B); a new septum was formed (C) and sutured to the splinting spreader grafts (D, E); a columellar strut, shield graft and lateral crural onlay grafts were used (F, G, H); cartilage chips were inserted in rectus abdominis fascia (I, J, K); after two years, the patient was happy with the result (L, M, N)

CONCLUSION

There are two main types of costal cartilage sculpting: symmetrically balanced cross-section and oblique split method. The author's clinical experience over the past decade has demonstrated the superiority of the oblique split method in terms of graft material and reduction in clinical significant warping.

DECLARATIONS

Authors' contributions

The author contributed solely to the article.

Availability of data and materials

Not applicable.

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Conflicts of interest

The author declared that there are no conflicts of interest.

Ethical approval and consent to participate

An informed consent from the patients to participate in the study has been taken.

Consent for publication

An informed consent for publication has been taken from the patients.

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REFERENCES

1. Gibson T, Davis WB. The distortion of autogenous cartilage grafts: Its cause and prevention. *Br J Plast Surg* 1958;10:257-74.
2. Taştan E, Yücel ÖT, Aydın E, Aydoğan F, Beriat K, et al. The oblique split method: a novel technique for carving costal cartilage grafts. *JAMA Facial Plast Surg* 2013;15:198-203.
3. Kim DW, Toriumi DM. Management of posttraumatic nasal deformities: the crooked nose and the saddle nose. *Facial Plast Surg Clin North Am* 2004;12:111-32.
4. Rettinger G. Reconstruction of the pronounced saddle nose. *Laryngorhinootologie* 1997;76:672-5. (in German)
5. Foulad A, Hamamoto A, Manuel C, Wong BJ. Precise and rapid costal cartilage graft sectioning using a novel device: clinical application. *JAMA Facial Plast Surg* 2014;16:107-12.
6. Apaydin F. The "Chef's Knife" in oblique split technique for rhinoplasty. *JAMA Facial Plast Surg* 2015;17:382-3.
7. Erol OO. The Turkish delight: a pliable graft for rhinoplasty. *Plast Reconstr Surg* 2000;105:2229-41; discussion 2242-3.
8. Daniel RK, Calvert JW. Diced cartilage grafts in rhinoplasty surgery. *Plast Reconstr Surg* 2004;113:2156-71.

Original Article

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Skin grafting the vascular pedicle: a useful technique to avoid microvascular collapse in free tissue transfer for limb salvage

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Abstract

Aim: Free tissue transfer is essential for extremity reconstruction following traumatic injuries, oncologic resection, and diabetic complications. However, given the circumferential shape of the arm and leg, a small amount of ongoing edema can prevent a tension-free closure. Additionally, intraoperative thrombosis, vascular disease can lead to proximal exposure of the pedicle or vein grafts. This study evaluates the outcomes of microvascular transfers that utilized a skin graft for closure over the pedicle, in comparison with a matched cohort with a tension-free primary closure.

Methods: A retrospective review was completed of all patients that underwent free flap reconstruction of an extremity defect from January 2014 to December 2017 at a single academic institution. Flaps that utilized skin grafting for closure were compared to those closed primarily. Adjunct operative procedures, demographics, and complications were evaluated.

Results: A total of 71 patients fulfilled the inclusion criteria. The 11 flaps in 10 patients underwent skin grafting over the pedicle. The two cohorts were comparable in age, gender, BMI, and co-morbidities, excluding renal disease which was present in 40% ($n = 4$) of skin grafted group compared to 6.5% ($n = 4$) in the primary closure group. Flap area, operative time, and anastomosis technique were comparable between the two groups. There was no significant difference in the rates of post-operative complications including partial flap loss, complete flap loss, infection. Mean follow up time in the skin grafting group was 14.2 months and 20.2 months for the primary closure group.



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Conclusion: As per the principal, a tension-free closure is paramount to preventing tissue complications including direct compression of a microvascular pedicle. However, with ongoing tissue edema skin grafting should be considered as a reliable technique to ensure both protection of the pedicle as well as prevention of direct compression without additional complications and comparable post-operative outcomes.

Keywords: Free flap, limb salvage, skin graft, microsurgery

INTRODUCTION

Extremity reconstruction after trauma, oncologic resection, and diabetic complications often requires free tissue transfer to provide soft tissue coverage of bone, vessel, and nerve. The circumferential shape of the arm and leg, joint surfaces, motion, tendon glide and potential for weight bearing in addition to the relative lack of elasticity of injured soft tissue, provides unique challenges for a tension free closure. Appropriate flap design requires attentive preoperative planning toward the dimension and thickness of a given defect while taking into consideration the anastomotic location, pedicle lie, vector, tension, motion, tendon glide and potential for weight bearing. Even with optimal planning, excess tension placed over a vascular pedicle can lead to flap demise. Tissue edema, ruddiness and tension can impact the survival of free flaps if pressure is applied over anastomoses. Additional factors such as intraoperative thrombosis, pre-existing vascular disease, or other perioperative patient risk factors can lead to proximal exposure of the pedicle or vein grafts^[1-3].

Tissue edema, especially secondary to renal disease, can be exacerbated in extremity surgery, secondary to the inflammation of the injury itself, restricted motion, lymphatic disruption or radiation therapy, and tourniquet use^[4-7]. Unfortunately, these factors can predate the surgery, and in fact represent a contribution to the primary disease state and extremity wound.

With ongoing tissue edema, primary closure after vascular exposure can become increasingly difficult, even to the point of potentially compressing the vascular pedicle or anastomosis. In these cases, the surgeon could choose to mobilize the flap proximally to prevent vascular exposure, but this may leave a portion of the recipient site uncovered. Alternatively, the flap can be left in place as intended to cover the recipient site, and instead, the vascular pedicle is covered with a full or split thickness skin graft. The latter option may prevent desiccation, but it is unclear if skin grafting the anastomosis, vein grafts and pedicle may provoke microvascular collapse.

This study evaluates the outcomes of microvascular transfers that utilized a skin graft for closure over the pedicle, in comparison with a matched cohort that achieved primary closure. The authors hypothesized that skin grafting provides a tension-free closure when primary closure is unable to be performed and can safely salvage a free-flap reconstruction without an increase in flap related or patient morbidity.

METHODS

All extremity free flaps performed at a single, Level 1 trauma center were entered into a prospectively maintained registry including patient demographic information, clinical history, radiographic imaging, procedural data, operative reports, postoperative care and long-term complications across 118 unique variables. A REDCap database was utilized as a secure web-based application for data maintenance. A trained member of the research team uploads data once monthly. Follow up clinic visits and photography are specifically analyzed to identify limb salvage, flap failure, wound recurrence, patient ambulation, use of assistive devices, patient disposition and rates of amputation. The database is maintained via institutional review board approval. Operative reports were queried specifically wherein description of skin grafts placed

directly over the pedicle were separated from those reports with skin grafting elsewhere such as the donor site or atop the flap.

For the purposes of this study, the database was queried in October 2018 for cases performed from January 2014 to December 2017. For each patient, relevant demographic information, comorbidities, presence of chronic kidney disease, arterial revascularization, anticoagulant use, wound etiology, pre-operative imaging, anatomical wound location, skeletal fixation, flap thickness, operative characteristics, complications and follow-up were reviewed.

Guiding principles in lower extremity reconstruction were followed: appropriate debridement to perfused tissue, preservation of vital structure, muscle, nerve and tendon along with isolation and control of major vascular inflow. Wounds amenable to local tissue reconstruction with advancement flaps, skin-graft, regional pedicle flaps, freestyle propeller flaps were utilized when-able but excluded from this study.

During free tissue transfer, we preferentially performed end-end anastomosis in patients with adequate runoff. However, in settings of critical limb ischemia or compromised in-flow an end to side anastomosis was performed. We have previously studied an algorithm for venous anastomosis and preferentially utilize the deep venous system, avoiding refluxing veins and matching for size^[8].

An enhanced recovery protocol was utilized for the majority of our patients including the use of regional anesthetic block^[9] and an early limb dependency program^[10] helped patients dangle early in their post-operative course expediting hospital stay, discharge to rehabilitation facilities, and return toward functional ambulation.

Primary closure over the pedicle was defined as direct closure of at least the skin layer with tissue from the recipient site, or in combination with a portion of the flap. Tension was evaluated by the inability to close the skin and or skin-flap interface with a 3-0 nylon and a double-knot throw, without slipping. Skin grafting closure required a separate donor site for harvesting the skin graft to place over the fasciocutaneous free flap to provide an additional layer of coverage. Often, in the case of anterolateral thigh free flaps - we were able to utilize the dog-ears from the apices of the lateral thigh incision to create a full thickness skin graft in cases of small ($< 6 \text{ cm} \times 6 \text{ cm}$) areas of pedicle exposure. For any larger dimensions a dermatome was used at 1/14,000 of an inch to place a split thickness skin graft over the pedicle. Thorough attention toward dressing and splinting the extremity was performed. Xeroform (Covidien, Dublin, Ireland) was placed over the skin-graft and pedicle construct without a bolster or pressure dressing. The flap and extremity were wrapped in bulky jones cotton, a plaster splint and ACE to ensure appropriate padding and pressure off-loading of both flap and pedicle. We monitored the flaps using clinical exam, Doppler probes and ViOptix (ViOptix Inc. Newark, CA).

Outcome measures

Outcomes pertaining to flap specific morbidity such as partial flap loss, microvascular collapse, vessel thrombosis, site infection and dehiscence were analyzed in addition to systemic complications as well as need for operative take-back. Additionally, vascular pedicle exposure and loss of the skin graft were also analyzed.

Analysis

Descriptive statistics were utilized to compare patient demographic information in regard to number, frequency, mean and standard deviation. Student *t*-test for continuous data and Fischer's exact test for categorical data were used for univariate analysis to determine significant differences between skin graft and primary closure groups. Those variables achieving significance $P < 0.05$ were entered into a multivariable

Table 1. Patient and wound characteristics compared between patients with vascular pedicle skin grafting and primary closure

Variable	Skin graft to pedicle (n = 13)	Pedicle closed (n = 63)	Odds ratio	P value
Demographics				
AGE Mean (Range)	47 (47-69)	59 (20-77)	-	> 0.05
Male	8 (61%)	48 (76%)	0.41	0.21
Comorbidity				
BMI	28 (21-40)	27 (19-44)	-	> 0.05
Diabetes	7 (54%)	18 (28%)	2.3	0.21
Malnourished albumin > 3	7 (54%)	10 (16%)	5.1	0.02
Renal disease CKD	6 (46%)	4 (6.3%)	9.5	0.0065
Tobacco	2 (15%)	25 (39.6%)	0.16	0.09
Peripheral arterial disease	4 (31%)	13 (20.6%)	1.6	0.54
Coronary artery disease	1 (7.7%)	7 (11.1%)	0.86	0.89
Preop antiplatelet agent (ASA/Plavix)	5 (38%)	43 (68.3%)	0.41	0.21
Preop vascular imaging (CTA/Angio)	6 (46%)	33 (52.3%)	1.27	0.72
Recipient wound				
Pre-flap vascular intervention	2 (15%)	7 (11.1%)	1.9	0.45
Peripheral bypass	0 (0%)	2 (3.1%)	-	-
Endo vascular revascularization	2 (15%)	6 (9.5%)	2.3	0.36
Procedure done	Aplasty, bypass	Aplasty, bypass		
< 3 Vessel runoff	7 (54%)	16 (25.4%)	6.56	0.01
Upper extremity	1 (7%)	7 (11.1%)	-	-
Lower extremity	12 (93%)	54 (85%)	1.56	0.69
Previous amputation	4 (31%)	8 (12.7%)	4.42	0.04
Wound etiology				
Arterial	6 (46%)	27 (42.8%)	1.89	0.36
Traumatic	5 (38%)	35 (55.5%)	0.49	0.31
Malignant	2 (15%)	8 (12.7%)	1.65	0.56
Chronic wound	4 (31%)	25 (39.6%)	0.96	0.95
Infected	5 (38%)	37 (58.7%)	0.64	0.52
Hardware	2 (15%)	21 (33.3%)	0.47	0.37
Osteomyelitis proven	3 (23%)	17 (26.9%)	1.1	0.89
Revascularization	2 (15%)	6 (9.5%)	2.29	0.35

The table compares patients with pedicle skin-grafting versus primary closure over the pedicle. Patient demographic features, comorbidities, wound etiology and location are described by rate and frequency. Univariate analysis was performed and reported as odds ratios where appropriate. $P < 0.05$ are highlighted and reached statistical significance

regression model to identify independent risk factors associated with flap loss. Statistical significance was defined as a $P < 0.05$. All analyses were performed using Prism, version 5.0b (GraphPad Software, La Jolla, CA).

RESULTS

The review identified 75 patients who underwent a total of 76 fasciocutaneous free flaps with either a primary closure over the vascular pedicle ($n = 63$) or a skin graft ($n = 13$) closure [Table 1].

Patient comorbidities included diabetes ($n = 25$), chronic kidney disease ($n = 10$), tobacco use ($n = 27$), peripheral vascular disease ($n = 17$), and coronary artery disease ($n = 8$). Additional clinical characteristics, such as antiplatelet use, were assessed as contributing factors to wound etiology. The two cohorts were comparable in age, gender, BMI, and co-morbidities, excluding renal disease which was present in 46% ($n = 6$) of skin grafted group compared to 6.3% ($n = 4$) in the primary closure group. The pathogenesis of all patient wounds included history of trauma ($n = 40$), malignancy ($n = 10$), chronic wounds ($n = 29$), infected wounds ($n = 42$), and hardware exposure requiring tissue coverage ($n = 23$).

Skin grafting closure was performed for 13 flaps, while the remaining 63 flaps utilized primary closure. The difference in flap area was not significantly different between the skin graft and primary closure groups,

Table 2. Surgical details compared between groups of vascular pedicle closure

Surgical details	Skin graft to pedicle (n = 13)	Pedicle covered (n = 63)	Odds ratio	P value
Operative details				
Single vein	4 (31%)	24 (38.1%)	1	0.96
Dual venous outflow	6 (46%)	37 (58.7%)	0.97	0.97
End-to-end	11 (85%)	58 (92%)	-	> 0.05
End-to-side	2 (15%)	3 (4.8%)	-	> 0.05
Coupler sizes mode (Min-Max) mm	2.0 mm (1.5-2.5 mm)	2.5 mm (1.5-3.5 mm)	-	> 0.05
Flap area (Avg)	17.3 cm × 8.4 cm	19.1 cm × 8.2 cm	-	> 0.05
OR time (Minimum)	420 min (340)	445 min (180)	-	> 0.05

145.3 cm² and 156.6 cm² respectively. OR time was also similar between the two groups with 420 min in the skin graft group and 445 min in the primary closure group. Arterial anastomoses were done in an end-to-end fashion in 82% (n = 11) skin grafting cases and 92% (n = 58) of primary closure cases. Dual venous outflow was used to drain the flaps in 46% of the skin grafted group and 58.7% of the primary closure group (n = 6, n = 37). Operative details are described in Table 2.

Mean follow up time in the skin grafting group was 16.2 months and 22.2 months for the primary closure group. Flap complications occurred in 23 cases (n = 4, n = 19). Individual patient complications are outlined in Table 3.

Total flap loss occurred in 4 primary closure flaps and 1 skin grafted flap. Partial flap loss occurred in 3 primary closure flaps and only 1 skin grafted flap. The most common risk factors among patients with flap loss were pre-existing vascular disease and pre-operative endovascular interventions. In multivariable regression, preoperative arterial revascularization was the only factor identified as associated independently with flap loss. There were no instances of arterial thrombosis or insufficiency in the skin grafted group. There was no statistically significant difference between rates of post-operative complications between the two groups including partial flap loss, complete flap loss, arterial inflow or outflow complications, flap infection, and dehiscence. No flap removals occurred in the skin grafted cohort compared to 7.9% (n = 5) in the primary closure group.

DISCUSSION

The results of this study demonstrate that skin graft closure over a microvascular pedicle can be performed without an increased rate of microvascular complications. Grafting over the pedicle is a safe alternative to primary closure when undue tension may create a risk for vascular compression. There were no cases of arterial thrombosis or insufficiency in the skin grafted group that is likely due to the lack of pressure from a tight, primary closure. There were no statistically significant differences in the post-operative complications between the two groups, no flaps in the skin grafted group required flap removal where there were 5 cases in the primary closure group.

To date, one article was identified in the literature documenting a single case report of primary skin grafting over the vascular pedicle leading to flap salvage^[11]. However, this technique is performed routinely at our institution. The venous flow-through flap is reported with greater frequency in digital and upper extremity replantation/revascularization literature^[12] particularly for coverage of volar soft tissue defects with exposure of digital vessels in ring avulsions, or amputations with soft tissue destruction. However, full thickness skin grafts have also been used in this setting and reported.

Literature regarding flap complications is heterogeneous and limited to retrospective analysis of perioperative patient factors^[3,13,14]. Diabetes, tobacco use, long operating times have all been identified as contributing to flap demise. Diabetes negatively affects the microvasculature causing changes in

Table 3. Flap related complications compared between groups by vascular pedicle coverage

Complication	Skin graft to pedicle (n = 13)	Pedicle covered (n = 63)	Odds ratio	P value
Flap outcomes				
Any flap complication	4 (31%)	19 (30.1%)	1.7	0.44
Early than 7 days take back	2 (15%)	8 (12.6%)	1.9	0.46
Later than 7 days surgery	1 (7%)	9 (14.2%)	0.64	0.69
Venous thrombosis	2 (15%)	5 (7.9%)	4.8	0.11
Arterial thrombosis	0 (0%)	3 (4.7%)	-	-
Arterial insufficiency	0 (0%)	1 (1.6%)	-	-
Partial flap loss skin soft tissue fascia	1 (7%)	3 (4.7%)	3.3	0.34
Complete flap loss	1 (7%)	4 (6.3%)	1.58	0.69
Flap infection	0 (0%)	4 (6.3%)	-	-
Dehiscence	2 (15%)	4 (6.3%)	3.56	0.11
Contour surface irregularity	0 (0%)	0 (0%)	-	-
Debulking	1 (7%)	2 (3.2%)	3.2	0.35
Flap elevation	1 (7%)	9 (14.3%)	0.64	0.69
Flap removal	0 (0%)	5 (7.9%)	-	-
Amputation	0 (0%)	2 (3.1%)	-	-
Follow up average	16.2 months	22.21 months		P > 0.05

compliance, elasticity, and ultimately the blood flow through the vessel. These damaged vessels are used for the anastomosis in a free flap^[15-17]. Lee *et al.*^[15] demonstrated that patients with serum Creatinine greater than 1.28 mg/dL had significantly higher post-operative complication rates including, partial and total necrosis. Flap reconstruction to previously radiated tissues has been shown to have complication rates between 8%-39%, likely due to reduction in vascularization and mean capillary lumen^[18,19]. Utilizing surgical techniques to minimize the tension, pressure, and manipulation of these vessels is imperative for flap survival.

Limb salvage techniques are utilizing thinner flap techniques more frequently as outcomes are proving to be equivalent to the standard anterolateral thigh (ALT) flap with the added benefit of reduced re-operations and revisions for debulking, as seen in Figure 1^[20,21]. In a series of 25 super-thin or supra-fascial ALT flaps, Seth *et al.*^[21] had no episodes of partial or total flap losses. In another study by Hong *et al.*^[7], a flap survival rate of 98% was demonstrated with the super-thin ALT technique. Dr. Hong^[16], like our group, identified preoperative revascularization as an independent risk factor toward flap loss even when utilizing supermicrosurgery and outflow preserving techniques.

Primary closure of a fasciocutaneous flap, as in Figure 2, can be difficult when the original defect's contour has changed due to long OR exposure, fluid resuscitation, and tissue manipulation. There is no current literature evaluating alternative techniques. This study demonstrates skin grafting as a method for flap closure that will minimize risk of vascular compromise and maintain the preoperative dimensions of the flap.

The retrospective design of this study limits the scope of the data that is obtained and potential for randomization. Our series consists of 75 patients over a period of 36 months. Although this is a small volume study of 76 flaps, this is the first series to evaluate skin graft closure. A limitation of this study is the difference between the two cohorts and co-morbid conditions. Patients in the skin grafted group had increased rates of peripheral vascular disease, renal disease, and history of amputations. These specific co-morbid conditions are associated with increased post-operative complication rates; however, our study did not demonstrate this. This study found comparable outcomes between skin graft closure and primary closure in a higher risk cohort, demonstrating another indication for this surgical technique. A prospective, randomized study aimed at evaluating closure techniques and the clinical outcomes is necessary.

In conclusion, skin graft closure over free flap anastomoses and pedicles may be considered a safe, alternative technique to prevent compression of the microvascular pedicle for extremity free tissue transfers. Skin grafting

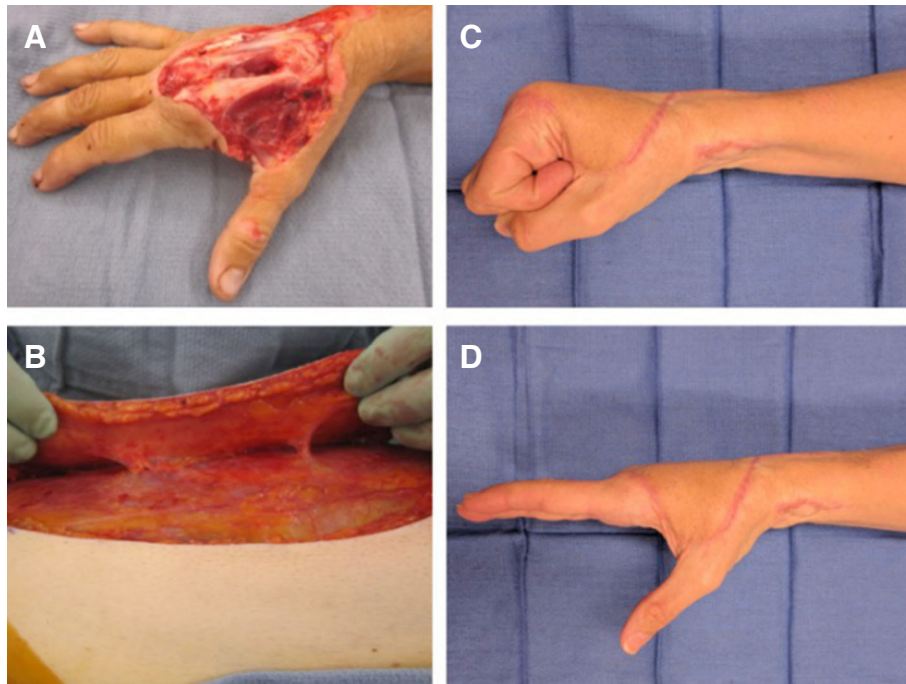


Figure 1. Right hand suprafascial anterolateral thigh (ALT) coverage with skin graft over radial artery. A patient with dorsal hand degloving and exposed extensor tendon in zones 5, 6, 7 (A) preoperative photograph after debridement; (B) shows a suprafascial ALT to match the defect thickness, allow tendon glide and two-stage tendon reconstruction with the ability to elevate. The ALT pedicle was tunneled in the region of the anatomic snuffbox. The LFCA was anastomosed to the radial artery at the level of the wrist. A small full thickness skin graft was used to cover the anastomosis and came from the dog-ear of the lateral thigh donor; Postoperative photos after tendon reconstruction show restoration of hand function (C) (D) and a low profile skin graft at the wrist

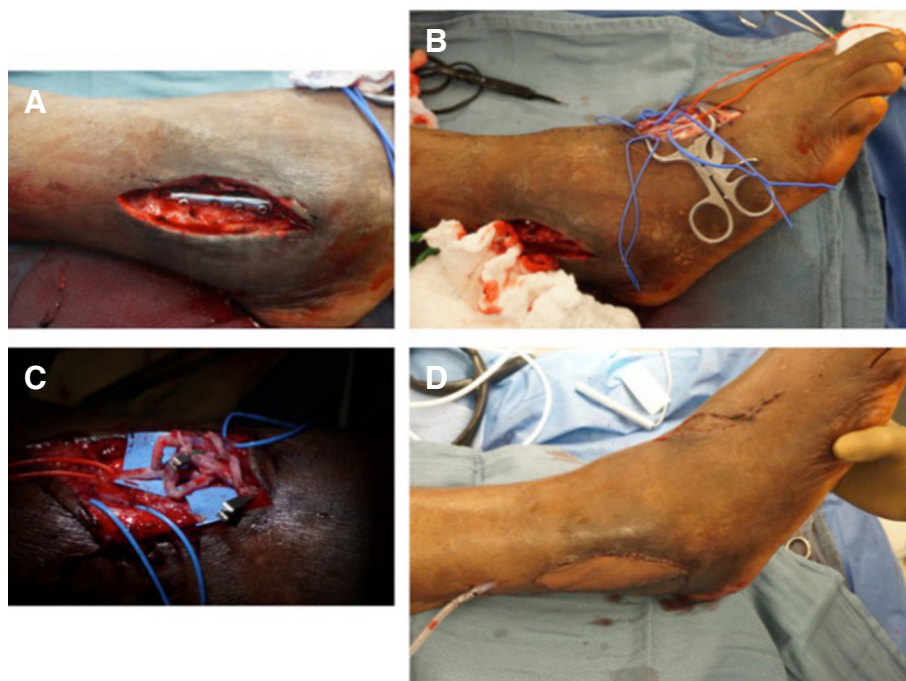


Figure 2. Exposed hardware and fibular non-union - radial forearm flap with dorsalis pedis skin graft A patient with (A) exposed hardware over a fibula fracture at ankle mortis; (B) after exposure of the dorsalis pedis artery, venae comitantes and saphenous vein; (C) showing the vascular anastomosis of a single artery end-side, two venae comitantes of the radial artery system to dorsalis pedis and cephalic to saphenous anastomosis; (D) this created a bulky vascular group ultimately covered with a split thickness skin graft. The small 3 cm x 1 cm skin graft donor site was closed primarily

ensures both protection of the pedicle as well as prevention of direct compression as well as dessication. This technique should be applied to flaps at high risk for major complication, including those exposed to long operative times, pre-existing vascular disease, and flaps requiring anastomotic revisions.

DECLARATIONS

Authors' contributions

Concept and design: Iorio ML

Data acquisition and analysis: Diamond S

Manuscript preparation: Kovar A

Critical revision and completion of manuscript: Kovar A, Diamond S, Iorio ML

Availability of data and materials

Data were strictly obtained from medical records, in accordance with the privacy policy and code of ethics at our institutions.

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None.

Conflicts of interest

All authors declare that there are no conflicts of interest.

Ethical approval and consent to participate

The study was approved by the BIDMC Institutional Review Board (2017-P-000253).

Consent for publication

Not applicable.

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REFERENCES

1. Pohlenz P, Blessmann M, Blake F, Li L, Schmelzle R, et al. Outcome and complications of 540 microvascular free flaps: the Hamburg experience. *Clin Oral Investig* 2007;11:89-92.
2. Preidl RH, Wehrhan F, Schlittenbauer T, Neukam FW, Stockmann P. Perioperative factors that influence the outcome of microsurgical reconstructions in craniomaxillofacial surgery. *Br J Oral Maxillofac Surg* 2015;53:533-7.
3. Gedebo TM, Wei FC, Lin CH. Clinical experience of 1284 free anterolateral thigh flaps. *Handchir Mikrochir Plast Chir* 2002;34:239-44.
4. Li RG, Ren GH, Tan XJ, Yu B, Hu JJ. Free flap transplantation combined with skin grafting and vacuum sealing drainage for repair of circumferential or sub-circumferential soft-tissue wounds of the lower leg. *Med Sci Monit* 2013;19:510-7.
5. Eisenhardt SU, Schmidt Y, Thiele JR, Iblher N, Penna V, et al. Negative pressure wound therapy reduces the ischaemia/reperfusion-associated inflammatory response in free muscle flaps. *J Plast Reconstr Aesthet Surg* 2012;65:640-9.
6. Hong JP. Reconstruction of the diabetic foot using the anterolateral thigh perforator flap. *Plast Reconstr Surg* 2006;117:1599-608.
7. Hong JP, Chung IW. The superficial fascia as a new plane of elevation for anterolateral thigh flaps. *Ann Plast Surg* 2013;70:192-5.
8. Mattos D, Diamond S, Chattha AS, Riesel JN, Iorio ML. Venous anastomoses in anterolateral thigh flaps for the lower extremity: vessel selection in lieu of obligatory number. *Ann Plast Surg* 2018; doi: 10.1097/SAP.0000000000001431.
9. Ruan QZ, Diamond S, Zimmer S, Iorio ML. Assessing the safety and efficacy of regional anesthesia for lower extremity microvascular reconstruction: enhancing recovery. *J Reconstr microsurg* 2018;34:293-9.
10. Seth AK, Diamond S, Iorio ML. Outcomes of an early protocol for dependent conditioning in lower extremity microsurgical free flaps. *J Reconstr Microsurg* 2017;33:670-8.
11. Thione A, Cavadas PC, Landin L, Ibañez J. Microvascular pedicle coverage with split thickness skin graft: Indications and surgical tips. *Indian J Plast Surg* 2011;44:528-9.
12. Brandt K, Khouri RK, Upton J. Free flaps as flow-through vascular conduits for simultaneous coverage and revascularization of the hand or digit. *Plast Reconstr Surg* 1996;98:321-7.

13. Adler SS, Afanasiev S, Aidala C, Ajitanand NN, Akiba Y, et al. Measurement of transverse single-spin asymmetries for midrapidity production of neutral pions and charged hadrons in polarized p + p collisions at square root(s) = 200 GeV. *Phys Rev Lett* 2005;95:202001.
14. Kwok AC, Agarwal JP. An analysis of free flap failure using the ACS NSQIP database. Does flap site and flap type matter? *Microsurgery* 2017;37:531-8.
15. Lee YK, Park KY, Koo YT, Baek RM, Heo CY, et al. Analysis of multiple risk factors affecting the result of free flap transfer for necrotising soft tissue defects of the lower extremities in patients with type 2 diabetes mellitus. *J Plast Reconstr Aesthet Surg* 2014;67:624-8.
16. Hong JPI, Goh TLH, Choi DH, Kim JJ, Suh HS. The efficacy of perforator flaps in the treatment of chronic osteomyelitis. *Plast Reconstr Surg* 2017;140:179-88.
17. Suh HS, Oh TS, Lee HS, Lee SH, Cho YP, et al. A new approach for reconstruction of diabetic foot wounds using the angiosome and supermicrosurgery concept. *Plast Reconstr Surg* 2016;138:702e-9e.
18. Schultze-Mosgau S, Grabenbauer GG, Radespiel-Tröger M, Wiltfang J, Ries J, et al. Vascularization in the transition area between free grafted soft tissues and pre-irradiated graft bed tissues following preoperative radiotherapy in the head and neck region. *Head Neck* 2002;24:42-51.
19. Wehrhan F, Rödel F, Grabenbauer GG, Amann K, Brückl W, et al. Transforming growth factor beta 1 dependent regulation of Tenascin-C in radiation impaired wound healing. *Radiother Oncol* 2004;72:297-303.
20. Diamond S, Seth AK, Chattha AS, Iorio ML. Outcomes of subfascial, suprafascial, and super-thin anterolateral thigh flaps: tailoring thickness without added morbidity. *J Reconstr Microsurg* 2018;34:176-84.
21. Seth AK, Iorio ML. Super-thin and suprafascial anterolateral thigh perforator flaps for extremity reconstruction. *J Reconstr Microsurg* 2017;33:466-73.

Original Article

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Surgical management of zygomatic complex fractures in a major trauma centre

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Abstract

Aim: To analyse the epidemiology, aetiology, and surgical management of zygomatic complex (ZMC) fractures in our major trauma centre, and to compare the number and location of fixation points and surgical access in our patient cohort with the literature.

Methods: Retrospective analysis of all operative cases (Open Reduction and Internal Fixation) of zygomatic complex fractures over a one year period (2016).

Results: A greater proportion of patients in our cohort (54%) were treated with one-point fixation compared to the literature, with the zygomaticomaxillary (ZM) buttress being the most popular fixation point (90%). ZM buttress and frontozygomatic (FZ) suture were the commonest choices for two-point fixations (70%). Buccal sulcus incision was used for ZM access in all cases. For FZ access, upper blepharoplasty incision was the most common (56%). For infra-orbital margin access, transconjunctival incision was the most common (75%). There was no significant association between number of fixation points and presence of associated injuries, impact of injury, or time to operation. There were no post-operative complications.

Conclusion: A greater proportion of patients in our cohort were successfully treated with one point fixation compared to the literature, and fewer patients underwent orbital floor exploration and repair in our cohort compared to the literature. This study highlights the ongoing variation in the surgical management of ZMC fractures.



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Keywords: Zygomatic complex fractures, ZMC, open reduction internal fixation, zygomaticomaxillary buttress

INTRODUCTION

Zygomatic complex (ZMC) fractures are relatively common. A literature search showed ZMC fractures to account for approximately 15%-23.5% of maxillofacial fractures^[1-3]. The incidence of ZMC fractures varies with geographical location, socioeconomic trends, and incidence of road traffic collisions (RTCs), alcohol abuse and drug abuse^[4]. A number of studies had shown ZMC fractures to be the second most common facial fracture, after nasal bone or mandible fractures^[3-6]. Common causes of ZMC fractures include interpersonal violence (15%-64.5%), RTCs (13.9%-49%), as well as falls, occupational accidents, and sport-related injuries^[3,7,8]. Furthermore, ZMC fractures are more common in men than women, and most commonly occur in the third decade of life^[2].

An intact zygoma (or zygomatic bone) and its surrounding bony anatomy are essential for maintaining facial contour, such as cheek prominence, as well as orbital integrity^[5]. Anatomically, the zygoma is attached to the frontal bone (via the frontozygomatic suture), the maxilla (via the zygomaticomaxillary suture), the squamous part of the temporal bone (via the zygomaticotemporal suture) and the sphenoid bone (via the zygomaticosphenoid suture) [Figure 1]^[6]. Fractures that involve the zygoma often occur at these four suture sites, leading to a “tetrapod” fracture pattern, known as a “zygomatic complex fracture” (ZMC). Furthermore, the zygoma is connected to the maxilla and sphenoid bone as part of the inferior orbital floor, and forms the lateral orbital margin with the frontal bone. Thus, fractures of the zygomatic complex inevitably lead to a certain degree of orbital defect. Other fracture patterns, include isolated zygomatic arch fractures, or ZMC fractures with associated pan-facial fractures, such as Le Fort II and III fracture patterns. Indication for fixation of zygomatic fractures includes aesthetic defects (e.g., cheekbone flattening or a dimple) or functional defects (e.g., restrictive mouth opening, malocclusion or ophthalmic issues such as diplopia, restricted eye movements, enophthalmus and hypoglobus).

There are currently no widely accepted treatment protocols or guidelines on the surgical management of ZMC fractures. The fixation points used in the Open Reduction and Internal Fixation (ORIF) of ZMC fractures are shown in Figure 2. A review of the literature shows that for ORIF of ZMC fractures, the number of fixation points used, their location, as well as the incisional access to these fixation points is variable^[1-4]. A multidisciplinary survey by Farber *et al.*^[10] in 2016 involving Otorhinolaryngology (ENT), Plastic and Oral and Maxillofacial (OMF) surgeons, demonstrated variable treatment choices for ZMC fractures regarding the location and number of fixation points, surgical approaches, as well as the need for orbital floor exploration. Interestingly, across all three specialties, it was demonstrated that a greater number of fixation points were chosen by surgeons with less than 10 years' experience^[10].

With regards to one-point fixation, there is variable support from the literature regarding its efficacy, and there is no consensus regarding the optimum anatomical position for one point fixation between the zygomaticomaxillary (ZM) buttress, the infraorbital margin (IOM) and the frontozygomatic (FZ) region, as well as the optimum surgical access to these anatomical fixation points^[4,11,12]. The ZM buttress has been quoted to be a popular choice for one-point fixation in some literature, whilst others have quoted the FZ suture as their first choice, but beyond this, there is little consensus^[4,11-13]. Some literature advocates the fixation of both the IOM and FZ suture for any displaced ZMC fractures, and for cases with displacement greater than 5mm, the use of 3-point fixation is recommended^[13].

METHODS

We retrospectively retrieved, from an online database, all operative cases (ORIF) of zygomatic complex fractures, isolated zygomatic arch fractures, with and without other associated operative procedures (e.g.,

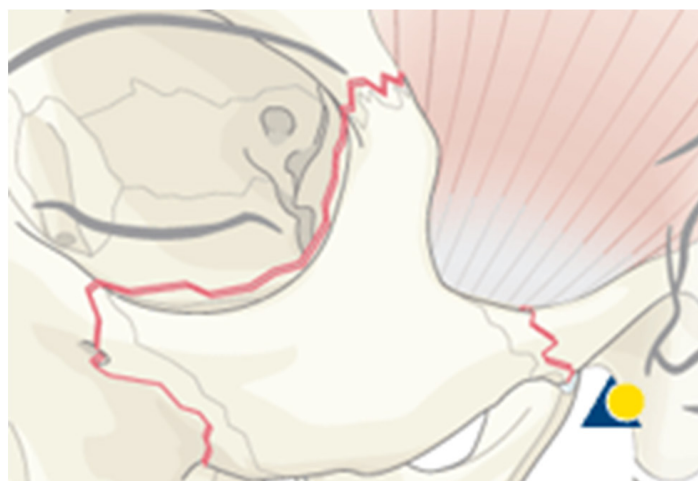


Figure 1. Image reproduced with permission from AO Surgery Reference www.aosurgery.org showing the left zygomatic bone outlined in red, with its anatomical relationship to the frontal bone (superiorly, forming the frontozygomatic suture), maxilla (medially, forming the zygomaticomaxillary suture and infraorbital rim), and squamous part of the temporal bone (laterally, forming the zygomaticotemporal suture), as well as forming part of the orbital floor. Fractures commonly occur at the three above mentioned suture sites, thus result in a classic “tripod fracture”^[9]

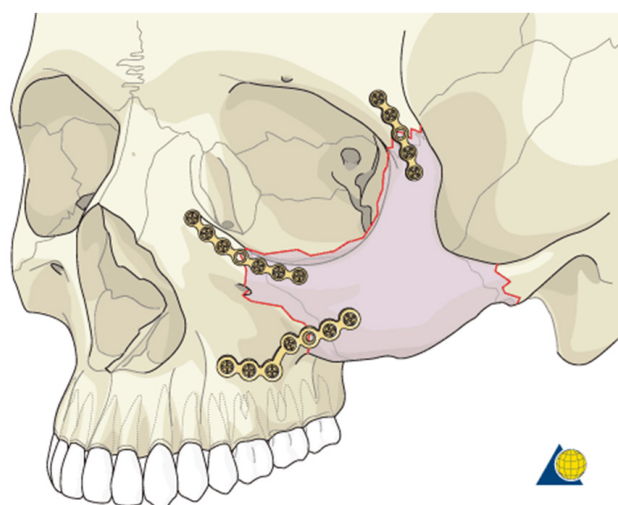


Figure 2. Image reproduced with permission from AO Surgery Reference, www.aosurgery.org illustrating a three-point fixation of a ZMC fracture at the frontozygomatic (FZ) suture (top), infraorbital margin (IOM) (middle), and zygomaticomaxillary (ZM) buttress (bottom)

MUA nose, orbital floor exploration, orbital floor fixation or Le Fort fracture fixations) over a one year period (2016) at our trauma centre, Kings College London Hospital.

Our data set included demographic data (age, sex, relevant past medical history, smoking and alcohol intake status), aetiology (mechanism and impact of injury), treatment timeline (including presentation, referral pathway, time to outpatient clinic and time to operation), clinical features (including head injury, eye signs e.g., enophthalmus, hypoglobus, diplopia, restricted eye movements, infraorbital nerve paraesthesia, aesthetic deficit e.g., cheek flattening, infraorbital rim deformity and functional deficit e.g., restricted mouth opening and malocclusion), diagnosis, type of operation (ORIF, indirect reduction, with or without associated operative procedures, location and number of fixation points, and type of incision used for access), and outcomes and follow up.

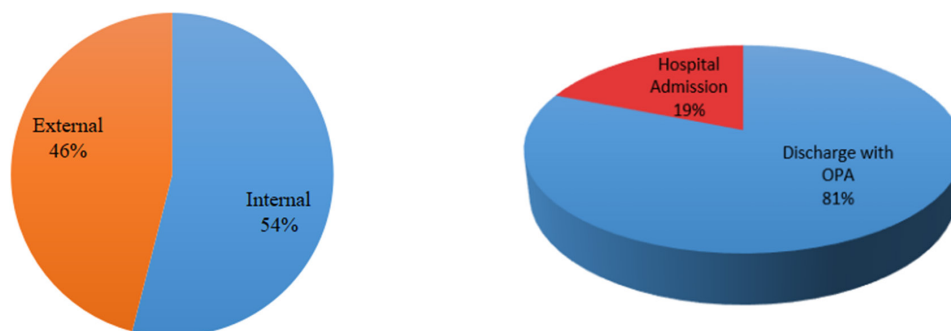


Figure 3. Chart demonstrating the referral pathway and outcome from initial presentation: (left) referral: 55% cases were internal referrals from our emergency department, and 45% were from external sources e.g., other hospitals, urgent care centre or general practice; (right) initial outcome: majority of patients were discharged after initial review (81%), with the remaining being admitted (19%), often with other associated injuries

All conservatively managed cases of ZMC fractures were excluded. The data was collected and recorded on a shared data-protected Excel spread sheets and was conducted by the author and co-authors. The project was authorised by the Kings College Hospital NHS Foundation Trust, and there was no conflict of interest issues.

RESULTS

The 2016 cohort consisted of 53 operative cases. There were 40 ZMC fractures and 13 isolated zygomatic arch fractures.

One ZMC fracture case was excluded from the points of fixation and surgical incision analysis. This patient was a polytrauma patient who had surgery delayed by 49 days due to their concurrent injuries, and it was not possible to reduce the ZMC fracture intra-operatively. A bone graft was therefore taken from the anterior maxillary sinus wall and secured to zygomatic body to aesthetically improve the patient's cheek flattening.

Demographics

Of the operated ZMC fractures in 2016, the mean age was 33.1, median of 30.0, mode of 27 and range was 16-69 years. The majority of cases were male (89%, $n = 47$), with 11% ($n = 6$) female, and 87% ($n = 46$) were fit and well, with 13% ($n = 7$) having associated medical comorbidity (including hypertension, asthma, high cholesterol and chronic gastritis).

Referral, presentation and treatment timeline

Just over half of the cases (55%, $n = 29$) were direct internal referrals from our Emergency Department and 45% ($n = 24$) were external referrals [Figure 3]. The majority (81%, $n = 43$) of cases (internal or external referrals) were discharged on initial presentation and arranged for an OMFS outpatients appointment (OPA), 19% ($n = 10$) were admitted (most commonly under the trauma team) and received inpatient OMFS review [Figure 3]. The mean duration between time of injury to initial presentation was 0.28 days (median 0, mode 0, range 0-7), and between initial presentation to outpatient follow up was 7.9 days (median 7.5, mode 5, range 1-19) [Figure 4]. Furthermore, the mean duration between injury to operation was 15.4 days (median 15.5, mode 15, range 0-29), and between operation to discharge was 1 day (median 1, mean 1, range 0-12). The mean duration between discharge and first outpatients follow up was 14 days (median 12, mode 10, range 3-31) [Figure 4].

Aetiology

The most common cause of ZMC fracture was from interpersonal violence (53%, $n = 28$), followed by 23% ($n = 12$) falls, 13% ($n = 7$) RTCs. In the remaining six patients, causes included sports injuries and occupational injuries.

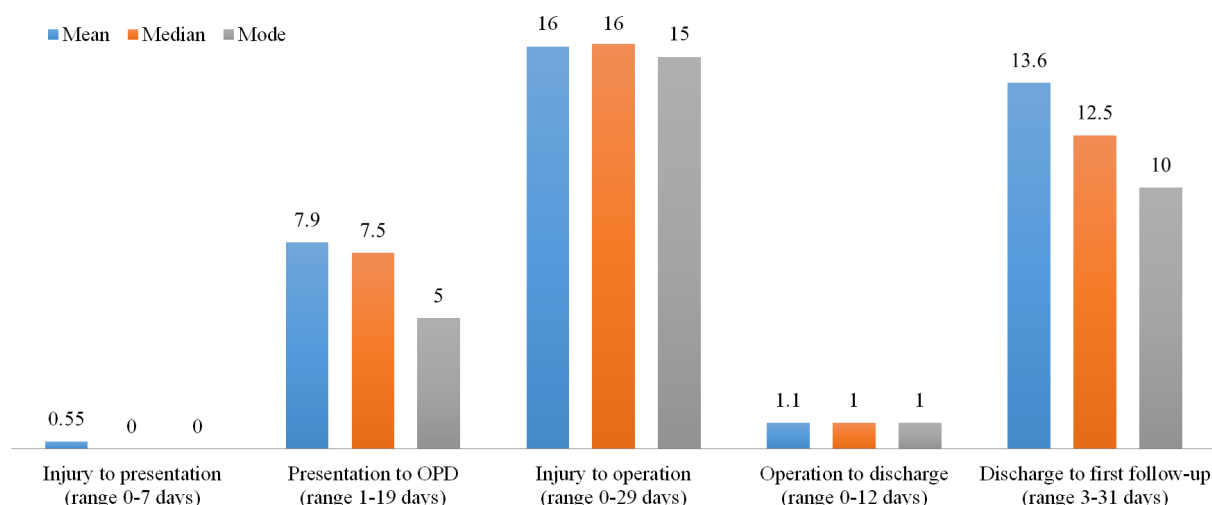


Figure 4. Graph demonstrating the duration (days) between various aspect of the treatment pathway (mean, median, mode and range): injury to initial presentation; initial presentation to outpatient department (OPD) follow-up; injury to time of operation; operation to discharge i.e., length of hospital stay post-op; time between discharge and first follow-up

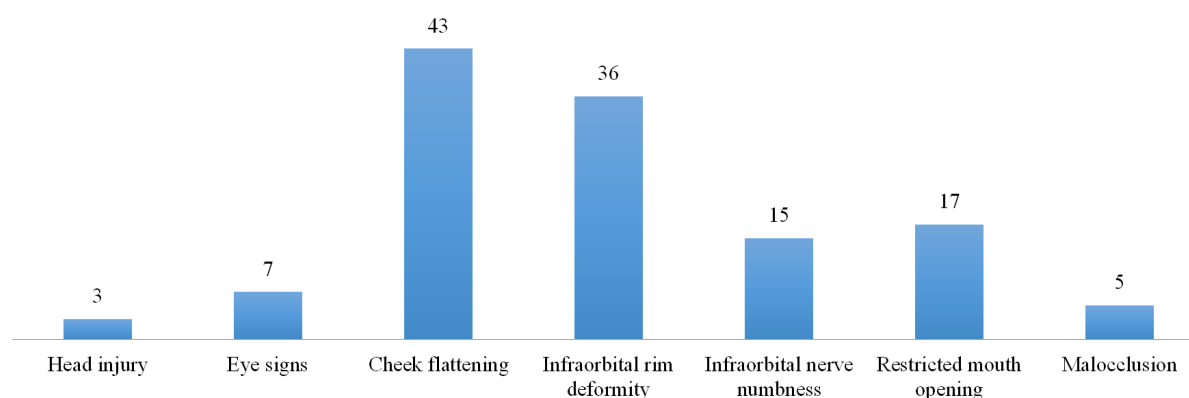


Figure 5. Graph showing the number of patients with particular clinical features in the 2016 cohort ($n = 53$)

There was inadequate documentation to determine the possible association of alcohol and/or illicit drug intoxication to the injury. Regarding impact of injury, 81% ($n = 43$) were low impact, 15% ($n = 8$) were high impact, and 4% ($n = 2$) was not recorded. Low impact injuries included punch-related assaults or minor mechanical falls (less than 2 m in height), compared to RTCs, assaults from hard objects, or falls from a significant height (greater than 2 m), which were considered high impact injuries.

Clinical features

There were 6% ($n = 3$) of patients who had an associated head injury, 13% ($n = 7$) with eye signs (e.g., diplopia, enophthalmus, hypoglobus, limitation of eye movements), 81% ($n = 43$) with flattening of malar prominence 68% ($n = 36$) with palpable infraorbital step, 28% ($n = 15$) with infraorbital nerve numbness, 32% ($n = 17$) with restricted mouth opening and 9% ($n = 5$) with malocclusion [Figure 5].

Diagnosis

Of the 53 patients in our 2016 cohort, 55% ($n = 29$) were isolated ZMC fractures without significant orbital floor defect, 20% ($n = 11$) were ZMC fractures with other associated maxillofacial injuries, and 25% ($n = 13$) were isolated zygomatic arch fractures only [Figure 6].

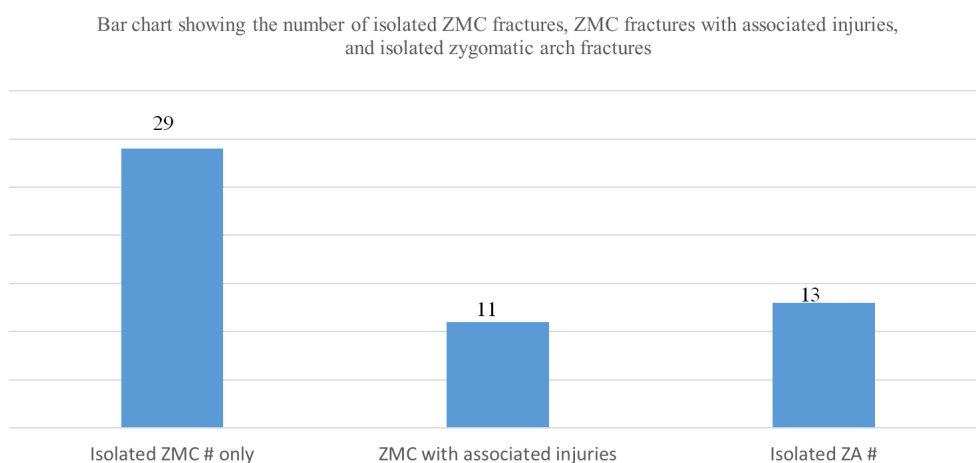


Figure 6. Bar chart showing the number of isolated ZMC fractures, the number of patients who also had associated maxillofacial injuries, and the number of isolated zygomatic arch fractures

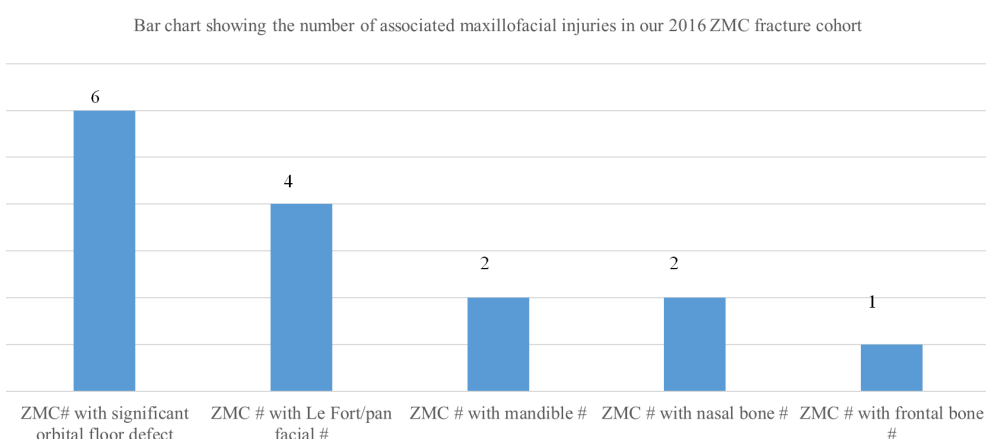


Figure 7. Bar chart showing the number associated maxillofacial injuries in our ZMC fracture cohort of 2016

Of those patients who had a ZMC fracture and associated maxillofacial injuries (20%, $n = 11$), there were six cases of significant orbital floor defect. Orbital floor defects that resulted in eyes signs were confirmed radiologically on CT scans and were considered significant. There were additional associated maxillofacial injuries including four cases of Le Fort fracture patterns, two mandible fractures, two nasal bone fractures, and one frontal bone fracture [Figure 7].

Operations

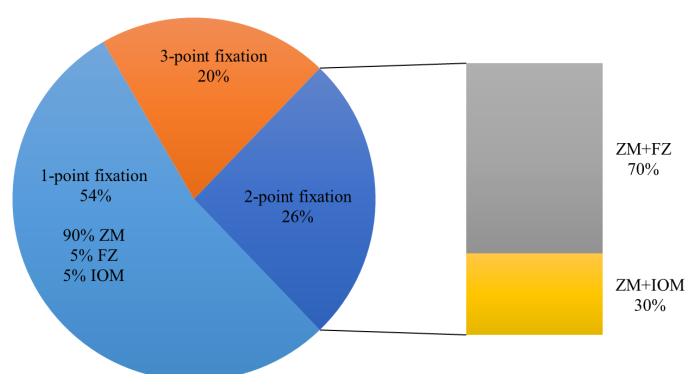
As shown in Table 1, there were a total of 39 open reduction internal fixation (ORIF) of ZMC fractures. Of these, 27 (69%) cases were ORIF of ZMC fracture only, and in 12 cases (31%) there were other associated procedures including orbital floor exploration (10%, $n = 4$), orbital floor repair (7.5%, $n = 3$), ORIF of Le Fort fractures (5%, $n = 2$), ORIF of Mandible and Le Fort fractures (5%, $n = 2$) and one nasal MUA (2.5%).

In one case, a polytrauma patient who had surgery delayed by 49 days due to their concurrent injuries, it was not possible to reduce the ZMC fracture intra-operatively. A bone graft was therefore taken from the anterior maxillary sinus wall and secured to zygomatic body to aesthetically improve the cheek flattening.

Table 1. Distribution of operative cases of ZMC fractures in 2016: including ORIF ZMC only, ORIF ZMC and associated operative procedures, and indirect reduction (Gillies and Keen's)

OPERATION	Number (n), (%)
ORIF	Total = 39
ORIF ZMC only	27 (69%)
ORIF ZMC + Orbital floor exploration	4 (10%)
ORIF ZMC + Orbital floor repair	3 (7.5%)
ORIF ZMC + ORIF Le Fort	2 (5%)
ORIF ZMC + ORIF Mandible + ORIF Le Fort	2 (5%)
ORIF ZMC + Nasal MUA	1 (2.5%)
BONE GRAFT	Total = 1
Not possible to reduce fracture intra-operatively	1
INDIRECT REDUCTION	Total = 13
Gillies lift	11 (85%)
Keen's	2 (15%)

ORIF: Open Reduction and Internal Fixation; ZMC: zygomatic complex

**Figure 8.** Chart illustrating the number of fixation points used and their location in all cases of ORIF ZMC fractures in the 2016 cohort ($n = 39$)

All of the 13 isolated zygomatic arch fractures were treated with indirect reduction using Gillies (85%, $n = 11$) and Keen's (15%, $n = 2$) approaches.

Points of fixation and access (incisions)

Up to three anatomical points of fixation (plating) were used for ORIF of ZMC fractures: zygomaticomaxillary (ZM) buttress, frontozygomatic (FZ) suture and infraorbital margin (IOM). For FZ suture fixation, three types of incisions were used: upper blepharoplasty, lateral eyebrow, and existing scar. For IOM fixations, three types of incisions were used: subciliary, subtarsal and transconjunctival.

As previously mentioned, one ZMC fracture case in a polytrauma patient who had surgery delayed 49 days due to concurrent injuries was managed with a bone graft as it was not possible to reduce the ZMC fracture intra-operatively. We shall therefore use the remaining 39 ORIF ZMC cases to analyse points of fixations and surgical access used.

Of these 39 cases of ORIF ZMC (with or without other associated fixations): 54% ($n = 21$) had one-point fixations, 26% ($n = 10$) had two-point fixations, and 20% ($n = 8$) had three-point fixations [Figure 8]. Of the one-point fixations ($n = 21$), 90% ($n = 19$) had fixation at the ZM buttress, and in the remaining two cases, one had fixation at the FZ via a lateral eyebrow incision, and the other had fixation at the IOM via a transconjunctival incision. Of the two-point fixations ($n = 10$), 70% ($n = 7$) had fixation at the ZM buttress and FZ, and 30% ($n = 3$) had fixation at the ZM buttress and IOM.

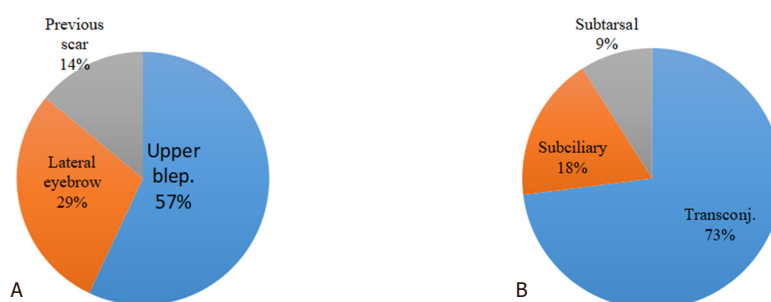


Figure 9. Graphs illustrating the type of incision used to access the frontozygomatic (FZ) suture (upper blepharoplasty, lateral eyebrow and previous scar) (A); and the infraorbital margin (IOM) (transconjunctival, subciliary and subtarsal) (B)

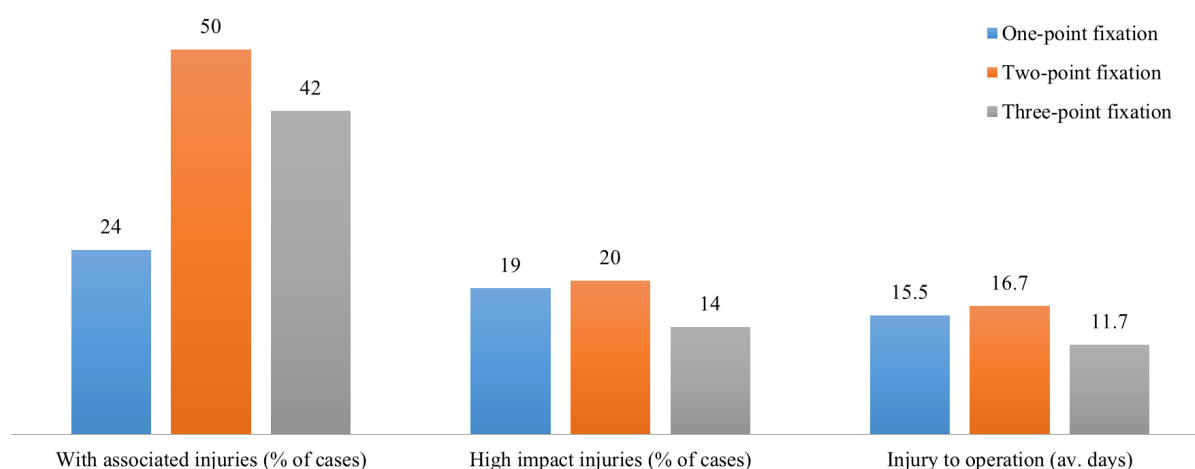


Figure 10. Graphs showing the association between number of fixation point versus: associated injuries, high impact injuries, and injury to operation time

Overall, 95% ($n = 37$) of cases involved a ZM buttress fixation, all accessed through an intra-oral buccal-sulcus incision. Furthermore, 41% ($n = 16$) of cases involved an FZ fixation: one case for a one-point fixation, 7 cases for a two-point fixation, and 8 cases for a three-point fixation. Upper blepharoplasty incision was used in 56% ($n = 9$) of FZ fixations, with 31% ($n = 5$) via a lateral eyebrow incision, and 13% ($n = 2$) via a previous scar [Figure 9]. Lastly, 31% ($n = 12$) of cases involved an IOM fixation: one case for a one-point fixation, 3 cases for a two-point fixation, and 8 cases for a three-point fixation. Of the IOM fixations ($n = 12$), 75% ($n = 9$) were via a transconjunctival incision, 17% ($n = 2$) via a subciliary incision and 8% ($n = 1$) via a subtarsal incision [Figure 9].

Number of fixation versus associated injuries, impact of injury, and injury to operation duration

Of the two-point fixation cases ($n = 10$), 50% ($n = 5$) had other associated maxilla-facial injuries, of the three-point fixation cases ($n = 8$), 42% ($n = 3$) had other associated maxillofacial injuries. In the one-point fixation cases ($n = 21$), only 24% ($n = 4$) had other associated facial injuries [Figure 10]. However, there was statistically significant correlation shown between the number of fixation points and presence of associated injuries ($P = 0.52$).

High impact injuries accounted for 19% ($n = 4$) of one-point fixation cases, 20% ($n = 2$) of two-point fixation cases and 14% ($n = 1$) of three-point fixation cases [Figure 10]. RTCs, assaults from hard objects, or falls from a significant height (greater than 2 m), were considered high impact injuries. There was no significant correlation found between the number of fixation points and the impact of injury.

The average duration (days) between injury to operation was 15.5, 16.7 and 11.7, for one-, two- and three-point fixations, respectively [Figure 10]. There was no significant correlation between the number of fixation points and duration from injury to operation.

Immediate and long-term complications

There were no immediate postoperative complications. As previously mentioned, in one case, a polytrauma patient who had surgery delayed by 49 days due to their concurrent injuries, it was not possible to reduce the ZMC fracture intra-operatively. A bone graft was therefore taken from the anterior maxillary sinus wall and secured to zygomatic body to aesthetically improve the cheek flattening from the ZMC fracture. The patient had an aesthetically satisfactory result and on subsequent outpatient follow-up the patient was pleased with their improved cheek contour from the bone graft. Another patient had delayed improvement of mouth opening, which subsequently resolved.

Follow up

Of the 53 surgically managed patients in our cohort, 4 (7.5%) did not attend follow up and in 11 (21%) patients follow up status was not documented. Twenty (38%) patients were discharged from OMFS after their first outpatient follow up consultation, 13 (25%) were discharged after their 2nd consultation, and 5 (9%) after their 3rd. All patients who attended follow up had satisfactory aesthetic and functional outcomes.

DISCUSSION

This article provides an overview of the epidemiology, aetiology, presentation, and management of surgically-treated cases of ZMC fractures at our major trauma centre over a one year period.

The demographic data showed that the commonest age group (mode) presenting with ZMC fractures was 27 years of age, and the incidence was significantly greater (89%) in men compared to women (11%), which was in keeping with the current literature^[1-4]. The commonest aetiology was interpersonal violence (53%), followed by falls, RTCs and sport-related injuries. According to existing literature, aetiology is variable, with one study in Poland quoting assault as the most common, followed by RTC and other studies from Brazil and Amsterdam, showing RTCs to be most common, followed by assault^[2,4,7,8]. These variations confirm that the aetiology of ZMC fractures are influenced by multiple factors, including geographical location, incidence of RTCs and socioeconomic trends. Within our demographics, the majority were low impact injuries (81%), such as from punch-related assaults or mechanical falls (< 2 m), compared to 15% related to RTCs, assaults from hard objects, or falls from a significant height (> 2 m) which were considered as high impact injuries. We are unable to comment on the significance of alcohol or illicit drug use relating to injury due to inadequate documentation of this in patients' notes.

Of the 13 patients in our cohort with isolated zygomatic arch fractures, all were treated with indirect reduction using Gillies lift or Keen's approach. This was similar to a study in which 26 isolated zygomatic arch fractures were all managed with indirect reduction^[4].

Of the thirty-nine ZMC fractures in our cohort, all were treated with ORIF. This is in keeping with a study of 532 ZMC fractures in which all were treated with ORIF^[14]. However, in a retrospective study of 210 cases of ZMC fractures, 84% ($n = 177$) patients had ORIF, whilst 16% ($n = 33$) had closed reduction^[4]. A survey answered by over 1600 ENT, OMFS and plastic surgeons that showed 81% would choose ORIF for ZMC fractures^[15]. None of the ZMC fractures in our cohort were treated with closed reduction.

Out of the 39 ZMC fracture patients included in our study, 10% ($n = 4$) underwent orbital floor exploration and 7.5% ($n = 3$) underwent orbital floor repair. Our proportion of ORIF ZMC fractures undergoing associated

orbital floor exploration was lower in comparison to a study of 72 patients with ZMC fractures, where 30% of patients underwent orbital floor exploration^[16]. Some centres carry out orbital floor exploration in cases of primary diplopia or evidence of comminuted ZMC fractures only^[17]. Interestingly, as demonstrated in a survey involving facial reconstructive surgeons, it was shown that 35% would carry out an orbital floor exploration routinely^[15]. The proportion of patients in our cohort undergoing orbital floor repair was also lower when comparing to the literature. In a study of 758 patients with ZMC fractures, where intraoperative CT imaging was used, 40% of patients underwent orbital floor repair, compared to 7.5% in our cohort, although intraoperative CT imaging is not used in our centre for ZMC fracture fixation^[18]. Overall, these comparisons highlight the ongoing lack of consensus regarding the management of orbital floor defects in association with ZMC fractures.

Anatomically, although ZMC fractures will result in an orbital floor defect to a certain degree, not all cases warrant surgical exploration or repair of the orbital floor^[18]. Orbital floor exploration and/or repair is often required in the presences of eye signs (enophthalmus, hypoglobus, diplopia, restricted eye movements) or a significant defect with or without ocular muscular entrapment seen on CT imaging. At present, aside from clinical judgment based on examination and imaging, there is no clear consensus or guideline to determine which cases of ZMC fractures require orbital floor exploration or repair. Further investigation to compare pre-operative clinical eye signs in ZMC fractures (enophthalmus, hypoglobus, diplopia, restricted eye movements), pre-operative orbital floor CT imaging, and the frequency of subsequent orbital floor exploration and repair between different centres would be useful to aid developing such a protocol.

Of the 39 cases that underwent ORIF, one-point fixations were the most popular (54%, $n = 21$), followed by two-point fixations (26%, $n = 10$) and three-point fixations (20%, $n = 8$). Amongst the cases of one-point fixation, 90% ($n = 19$) had fixation at the ZM buttress, 5% ($n = 1$) at the FZ suture and 5% ($n = 1$) at the IOM. Some literature supports the ZM buttress as the first choice for one-point fixations, with it providing sufficient stability, without the need for fixation at the FZ site, whilst some studies advocate FZ suture as the first choice, claiming that greater stability and immobilisation can be achieved at the FZ suture^[4,11,13,19,20]. Of note, none of the literature reviewed advocated the IOM as the first choice location for one-point fixation.

Our incidence of one-point fixations was 54%, which was higher compared to the literature, including Covington *et al.*^[21], who quoted that 30%-40% of ZMC fractures were adequately stabilised by one-point fixations, and Ellis and Kittidumkerng^[22], who quoted 31%^[21,22]. A concern of one-point fixation can be that the zygoma may not be sufficiently stabilized against the rotational forces from the masseter upon mastication. In our cohort, there were no significant immediate or late post-operative complications, nor any long term aesthetic concerns of the malar area. We can therefore deduce that 54% of our cohort underwent successful ZMC stabilisation by one-point fixation. Of the two-point fixations, the most common sites of fixation were ZM buttress and FZ suture (70%, $n = 7$), followed by ZM buttress and IO rim (30%, $n = 3$). This was in keeping with a study of 210 surgically-managed ZMC fractures, in which similar anatomical locations for two-point fixations were used^[4].

All ZM buttress fixations in our cohort were accessed via an intraoral buccal sulcus incision, which was in keeping with the literature^[4,9]. Given that this approach is intraoral, it has the advantage of avoiding any external facial scarring^[23]. For FZ access ($n = 16$), upper blepharoplasty incision (56%, $n = 9$) was the most common, followed by lateral eyebrow (31%, $n = 5$) and 2 cases through an old scar or current laceration (13%, $n = 2$). For IOM access ($n = 12$), the most common incision was transconjunctival incision (75%, $n = 9$), followed by subciliary (17%, $n = 2$) and subtarsal (8%, $n = 1$). Some literature suggests that the incisions for infraorbital or orbital floor access carried the most complications, such as a study conducted on 180 patients showing complication rates of 1.5% and 14% for entropion in transconjunctival and subciliary incision, respectively, and a 3.4% incidence of hypertrophic scarring with subtarsal incisions^[12,18]. Furthermore, the author of the

same study stated a preference for sub tarsal incisions for ZMC fractures and transconjunctival incision for isolated orbital floor fractures (blow-out fracture)^[12]. Despite some reservations on the transconjunctival approach due to its close association with the eye, a study of 8 patients displayed no ocular complications (such as chemosis)^[24]. Similarly, the 9 patients that underwent transconjunctival incision in our cohort did not present with any complications. The transconjunctival approach was also favoured by another study claiming that it has the advantages of both good intra-operative visualisation of the infraorbital rim, as well as having favourable aesthetic results for the patient^[25]. In another study, Y-modification of a transconjunctival incision has been advocated for access the IOM and FZ area, with the advantage of potentially avoiding a second incision in the FZ area, although detailed knowledge of the lateral canthal anatomy is required and may increase operating time^[26]. For FZ suture access, in our cohort, the literature favoured the upper blepharoplasty incision over the lateral eyebrow incision, with the latter tending to show more scarring and less surgical access than the former, which often produces an inconspicuous scar that can only be seen when the eye lids are closed^[26,27].

Limitations of the study: ZMC fractures that were treated conservatively were not included in our data collection. It would be beneficial to elicit the epidemiology and presentations of conservatively treated cases compared to surgically treated cases. There was insufficient documentation of alcohol and illicit drug use to determine their possible link to ZMC fracture aetiology within our patient cohort. Additionally, further data collection of pre-operative imaging and fracture displacement measurements to ascertain the correlation between the radiographic findings and each surgical procedure chosen would be useful. This would provide valuable information regarding the correlation between the type of ZMC fracture i.e., degree of displacement or comminution, and the subsequent choice of number of fixation points.

This study supports aspects of the current literature regarding the aetiology and surgical management of ZMC fractures. It has been shown that the aetiology of ZMC fractures does indeed vary with geographical areas and incidence of RTCs. At our centre, one-point fixation was the most popular technique for surgical stabilization of ZMC fractures, with the ZM buttress being the most popular choice. It is generally accepted that sufficient stability is obtained with one-point fixation when there is no comminution of the ZMC fracture, with two-point and three-point fixation providing increasing stability where necessary, and often based on fracture comminution and surgeon's preference^[15]. The upper buccal sulcus incision is widely accepted as the best approach for ZM buttress fixation. For IOM access, the transconjunctival and subciliary incisions appear to be most popular within the literature, both having advantages of providing good intra-operative views, low incidence of ocular complications, and good aesthetic outcomes. Interestingly, our incidence of orbital floor exploration and orbital floor repair was lower than that reviewed in the literature. It would be of benefit to further investigate this, with the aim of developing a specific protocol for orbital floor exploration and repair based on pre-operative imaging and clinical signs.

Although there is some agreement amongst certain aspects of the surgical management of ZMC fractures, there is still an ongoing lack of consensus in many aspects, particularly with regards to the number and location of fixation points used and orbital floor exploration and repair. It appears that the surgeon's experience, training background, and preferences may play a significant role in contributing to and maintaining the variety of surgical approaches to ZMC fractures.

Further work in constructing a management protocol for ZMC fractures, alongside well-designed prospective research, would minimise the lack of consensus and optimise care for ZMC fracture patients.

DECLARATIONS

Authors' contributions

All authors contributed to the manuscript.

Availability of data materials

All data can be found on King's College London Hospital NHS Foundation Trust Online Database.

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Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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REFERENCES

1. Venugopal MG, Sinha R, Menon PS, Chattopadhyay PK, Roy Chowdhury SK. Fractures in the maxillofacial region: a four year retrospective study. *Med J Armed Forces India* 2010;66:14-7.
2. Brasileiro BF, Passeri LA. Epidemiological analysis of maxillofacial fractures in Brazil: a 5-year prospective study. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod* 2006;102:28-34.
3. Ribeiro Ribeiro AL, da Silva Gillet LC, de Vasconcelos HG, de Castro Rodrigues L, de Jesus Viana Pinheiro J, et al. Facial fractures: large epidemiologic survey in Northern Brazil reveals some unique characteristics. *J Oral Maxillofac Surg* 2016;74:2480.e1-12.
4. Forouzanfar T, Salentijn E, Peng G, van den Bergh B. A 10-year analysis of the "Amsterdam" protocol in the treatment of zygomatic complex fractures. *J Craniomaxillofac Surg* 2013;41:616-22.
5. McBride S, Barry T. Fractures of the zygomatic complex - a comprehensive review over 10 years of surgical management. *Br J Oral Maxillofac Surg* 2015;53:e72.
6. Dakir A, Muthumani T, Prabu NP, Mohan R, Maity A. One point fixation of zygomatic tripod fractures in the zygomatic buttress through Keen's intraoral approach: a review of 30 cases. *J Pharm Bioallied Sci* 2015;7:S238-41.
7. Calderoni DR, Guidi Mde C, Kharmandayan P, Nunes PH. Seven-year institutional experience in the surgical treatment of orbito-zygomatic fractures. *J Craniomaxillofac Surg* 2011;39:593-9.
8. Bogusiak K, Arkuszewski P. Characteristics and epidemiology of zygomaticomaxillary complex fractures. *J Craniofac Surg* 2010;21:1018-23.
9. AOFoundation. AO Craniomaxillofacial (AOCMF). 2017. Available from: <https://aocmf.aofoundation.org/Structure/about-aocmf/Pages/about.aspx>. [Last accessed on 17 May 2019]
10. Farber SJ, Nguyen DC, Skolnick GB, Woo AS, Patel KB. Current management of zygomaticomaxillary complex fractures: a multidisciplinary survey and literature review. *Craniomaxillofac Trauma Reconstr* 2016;9:313-22.
11. Habal MB. The orbits: it is less important what you put in than how you secure it. *J Craniofac Surg* 2010;21:965-6.
12. Ridgway EB, Chen C, Colakoglu S, Gautam S, Lee BT. The incidence of lower eyelid malposition after facial fracture repair: a retrospective study and meta-analysis comparing sub tarsal, subciliary, and transconjunctival incisions. *Plast Reconstr Surg* 2009;124:1578-86.
13. Olate S, Lima SM Jr, Sawazaki R, Moreira RW, de Moraes M. Surgical approaches and fixation patterns in zygomatic complex fractures. *J Craniofac Surg* 2010;21:1213-7.
14. Ji SY, Kim SS, Kim MH, Yang WS. Surgical methods of zygomaticomaxillary complex fracture. *Arch Craniofac Surg* 2016;17:206-10.
15. Baylan JM, Jupiter D, Parker WL, Czerwinski M. Management of zygomatic fractures: a national survey. *J Craniofac Surg* 2016;27:1571-5.
16. Shumrick KA, Kersten RC, Kulwin DR, Smith CP. Criteria for selective management of the orbital rim and floor in zygomatic complex and midface fractures. *Arch Otolaryngol Head Neck Surg* 1997;123:378-84.
17. Kovacs AF, Ghahremani M. Minimization of zygomatic complex fracture treatment. *Int J Oral Maxillofac Surg* 2001;30:380-3.
18. Ellis E 3rd, Perez D. An algorithm for the treatment of isolated zygomatico-orbital fractures. *J Oral Maxillofac Surg* 2014;72:1975-83.
19. Davidson J, Nickerson D, Nickerson B. Zygomatic fractures: comparison of methods of internal fixation. *Plast Reconstr Surg* 1990;86:25-32.
20. Kim JH, Lee JH, Hong SM, Park CH. The effectiveness of 1-point fixation for zygomaticomaxillary complex fractures. *Acta Otolaryngol* 2012;138:828-32.

21. Covington DS, Wainwright DJ, Teichgraeber JF, Parks DH. Changing patterns in the epidemiology and treatment of zygoma fractures: 10-year review. *J trauma* 1994;37:243-8.
22. Ellis E 3rd, Kittidumkerng W. Analysis of treatment for isolated zygomaticomaxillary complex fractures. *J Oral Maxillofac Surg* 1996;54:386-400; discussion 400-1.
23. Kim ST, Go DH, Jung JH, Cha HE, Woo JH, et al. Comparison of 1-point fixation with 2-point fixation in treating tripod fractures of the zygoma. *J Oral Maxillofac Surg* 2011;69:2848-52.
24. Kumar S, Shubhalaksmi S. Clinical outcome following use of transconjunctival approach in reducing orbitozygomaticomaxillary complex fractures. *Contemp Clin Dent* 2016;7:163-9.
25. Manganello-Souza LC, Rodrigues de Freitas R. Transconjunctival approach to zygomatic and orbital floor fractures. *Int J Oral Maxillofac Surg* 1997;26:31-4.
26. Rajkumar K, Mukhopadhyay P, Sinha R, Bandyopadhyay TK. 'Y' modification of the transconjunctival approach for management of zygomatic complex fractures: a prospective analysis. *J Maxillofac Oral Surg* 2016;15:45-51.
27. Fonesca RJ, Walker RV, Betts NJ, Barber HD, Powers MP. *Oral and Maxillofacial Trauma*. 3rd ed. St Louis: Elsevier Saunders; 2005.

Original Article

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Reconstruction of extremity long bone defects with vascularized fibula bone grafts

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Abstract

Aim: Composite tissue defects encompassing bone and/or isolated bony defects can pose a surgical challenge; however, their reconstruction is critical for successful functional limb salvage. These cases become increasingly problematic as secondary defects, following multiple nonvascularized grafting attempts resulting in complex bony nonunion. Herein, our experience utilizing fibula vascularized bone grafts (VBGs) for bone restoration will be presented to demonstrate their utility in a variety of reconstructions for limb salvage.

Methods: This is a case series describing a series of vascularized fibula grafts for extremity reconstruction performed by a single academic surgeon over multiple institutions in seven years.

Results: Twenty-seven (27) total VBGs met inclusion criteria and underwent reconstruction for traumatic (16), oncologic (6) and chronic degenerative (5) etiologies. Bony union was achieved in 26 of 27 cases.

Conclusion: The decision-making process for bony reconstruction in these scenarios is difficult and multivariable. Fibula VBGs can provide a single-stage solution for autologous bony and soft tissue replacement of large or complex bone defects and can often be superior options compared with non-vascularized bone grafts or non-bone internal fixation techniques. Their osteogenic potential is unmatched by allogenic or synthetic substitutions. These benefits are evident in a variety of clinical settings such as pediatrics, oncology and trauma.



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Keywords: Vascularized bone, vascularized bone grafts, composite extremity defect restoration, bone reconstruction, free tissue transfer, microsurgery

INTRODUCTION

Segmental long bone defects and bony nonunions can arise after traumatic injury, oncologic resection, or osteomyelitis. Establishing a stable bony framework is critical to successful limb salvage; however, bony reconstruction often presents complex challenges to the reconstructive surgeon with seemingly limited available options. One must consider a variety of factors when selecting the appropriate treatment modality from a multitude of limb salvage options. Among these considerations are the surgeon's training background and experience, location and size of defect, associated injuries, availability of soft tissue coverage, and patient comorbidities.

Research and technology have led to a surge of products for bony reconstruction that obviate the need for autologous bone harvest, avoiding the potential donor site morbidity. These include both allografts and synthetic products such as bone morphogenetic protein (Medtronic, Minneapolis, MN), polymethylmethacrylate (Zimmer Biomet, Warsaw, IN) and tricalcium phosphate (Depuy Synthes, New Brunswick, NJ). Many of these technologies possess osteoconductive and/or osteoinductive properties, or can be combined with another product to achieve both. Clinical studies suggest that both allograft and autograft can lead to adequate healing in a well-vascularized wound bed, with the end points being time to incorporation and lack of wound healing complications such as nonunion^[1].

However, these products are subject to their own set of limitations and disadvantages, including the risk of disease transmission, infection and autoimmune rejection. More importantly, the Diamond Model of fracture healing describes 4 requirements for adequate fracture healing which are best met by autologous reconstruction: osteogenic cell supply, an osteoconductive scaffold, growth factors, and a stabilized environment^[2]. In particular, the lack of osteogenic cell supply in allograft and synthetic materials may be the reason they have demonstrated inferior outcomes in critically sized defects > 1 cm, or in those of increasing severity^[3].

Thus, autogenous bony reconstruction remains the gold standard for bone loss. As there are many options to consider in this category, an initial size-based elimination approach can be helpful. Intramedullary nail, external fixation, and internal fixation techniques are options when there is no bone gap. When there is a bone gap, more complex procedures are appropriate depending on the size of the gap; these are further illustrated in [Table 1](#).

While it serves as a good starting point, bone gap size is only one of many factors contributing to decision-making in orthopaedic and orthoplastic reconstructions. In the senior authors' practices, the utility and versatility of vascularized bone grafts (VBGs) for challenging bony reconstruction has expanded limb salvage options for many patients treated at our medical centers. The following cases demonstrate how fibula VBGs can optimize restoration of large segmental bone defects and resolution of nonunion cases to achieve definitive bony healing.

MATERIALS/METHODS

This is a retrospective case series of VBGs performed by a single surgeon over a seven-year period. Twenty-seven (27) total VBGs met inclusion criteria and underwent reconstruction for traumatic (16), oncologic (6) and chronic degenerative (5) etiologies. Patient age ranged from 5 to 64 years with the majority of patients being younger than 30 years old. Anatomical bony reconstructions included 13 upper vs. 11 lower extremity



Figure 1. Radiograph showing severely comminuted humerus fracture secondary to gunshot wound

Table 1 Characteristics of techniques for long bone reconstruction

Reconstructive Options for Segmental Bone Defects					
Technique	Suggested Maximum Length	Minimum # of operations	Soft tissue component	Strengths	Limitations
Corticocancellous bone graft	< 6 cm	1	No	Single operation, quick recovery	Small defects with adequate soft tissue coverage
Cortical bone graft	4-9 cm	1	No	Single operation, medium size defects	Small to medium defects with adequate soft tissue coverage, resorption and fracture with longer grafts
Induced membrane	1-25 cm	2	No	Technically simple operation	Medium to large defects with adequate soft tissue coverage. Two stages. Time to weight bearing 6-18 months.
Distraction osteogenesis	6-25+ cm	2	No	Early partial weight bearing	One mm/day, soft tissue restricts distraction, joint contracture
Free fibula	6-30 cm	1	Multiple soft tissue options (skin, muscle, and chimeric configurations)	Large soft tissue component, can shape the bone	Fibula often injured in lower extremity trauma, soft tissue contiguous with bone, iatrogenic injury to another extremity

defects and 3 pelvic defects. Successful union or bone healing was observed in 26 of 27 cases, with the following complications noted: 2 cases of delayed soft tissue wound healing and 1 case of complete resorption of a fibula bone flap requiring salvage with an expandable megaprosthesis and additional soft tissue flap coverage.

RESULTS

The following are examples of cases performed within the case series mentioned above. Free fibula grafts in extensive trauma:

Case 1. A 38-year-old male presented after high-velocity gunshot wound (GSW) to his right arm, resulting in a severely comminuted fracture of his humerus [Figure 1]. He had segmental bone loss of the humerus and complete segmental loss of his radial nerve. The only realistic treatment option in this case was the induced membrane technique or a free vascularized fibular graft. We proceeded with the fibular graft as it provided immediate stability and the ability to begin early gentle range of motion of the humerus [Figures 2A and B]. Anastomosis was performed to a muscular branch off of the brachial artery. This patient is now one year out

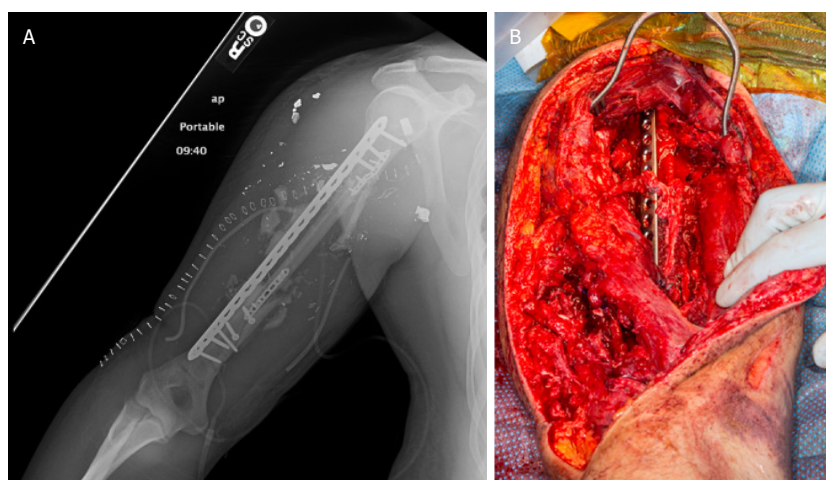


Figure 2. A: radiograph showing fixation of free fibula graft; B: Intraoperative photograph after fixation of free fibula graft



Figure 3. Complex radius fracture secondary to high-velocity gunshot wound

from his restorative surgery and has resumed an active lifestyle, including continuing his military service.

Case 2. A 36-year-old soldier presented with a complex radius fracture after suffering a high-velocity GSW to the proximal forearm [Figure 3 and 4]. The original plan was to fix the proximal radius with a bridging plate and place an antibiotic spacer. Intraoperatively, it was noted that the radial head and neck were not intact, and the longest radial head plate was not long enough to bridge the comminution. A free fibular graft was then utilized to bridge the 8 cm gap and provide immediate stability. The biceps tendon was excised from the bony fragment seen in the image and was attached to the fibula with suture anchors [Figure 4A-C]. The longest available radial head plate was utilized to secure the fibula in place to the proximal radial head. Note the intact posterior interosseous nerve draped over the fibula [Figure 4D]. The patient had a radial nerve palsy prior to this surgery which resolved with time. He has since returned to full activity including push-ups, pull-ups and weight lifting.

Free fibula graft for oncologic reconstruction

Case 3. We treated an 8-year-old male with a free fibula VBG following resection of a chondrosarcoma from his left humerus [Figure 5]. Free fibula VBGs are a good option for bone gaps greater than 6-7 cm, and have

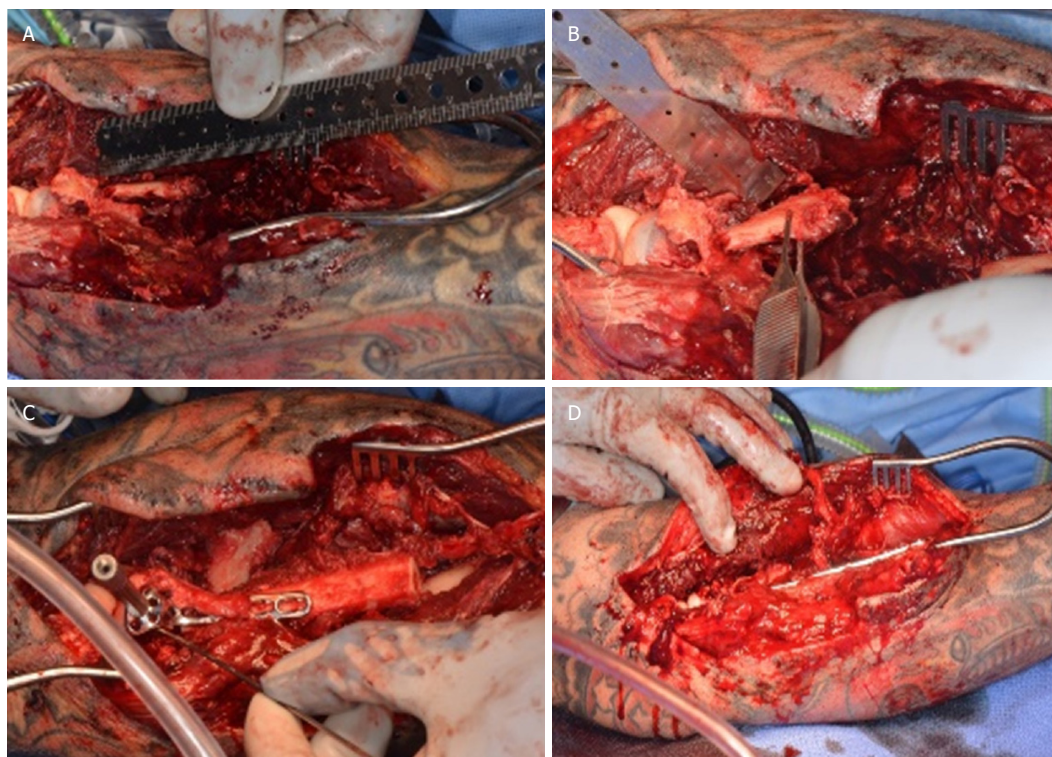


Figure 4. A: fracture separating radial head and neck with large bone gap; B: removal of bony fragment from biceps tendon; C: suture anchors used to attach biceps tendon to fibula graft; D: intact posterior interosseous nerve noted over fibula graft

been found in other reports to reliably achieve union at approximately 6 months^[4]. A recent systematic review of free fibula flap reconstruction of humeral bone defects after oncologic resection found 93% union in an average of 5 months^[5]. VBGs in the oncologic setting have the additional advantage of increased durability in the face of adjuvant chemotherapy and radiation^[6]. While allografts were previously utilized in oncologic reconstruction, these reconstructions were associated with a high fracture and nonunion rate of over 15%, with over 80% of grafts failing in the setting of infection, and approximately 50% failing in the setting of fracture^[7-9]. In a series of 20 patients who underwent both upper and lower extremity reconstruction with allograft after tumor resection, 60% required removal of their allograft followed by replacement with allograft of endoprosthesis due to failure^[10]. While fibula grafts are also prone to complications such as fracture, they possess higher healing potential without the need for a major reoperation in comparison to allograft. Houdek *et al.*^[11] reports a success rate of 100% after VBG fracture, with some patients undergoing operative fixation and others responding to conservative management alone. For the pediatric population, fibula VBGs have another advantage: the fibular head can be included to allow for bone growth while also replacing the humeral head in the glenohumeral joint for reconstruction of the humeral head and diaphysis in pediatric tumor resections. While classically, a proximal and distal segment are preserved at the donor site to protect the common peroneal nerve and maintain ankle stability, Shuck *et al.*^[12] did not report any peroneal nerve deficits or instability with walking after removing the fibular head. This patient is currently one year out from surgery and has resumed participation in competitive athletics without significant functional upper extremity limitations or impairment.

Case 4. A 56-year-old female presented with chondrosarcoma of the humerus [Figure 6], which after necessary resection resulted in a large bony defect. We reconstructed this extensive defect with a free fibula bone flap using the Capanna technique [Figure 7]. The Capanna technique combines methods of bony reconstruction, using a VBG in conjunction with allograft bone. Variations of the technique have been described with regard to the specific placement of the VBG with respect to the allograft: it can be placed completely within the



Figure 5. Fixation of free fibula flap to reconstruct bony defect after resection of a left humerus chondrosarcoma



Figure 6. Radiograph showing extensive nature of humerus chondrosarcoma

allograft's medullary canal, partially within the canal, or alongside the allograft as an onlay^[13-15]. Here, we chose to place the VBG partially within the medullary canal, inside a trough created through the bony cortex. VBGs are at risk for early fracture and thus require immobilization, sometimes for over a year depending on the anatomic location of reconstruction and rate of bony hypertrophy; the use of allograft contributes to early postoperative stability by bearing the load of bony fixation. In turn, VBGs provide osteogenic factors that allografts lack. This technique has been described in immediate and in delayed settings after resection with equivalent rates of union; this versatility allows for definitive reconstruction to be delayed to confirm surgical margins when they are in doubt^[16]. While originally described for reconstruction after tumor resection, surgeons are beginning to use the Capanna technique in specific traumatic settings when risk for infection is low^[15].

Case 5. A 63-year-old morbidly obese male with history of diabetes and chondrosarcoma of the femur presented with femur nonunion after he underwent neoadjuvant chemoradiation, tumor resection, and prior allograft placement complicated by infection and nonunion of the proximal allograft abutment [Figure 8A]. He required cane assistance in ambulation to reduce potential for hardware failure given his nonunion and body habitus. After a series of antibiotic nail exchanges, washouts, six months of negative microbacterial



Figure 7. Free fibula used in conjunction with allograft, per the Capanna technique

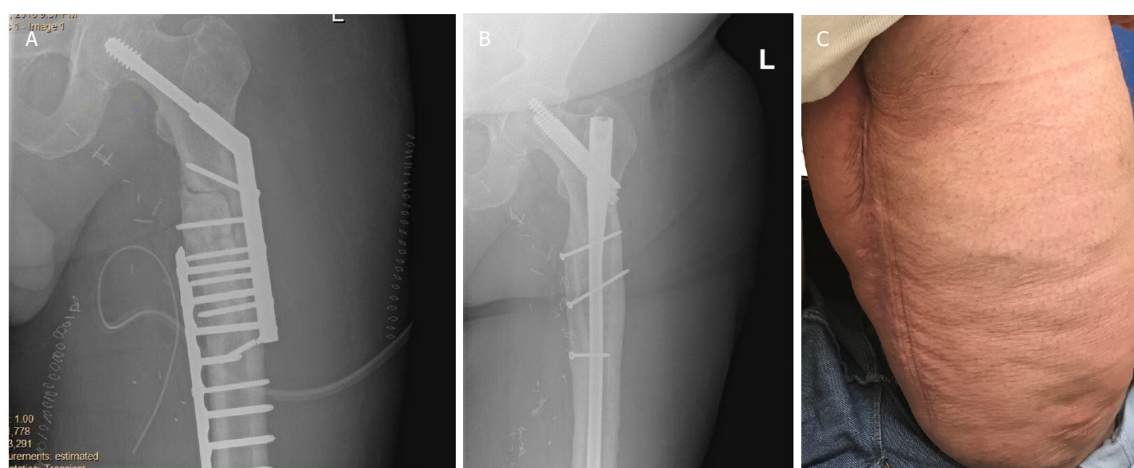


Figure 8. A: radiograph of case 5 before free fibula graft demonstrating nonunion; B: post operative radiograph of free fibula with IMN; C: two year follow-up with patient, who is ambulating and healing well

cultures and normalized limits of inflammatory parameters (White Blood Cell Count, ESR and CRP), the patient underwent reconstruction with a 14cm free fibula VBG for his left femur nonunion. He is now one-year post-reconstruction with radiographic and clinical evidence of complete bony healing, is ambulatory without cane assistance, and has returned to his full course of daily activities [Figures 8B, 8C].

Free fibula graft for salvage of complex bony nonunion

Cases 6 and 7. We treated two cases of middle-aged females who suffered traumatic tibial fractures complicated by nonunion despite failed allografting attempts [Figure 9]. Both of these tibial bone nonunions were definitively reconstructed with pedicled fibula VBGs [Figures 10A, 10B]. Pedicled ipsilateral fibula VBGs do not require advanced microsurgical techniques and can be especially helpful in patients who have failed previous bone grafting operations; they have also been reported in the reconstruction of oncologic tibial resections and in tibial plateau fractures requiring arthrodesis with acceptable surgical and functional outcomes^[17-19]. This pedicle flap can be directly translocated as a “slide” or as a “turnover” technique - i.e. rotated 180 degrees, and either technique can be based on antegrade or retrograde perfusion. Most commonly, the pedicle fibula flap is based on its antegrade flow pattern. Preoperative angiography or CT angiography can aid in assessing the peroneal as well as posterior and anterior tibial vascularity to ensure



Figure 9. Radiograph demonstrating tibial nonunion despite previous fixation and allografting attempts

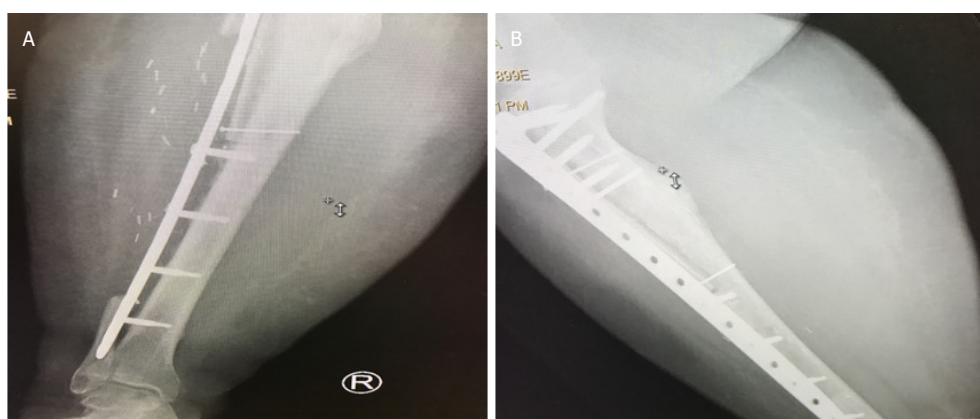


Figure 10. Radiographs demonstrating bony union following pedicled fibula reconstruction

viable blood flow to the ipsilateral fibula flap as well as preservation of dominant blood flow to the foot if the peroneal vessel is to be sacrificed distally. Of note, the pedicled fibula VBG can be difficult to harvest in traumatic or secondary salvage procedures due to extensive scarring, inflammation and abnormal anatomy.

Free fibula graft as an osteocutaneous flap for composite reconstruction

These cases represent additional advantages of the free fibula VBGs; when used as osteocutaneous flaps, they can reconstruct bony and associated soft tissue deficits in a single stage. With single-stage reconstruction, the patient is spared multiple flap reconstructions, avoids additional exposures to anesthetic risk, may preserve recipient vessels when performed in an end-to-side vascular anastomosis pattern, and eliminates the need to re-enter scarred wound beds for subsequent staged procedures^[20].

Case 9. This patient was 22-year-old army soldier who suffered a type I open both-bone forearm fracture complicated by infection that progressed to segmental infected nonunions [Figure 11]. The patient was treated with debridement, antibiotic spacer placement, and eventual free vascularized fibular graft to the ulna and a 3 cm non-vascularized segmental graft to the radius. The compromised soft tissue was replaced by the fibula skin paddle [Figure 12]. Both the radius and ulna healed successfully [Figure 13]. While his range of motion is decreased, the patient has returned to a productive life as a mechanic.



Figure 11. Radiograph demonstrating open both-bone forearm fracture



Figure 12. Osteocutaneous reconstruction with free fibula

Case 10. A 52-year-old male presented with hardware infection after his original distal tibia fracture was treated with plate fixation [Figure 14]. After necessary debridement, he was left with a segmental tibial and associated soft tissue defect. The ends of a free fibula graft were telescoped into the proximal and distal tibia and immediate stability was achieved. Small plates were utilized to ensure adequate fixation and a circular frame was then applied allowing for nearly immediate weight-bearing [Figure 15].

DISCUSSION

The decision-making process for reconstruction of segmental bone defects and osseous nonunion can be complex and multivariable. A multidisciplinary orthoplastic approach is recommended for optimal outcomes. Clear communication of reconstructive goals and options should be discussed among the orthoplastic surgery team. These goals should align with reconstructive goals, rehabilitation potential, and wound healing reserve of the patient at hand. In this illustrative case series, we sought to explore the utility and versatility of fibula vascularized bone grafts in reconstructing complicated bony defects and achieving bone union.

We found fibula VBGs to be an excellent method for single-stage bony reconstruction in patients with bony defects complicated by numerous factors, especially in cases with previously failed reconstruction.



Figure 13. Radiograph after fixation with free fibula



Figure 14. Previous distal tibia fixation complicated by hardware infection



Figure 15. Osteocutaneous free fibula reconstruction with circular frame applied for improved immediate stability

Allograft reconstruction can provide a shorter, less technically demanding reconstruction, but its success may be limited to well-vascularized wound beds of a smaller size. Current data suggests that larger defects with compromised vascularity may lead to a significantly higher rate of major complications in bony defects reconstructed with allograft when compared to autograft^[21]. However, further study is required to explore the outcomes of different classes of allograft as the age and processing of the allograft may allow it to retain more osteoinductive properties. Autologous reconstruction can be performed in several ways and is also subject to its own limitations. The major reasons for the failure of traditional non-vascularized reconstructive techniques are large size of defect, residual nonviable bone secondary to avascularity or infection, and inadequate soft tissue coverage^[17]. In such challenging cases, fibula VBGs - in the form of bone flaps and osteocutaneous flaps - provide reconstructive options that incorporate stable vascularity and supply osteoinductive, osteoconductive and osteoprogenitor elements^[20]. We found these properties of fibula VBGs to be useful in cases of severe trauma and composite tissue injuries, where the zone of injury often extends beyond what is perceived clinically or radiographically. In our oncologic and degenerative disease cohorts, fibula VBGs provide reliable blood flow to the bone as vascularity is often compromised in these situations due to chronic disease and/or radiation. Additionally, the use of the Capanna technique capitalizes on the ability of fibula VBGs to be used in combination with allografts to enhance vascular perfusion, allograft incorporation, and restoration of long bone osseous defects.

In conclusion, at our respective institutions, the orthoplastic surgeons have achieved excellent surgical outcomes, the most notable of which is high rates of successful bony union in patients with extremity bone defects and osseous nonunion cases from traumatic, oncologic, degenerative and congenital etiologies. The major disadvantages of fibula VBGs include longer operative times and higher technical demand, prolonged immobilization following surgery, and risk of early fracture. Fibula VBGs nonetheless provide an excellent reconstructive option for segmental bony defects and to address cases of failed nonvascularized nonunion grafting attempts in the extremities, and they offer promise in the efforts to improve outcomes and success in limb salvage. Our knowledge of the subject and our mastery of the techniques are continually expanding, fueled in part by multidisciplinary collaboration among trauma, oncologic, orthopaedic and plastic and reconstructive surgeons. It is our hope that this growing experience will lead to improved care for patients affected by limb-threatening bony pathology.

DECLARATIONS

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Authors' contributions

All authors made substantial contributions to conception and design of the study, performed data analysis and interpretation, as well as provided administrative, technical, and material support: Wee C, Ruter D, Schulz S, Sisk G, West J, Tintle S, Valerio I

Availability of data and materials

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All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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REFERENCES

1. Dolan CM, Henning JA, Anderson JG, Bohay DR, Kornmesser MJ, et al. Randomized prospective study comparing tri-cortical iliac crest autograft to allograft in the lateral column lengthening component for operative correction of adult acquired flatfoot deformity. *Foot Ankle Int* 2007;28:8-12.
2. Giannoudis PV, Einhorn TA, Marsh D. Fracture healing: The diamond concept. *Injury* 2007;38:S3-6.
3. Cannada LK. A Randomized Controlled Trial Comparing rhBMP-2/ACS vs. Autograft for the Treatment of Tibia Fractures with Critical Size Defects. *J Orthop Trauma* 2019; doi:10.1097/BOT.0000000000001492
4. Adani R, Delcroix L, Tarallo L, Baccarani A, Innocenti M. Reconstruction of posttraumatic bone defects of the humerus with vascularized fibular graft. *J Shoulder Elbow Surg*;2008;17:578-84.
5. Landau MJ, Badash I, Yin C, Alluri RK, Patel KM. Free vascularized fibula grafting in the operative treatment of malignant bone tumors of the upper extremity: a systematic review of outcomes and complications. *J Surg Oncol* 2018;117:1432-9.
6. Canosa R, González del Pino J. Effect of methotrexate in the biology of free vascularized bone grafts. A comparative experimental study in the dog. *Clin Orthop Relat Res* 1994;291:301.
7. Berrey BH Jr, Lord CF, Gebhardt MC, Mankin HJ. Fractures of allografts. Frequency, treatment, and end-results. *J Bone Joint Surg Am* 1990;72:825-33.
8. Mankin HJ, Doppelt S, Tomford W. Clinical experience with allograft implantation. The first ten years. *Clin Orthop Relat Res* 1983;69-86.
9. Mankin HJ, Gebhardt MC, Jennings LC, Springfield DS, Tomford WW. Long-term results of allograft replacement in the management of bone tumors. *Clin Orthop Relat Res* 1996;86-97.
10. Ogilvie CM, Crawford EA, Hosalkar HS, King JJ, Lackman RD. Long-term results for limb salvage with osteoarticular allograft reconstruction. *Clin Orthop Relat Res* 2009;467:2685-90.
11. Houdek MT, Wagner ER, Bishop AT, Shin AY, Rose PS, et al. Complications and long-term outcomes of free fibula reconstruction following resection of a malignant tumor in the extremities. *Plast Reconstr Surg* 2017;139:510e-9e.
12. Shuck J, Wood BC, Zarella C, Oh AK, Henshaw RM, et al. Near-complete humerus reconstruction in the pediatric patient with vascularized free fibula transfer. *Plast Reconstr Surg Glob Open* 2016;4:e1143.
13. Ridha H, Bernard J, Gateley D, Vesely MJ. Reconstruction of large traumatic segmental defects of the femur using segmental allograft with vascularized fibula inlay. *J Reconstr Microsurg* 2011;27:383-90.
14. Bakri K, Stans AA, Mardini S, Moran SL. Combined massive allograft and intramedullary vascularized fibula transfer: the capanna technique for lower-limb reconstruction. *Semin Plast Surg* 2008;22:234-41.
15. Venkatramani H, Sabapathy SR, Dheenadayalan J, Devendra A, Rajasekaran S. Reconstruction of post-traumatic long segment bone defects of the lower end of the femur by free vascularized fibula combined with allograft (modified Capanna's technique). *Eur J Trauma Emerg Surg* 2014;41:17-24.
16. Minami A, Kutsumi K, Takeda N, Kaneda K. Vascularized fibular graft for bone reconstruction of the extremities after tumor resection in limb-saving procedures. *Microsurgery* 1995;16:56-64.
17. Heller L, Phillips K, Levin LS. Pedicled osteocutaneous fibula flap for reconstruction in the lower extremity. *Plast Reconstr Surg* 2002;109:2037-42.
18. El-Sherbiny M. Long term behavior of pedicled vascularized fibular grafts in reconstruction of middle and distal tibia after resection of malignant bone tumors. *J Egypt Natl Canc Inst* 2008;20:187-95.
19. El-Negery A, Elmoghazy NA, Abd-Elatif MS, Elgeidi A. Vascularized fibular medialization for reconstruction of the tibial defects following tumour excision. *Int Orthop* 2017;41:2179-87.
20. Yazar S, Lin C-H, Wei F-C. One-stage reconstruction of composite bone and soft-tissue defects in traumatic lower extremities. *Plast Reconstr Surg* 2004;114:1457-66.
21. Zhao Z, Yan T, Guo W, Yang R, Tang X, et al. Surgical options and reconstruction strategies for primary bone tumors of distal tibia: a systematic review of complications and functional outcome. *J Bone Oncol* 2019;14:100209.

Commentary

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Plastic surgeons: critical members of the mass casualty team

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Plastic and reconstructive surgeons are uniquely positioned to care for a variety of patients in all walks of life. We routinely take part in the multidisciplinary care that ranges from prenatal consultation for congenital abnormalities such as cleft lip and palate to nuanced reconstructive care of our aging population after tumor extirpation. This intimate involvement in the acute management and longitudinal follow-up is exemplified in traumatic extremity reconstruction.

Extremity reconstruction, like other aspects of plastic surgery, is governed by principles that allow us to tailor sophisticated solutions to challenging problems^[1]. Crystal *et al.*^[2] highlight the full spectrum of solutions using all rungs of the reconstructive ladder. To add to an already comprehensive list are two additional innovative treatment modalities particularly germane to extremity reconstruction. These are the use of “spare parts”^[2-4] and considering the possibility of future vascularized composite allotransplantation (VCA)^[5]. Spare parts surgery is particularly appropriate in mass casualty incidents and blast injuries, as these can cause devastating segmental loss of domain with potentially viable distal tissues. These instances may present the opportunity for innovative use of these otherwise discarded tissues or “spare parts” as heterotopic or nonanatomic replantation or rearrangement. Over two decades since the first upper extremity VCA, transplantation now factors in the planning and execution of surgical plans to preserve limb length in lieu of optimal prosthetic fit^[6]. VCA has ushered new possibilities to fully restore and make whole whilst fulfilling Sir Harold Gillies’ dictum of replacing like with like^[7].



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Plastic surgeons have a comprehensive reconstructive armamentarium, and it is our responsibility to think expansively and innovatively about these problems to optimize form and function while limiting donor-site morbidity. Additionally, our knowledge of long-term functional outcomes, patient satisfaction and quality of life are fundamental to our specialty and daily work. These outcomes are particularly important to the care of patients affected by severe extremity trauma. As has been previously described, factors most important to patients affected by severe lower extremity injuries include their physical capacity and functional status, pain level, and the ability to return to work, among other factors^[8]. As this article and other similar collective experiences have suggested, reconstructive plastic surgeons remain a central participant in the care of complex trauma patients^[9,10].

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Authors' contributions

Writing of the manuscript: Aycart MA

Critically revised the manuscript: Talbot SG

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Consent for publication

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REFERENCES

1. Talbot SG, Pribaz JJ. Sophisticated surgical solutions for complex wound problems. *Clin Plast Surg* 2012;39:325-40.
2. Crystal DT, Ibrahim AMS, Lin SJ. The role of plastic surgeons in extremity reconstruction following mass casualty incidents. *Plast Aesthet Res* 2019;6:1.
3. Lin CH, Webb K, Neumeister MW. Immediate tissue transplantation in upper limb trauma: spare parts reconstruction. *Clin Plast Surg* 2014;41:397-406.
4. Peng YP, Lahiri A. Spare-part surgery. *Semin Plast Surg* 2013;27:190-7.
5. Shores JT, Brandacher G, Lee WPA. Hand and upper extremity transplantation: An update of outcomes in the worldwide experience. *Plast Reconstr Surg* 2015;135:351e-60e.
6. Singh M, Li H, Nuutila K, Collins KC, Wall J, et al. Innovative techniques for maximizing limb salvage and function. *J Burn Care Res* 2017;38:e670-e677.
7. Gillies HD, Millard DR. *The Principles and Art of Plastic Surgery*. Boston: Little, Brown; 1957.
8. O'Toole RV, Castillo RC, Pollak AN, MacKenzie EJ, Bosse MJ, et al. Determinants of patient satisfaction after severe lower-extremity injuries. *J Bone Joint Surg Am* 2008;90:1206-11.
9. Kim PS, Malin E, Kirkham JC, Helliwell LA, Ibrahim AM, et al. The Boston marathon bombings: the early plastic surgery experience of one Boston hospital. *Plast Reconstr Surg* 2013;132:1351-63.
10. Carty MJ, Caterson EJ, Caterson SA, Chun YS, Erdmann-Sager J, et al. Why we are here: early reflections on the role of reconstructive plastic surgery in the 2013 Boston marathon bombings. *Plast Reconstr Surg* 2013;132:1623-7.

Commentary

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Commentary of “skin grafting the vascular pedicle: a useful technique to avoid microvascular collapse in free tissue transfer for limb salvage”

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We commend the authors on an excellent paper comparing the outcomes of microvascular transfers that utilized a skin graft for closure over the pedicle to a tension-free primary closure^[1]. The retrospective cohort study of 71 patients found no significant difference in the rate of post-operative complications between the two groups. The authors concluded that skin graft closure over free flaps and pedicles may be an alternative technique to prevent compression in extremity free tissue transfers.

Free flaps offer the flexibility of mobilizing vascularized tissue to cover complex traumatic defects. It is important to emphasize the key principle in microsurgical reconstruction of traumatic limbs is performing the microvascular anastomosis well outside the zone of injury^[2]. This should be done to prevent free flap failure typically due to arterial thrombosis or inadequate venous outflow^[3].

We agree that unfortunately the inability of obtaining primary closure may occur in microsurgical reconstruction of limbs and we commend the authors for providing evidence for a potential alternative. The inability to obtain primary closure occurs when local tissue inflammation and trauma leads to an increase in edema^[4], which in turn makes primary closure a challenge. In our experience, the inability to obtain primary closure is predominantly associated with free flaps to cover upper extremity defects due to the lack of mobility of tissues (especially around the wrist)^[5]. It would have been interesting to see if an anatomical dominance existed in the study and if the complication rates differed based on them.



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It was interesting that conditions such as malnourishment and renal disease predispose patients to a significantly higher incidence of skin grafting use. In malnourishment, a lack of proteins may lead to a decrease in colloid osmotic pressure which in turn leads to diffusion of fluid in the interstitium, thus increasing edema^[6]. Similarly in renal disease, there is urinary protein loss leading to decrease of plasma albumin and subsequently lowering the plasma oncotic pressure leading to an imbalance of the Starling forces^[7]. This drives fluid from the intravascular space to the interstitial space leading to fluid imbalance and potential for fluid overload. Both of these conditions contribute to the difficulty in primary closure and consequently skin grafting.

Skin grafting can be a significant issue when placed over a vascular pedicle. The thin and non-vascularized nature of the graft places the pedicle at risk for dessication and injury. Skin grafting has a greater propensity to contract at the recipient site due to the reduced volume of included dermis^[8]. This can lead to compression of the pedicle secondary to scarring and graft contracture especially when localized around a joint. Furthermore, the skin graft donor site carries additional morbidities such as scarring, infection and pain^[9], though as the authors mentions, redundant skin from the flap donor site is usually available without increasing scar length.

The concept of using skin grafting to cover free flap pedicles should be considered a last resort when everything else fails because of a concern of vascular injury and flap compromise. Although this study concludes that it is safe to adopt this technique, the small sample size and underpower of the study may make the authors conclusion premature.

The indication to employ a free flap in the first place is to obtain durable coverage of exposed critical structures such as tendon, bone, hardware, and vessels. We include the flap pedicle in this category. We suggest several methods to avoid skin grafting. One strategy is to make the free flap large enough to cover the entire course of the pedicle. This technique is simple, but may have a poorer cosmetic outcome due to the larger surface area of flap skin. Another strategy is to create an adipofascial extension to the free flap or create a chimeric flap. The anterolateral thigh (ALT) flap is particularly amenable to this. If an ALT does not require primary thinning, an extension of vascularized fascia plus adipose tissue can be draped over the pedicle. If the anastomosis site is too far from the defect, a chimeric flap can be designed, either adipofascial tissue on its own perforator, or a small segment of vastus or rectus muscle based on a branch close to the pedicle origin. Yet another method consists of rearranging tissues adjacent to pedicle^[10,11]. Rearrangement strategies can be as simple as undermining and advancing local tissue or creating local flaps. When the incision to dissect recipient vessels is parallel to the defect, the skin bridge can be completely undermined and advanced as a bipedicle flap. If a local flap cannot be designed with primary closure of the donor site, we would prefer to have vascularized skin over the pedicle with a skin graft on the local flap donor site.

Designing a free flap that anticipates the steps required to obtain tension free closure over the pedicle can be challenging. Local tissue trauma or edema can compromise local flap options. If skin grafting is truly the only option, as situation we have also found ourselves in, we recommend harvesting the skin graft from the free flap donor site as described by the authors to avoid additional scarring. If this option is not available, a skin graft can be taken directly off the free flap^[12] to avoid the morbidity of a second donor site^[13]. At our institution, we do not have a preference between full thickness and split-thickness skin grafts^[14,15]. The established benefits and drawbacks of take, contracture, tissue thickness, and esthetics are weighed by the surgeon.

We are grateful to Kovar *et al.*^[1] for shining insight on a very interesting topic and offering data on the use of skin grafting of the vascular pedicle. We do believe skin grafting should be used only as a last resort.

However, it appears that skin grafting may be a suitable alternative for extremity free tissue transfers but further studies are warranted to confirm its safety and utility.

DECLARATIONS

Authors' contributions

Egro FM, Roy E, Soalri MG equally contributed to the ideation and writing of this commentary.

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REFERENCES

1. Kovar A, Diamond S, Iorio ML. Skin grafting the vascular pedicle: a useful technique to avoid microvascular collapse in free tissue transfer to limb salvage. *Plast Aesthet Res* 2019;6:10.
2. King EA, Ozer K. Free skin flap coverage of the upper extremity. *Hand Clin* 2014;30:201-9.
3. Wong AK, Joanna Nguyen T, Peric M, Shahabi A, Vidar EN, et al. Analysis of risk factors associated with microvascular free flap failure using a multi-institutional database. *Microsurgery* 2015;35:6-12.
4. Scallan J, Huxley VH, Korthuis RJ. Pathophysiology of Edema Formation. In: *Capillary Fluid Exchange: Regulation, Functions, and Pathology*. San Rafael (CA): Morgan & Claypool Life Sciences; 2010.
5. Ng ZY, Salgado CJ, Moran SL, Chim H. Soft tissue coverage of the mangled upper extremity. *Semin Plast Surg* 2015;29:48-54.
6. Coulthard MG. Oedema in kwashiorkor is caused by hypoalbuminaemia. *Paediatr Int Child Health* 2015;35:83-9.
7. Bobkova I, Chebotareva N, Kozlovskaya L, Shilov E. Edema in Renal Diseases-Current View on Pathogenesis. *Nephrol @ Point Care* 2016;2: doi: 10.5301/pocj.5000204.
8. Greenwood JE. The evolution of acute burn care - retiring the split skin graft. *Ann R Coll Surg Engl* 2017;99:432-8.
9. Shimizu R, Kishi K. Skin graft. *Plast Surg Int* 2012;2012:563493.
10. Fleming ME, O'Daniel A, Bharmal H, Valerio I. Application of the orthoplastic reconstructive ladder to preserve lower extremity amputation length. *Ann Plast Surg* 2014;73:183-9.
11. Gonzalez-Garcia R, Ruiz-Laza L, Manzano D, Monje F. Combined local triangular full-thickness skin graft for the closure of the radial forearm free flap donor site: a new technique. *Plast Reconstr Surg* 2010;125:85e-6e.
12. Ghanem TA, Wax MK. A novel split-thickness skin graft donor site: the radial skin paddle. *Otolaryngol Head Neck Surg* 2009;141:390-4.
13. Kim PD, Fleck T, Heffelfinger R, Blackwell KE. Avoiding secondary skin graft donor site morbidity in the fibula free flap harvest. *Arch Otolaryngol Head Neck Surg* 2008;134:1324-7.
14. Davis WJ 3rd, Wu C, Sieber D, Vandevender DK. A comparison of full and split thickness skin grafts in radial forearm donor sites. *J Hand Microsurg* 2011;3:18-24.
15. Prasetyono TO, Sadikin PM, Saputra DK. The use of split-thickness versus full-thickness skin graft to resurface volar aspect of pediatric burned hands: A systematic review. *Burns* 2015;41:890-906.

Commentary

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Commentary on “surgical management of zygomatic complex fractures in a major trauma centre”

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Zygomatic complex (ZMC) fractures are one of the most common facial fractures seen in trauma centers. The zygomatic bone has a quadrilateral shape with several processes that articulate with the frontal bone [via frontozygomatic (ZF) suture], the maxilla [via zygomaticomaxillary (ZM) buttress], the temporal bone [via zygomaticotemporal (ZT) suture], and the greater wing of the sphenoid bone within the orbit via zygomaticosphenoid suture. These four processes work to stabilize the position of the face with respect to the cranium and provide definition of facial width and midface projection. Fractures of the zygomatic bone often occur at these four suture sites resulting in ZMC fractures rather than fracture of the zygomatic bone alone. The management of ZMC fractures are usually of aesthetic nature except in two occasions. First, when the fracture impinges on the mandibular coronoid process, resulting in a restriction of mandibular movements and trismus^[1]. Second, ZMC fractures can disrupt the orbit foundation enough to cause ophthalmoplegia, diplopia, malposition of the globe, sensory deficits along distribution of the infraorbital nerve, or palpable irregularities of the lateral and inferior orbital rim^[1,2].

Surgical intervention of ZMC fractures require open reduction and internal fixation of the points of the tetrapod. Fracture fixation may be broadly classified by open reduction with anterior approach or an open reduction with anterior and posterior approach. The anterior approach involves up to three incisions, one for each suture in the tetrapod except for the ZT suture^[2]. For access to the ZF suture and lateral orbital wall, the upper blepharoplasty incision allows for less scarring and better surgical access to the region in comparison to the lateral brow approach or use of the current laceration^[3]. The transconjunctival incision is preferred for access to the infraorbital rim, however, it must also be noted that the lower-lid approach is not without significant risks, such as the possibility of lower-lid malposition and external lid scarring^[3].



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Finally, a gingivobuccal sulcus incision effectively exposes the maxilla for reduction and stabilization of the ZM buttress with aesthetically pleasing postoperative results^[4]. Historically, with the anterior approach, ZMC fractures required fixation of all three anatomical positions. However, recently there has been a trend toward fixation of fewer points depending on severity of injury.

The authors present a retrospective study analyzing the epidemiology and surgical management using open-reduction and internal fixation of 27 isolated ZMC fracture cases in Kings College London Hospital during 2016. Average time between fracture and surgical intervention was 15 days. They found one-point fixation was the most popular technique for surgical stabilization of zygomatic fractures, with the ZM buttress as the most common fixation point. The authors described that sufficient stability was achieved with one-point fixation when there is no comminution of the ZMC fracture. The authors concluded that there is a lack of consensus in the repair methodology of ZMC fractures likely due to surgeon preference, training, and experience.

Despite the efforts by the authors to assess the surgical management of ZMC fractures in their major trauma center and compare those findings with the literature, there are certain limitations that readers should consider when interpreting the results of this study. Firstly, edema after injury makes the exposure of the ZMC fractures challenging and for this reason many surgeons advocate to wait for the edema to decrease before operating. However, within fifteen days the fracture is often viscous in touch and difficult to maneuver^[5]. From our experience, five to seven days after the onset of the fracture has shown to be ideal time and we believe that waiting 15 days as highlighted in this paper might be too long.

Secondly, we do not agree that one-point fixation provides sufficient stability of the fracture and instead recommend two or three-point fixation, due to multiple variables that can influence the fracture's healing process. For example, the masseter pull on the zygoma could potentially displace the malar fragments. This is particularly important to take note of in a comminuted zygomatic fracture in which masseter forces could displace the segments and have suboptimal aesthetic outcomes when set^[6]. Previous literature has described that two-point or three-point fixation techniques of ZMC fractures provide more stability when compared to one-point fixation^[2,7-9]. A meta-analysis of randomized control trial data done by Jazayeri *et al.*^[10] suggests that three-point fixation of ZMC fractures are superior, however, when two-point fixation appears to provide stable fixation, potential benefits of a third fixation point should be weighed against costs such as operative time and morbidity of additional incision.

The authors' did not discuss the posterior approach to ZMC fractures, which involves open reduction and fixation of the zygomatic arch. This can be achieved with a coronal approach, where the entire zygomatic arch can be visualized while protecting the frontal branch of the facial nerve. Fractures with extreme posterior displacement, and those with lateral displacement of the zygomatic arch benefit from this approach. Benefits of the coronal incision include exposure of the entire zygomatic arch and roof of the glenoid fossa which allows for precise zygomatic arch reconstruction, eliminating the need for an upper blepharoplasty or lateral brow incision by exposing the ZF suture. Additionally, the bicoronal approach not only provides improved contour of the zygomatic arch/ZMC fractures but also provides access to other facial fractures like the naso-orbital ethmoid, frontal sinus, and superior and lateral orbits^[1].

Alternatives to the coronal approach to zygomatic arch repair include the Gillies approach, which is a temporal approach for reduction only of zygomatic arch fractures^[2]. In this study, the Gillies approach was used for the majority (85%) of the 13 isolated zygomatic arch fractures in this trauma center. However, based on our experience the Gillies approach produces less than ideal results in ZMC fractures and should be used for isolated zygomatic arch fractures. Results with this approach never fully project the malar eminence back to pre-morbid state, often resulting in a persistent depression of the lateral cheek. In

complex cases where the zygoma is comminuted in ZMC fractures, we advocate for the use of a bicoronal approach to re-establish adequate anteroposterior projection and width of the face.

Lastly, despite ones best efforts of improving the aesthetic contour by fixating the ZMC fractures, some postoperative asymmetry may persist. We believe that autologous fat grafting (AFT) plays a crucial role in the secondary reconstruction of facial deformities and an increasing level of evidence demonstrates its benefits. In a prospective study of AFT for posttraumatic and postsurgical craniofacial deformities, Bourne *et al.*^[11] demonstrated that AFT provides a safe and minimally invasive alternative to traditional methods (such as regional flaps and prostheses) to restore normal and symmetric facial morphology. AFT allows for better control of tissue volume and improves the quality of scarring and skin. The study concluded that for craniofacial defects, AFT is predictable and effective and reaching volume stability at 3 months.

Ongoing lack of consensus of the surgical management of ZMC fractures makes it challenging to develop a widely accepted treatment protocol. We commend the authors for this study and look forward to future research to evaluate optimal management of ZMC fractures.

DECLARATIONS

Authors' contributions

Made substantial contributions to this review of the literature as well as the writing of the commentary: Egro FM, Konanur A, Stofman GM

Availability of data and materials

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Conflicts of interest

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REFERENCES

1. Marcus JR, Erdmann D, Rodriguez ED. Essentials of craniomaxillofacial trauma. Louis, Mo: Quality Medical Pub; 2012.
2. Neligan P, Warren RJ, Van Beek A. Plastic surgery [still image]. London: Elsevier; 2018.
3. Lee EI, Mohan K, Koshy JC, Hollier LH Jr. Optimizing the surgical management of zygomaticomaxillary complex fractures. *Semin Plast Surg* 2010;24:389-97.
4. Ji SY, Kim SS, Kim MH, Yang WS. Surgical Methods of Zygomaticomaxillary Complex Fracture. *Arch Craniofac Surg* 2016;17:206-10.
5. Strong EB, Gary C. Management of Zygomaticomaxillary Complex Fractures. *Facial Plast Surg Clin North Am* 2017;25:547-62.
6. Kelley P, Hopper R, Gruss J. Evaluation and treatment of zygomatic fractures. *Plast Reconstr Surg* 2007;120:5S-15S.
7. Kim JH, Lee JH, Hong SM, Park CH. The effectiveness of 1-point fixation for zygomaticomaxillary complex fractures. *Arch Otolaryngol Head Neck Surg* 2012;138:828-32.

8. Papel ID. Facial plastic and reconstructive surgery [still image]. New York: Thieme; 2016.
9. Thorne C, Chung KC, Gosain A, Guntner GC, Mehrara BJ. Grabb and Smith's plastic surgery. 7th ed. Philadelphia: Wolters Kluwer/Lippincott Williams & Wilkins Health; 2014.
10. Jazayeri HE, Khavanin N, Yu JW, Lopez J, Shamliyan T, et al. Fixation Points in the Treatment of Traumatic Zygomaticomaxillary Complex Fractures: A Systematic Review and Meta-Analysis. *J Oral Maxillofac Surg* 2019. Epub ahead of print DOI: 10.1016/j.joms.2019.04.025.
11. Bourne DA, Bliley J, James I, Donnenberg AD, Donnenberg VS, et al. Changing the Paradigm of Craniofacial Reconstruction: A Prospective Clinical Trial of Autologous Fat Transfer for Craniofacial Deformities. *Ann Surg* 2019. Epub ahead of print DOI: 10.1097/SLA.0000000000003318.

Original Article

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Efficacy and safety of poly-D,L-lactic acid microspheres as subdermal fillers in animals

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Abstract

Aim: This animal study aims to examine the efficacy and safety of poly-D,L-lactic acid (PDLLA) microspheres as subdermal fillers.

Methods: Thirty 2-week-old male Sprague Dawley rats were used as test animals, and 0.5 mL filler solutions were injected into the subdermal tissues on their backs. Groups of five rats were randomly selected and sacrificed for examination on the 2nd, 4th, 8th, 12th, 16th, and 20th weeks after injection. Clinical and histological examinations were performed via the hematoxyline-eosin and immunohistochemical (IHC) staining of injected sites after collecting the injected masses. The body weights of the rats were measured, and the presence of filler substance in other organs was determined.

Results: Injected volumes were stable from the 2nd to the 20th week after injection, and no abnormalities were observed around the injection sites. The injected substance did not migrate to the surrounding tissues. In IHC staining experiments, myofibroblasts were observed from the 2nd week, and collagen was detected from the 4th week. Myofibroblast was observed in the spaces between and inside the microspheres in the 8th week after injection, whereas type I collagen was found between and inside the microspheres at 8th and 12th weeks, respectively.

Conclusion: The animal experiments confirm the efficacy and safety of injectable PDLLA as a subdermal filler.



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Keywords: Poly-D,L-lactic acid, injectables, fillers, microspheres, biostimulation

INTRODUCTION

Poly(lactic acid) (PLA) was originally synthesized from α -hydroxy acids by French chemists in 1954. This polymer has been used safely in resorbable suture materials, plates, and screws in orthopedic, neurologic, and craniofacial surgeries^[1-6]. PLA forms the chiral molecules of poly-L-lactic acid (PLLA), poly-D-lactic acid, poly-D,L-lactic acid (PDLLA), and meso-PLA types^[7]. Only PLLA and PDLLA have been extensively studied and have shown promising results^[8-10].

In 1999, injectable PLLA was approved for use in Europe (New-Fill; Biotech Industry SA, Luxembourg, Luxembourg). PLLA is used to increase the volumes of depressed skin areas, particularly to correct skin depressions such as creases, wrinkles, folds, scars, and eye rings^[11]. PLLA is also useful for treating degenerative skin lesions due to aging. In August 2004, injectable PLLA (Sculptra; Dermik Laboratories, Bridgewater, NJ) was approved for the treatment of HIV-associated facial lipoatrophy in the United States^[12]. In 2009, this approval was expanded to include cosmetic applications^[13].

Injectable PDLLA is a new subdermal stimulatory filler (AestheFill; REGEN Biotech, Seoul, South Korea), and it has identical features as injectable PLLA. Injectable PDLLA is biocompatible, biodegradable, biostimulatory and long lasting. But the difference is the microparticles of injectable PDLLA are spongiform microspheres with multiple micropores. The aims of this study were to test the in vivo efficacy and safety of the injectable PDLLA as a subdermal tissue filler. This biodegradable polymer was injected into animals from September 1, 2009, to May 1, 2011. The effects and long-term utility of injected PDLLA microspheres were then investigated in observations of the dorsal parts of 2-week-old Sprague Dawley (SD) rats.

MATERIALS AND METHODS

Materials

Biodegradable PDLLA filler

The injectable PDLLA used in this study was produced by REGEN Biotech, and comprised 30 to 70 μ m PDLLA microspheres that were white, frozen, and dried solid. The microspheres were suspended in sodium carboxymethylcellulose as a carrier for injection.

Experimental animals

All animal procedures were conducted in compliance with the relevant laws and regulations of the Institutional Animal Care and Use Committee of Hallym University. A total of thirty 2-week old male SD rats were fed sufficient water and food in the animal facility of Hallym University.

Methods

Filler injection

SD rats were anesthetized with ketamine and xylazine and received subdermal injections of 0.5 mL PDLLA filler into their backs.

Macroscopic observations of the injection sites

On the 2nd, 4th, 8th, 12th, 16th, and 20th weeks after injection, five rats were randomly selected for clinical observations, and the skin color and volume changes at the injection sites were recorded.

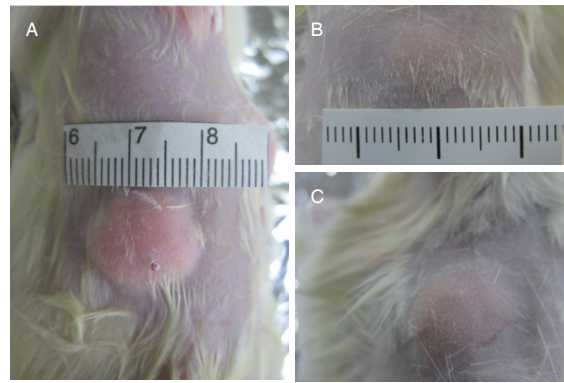


Figure 1. Macroscopic findings at injection sites. PDLLA filler injection sites can be visually confirmed. Inflammatory indicators, such as redness at the injection site or in the surrounding skin, were not present. A: immediately after PDLLA filler injection; B: at the 2nd week after PDLLA filler injection; C: at the 4th week after PDLLA filler injection. PDLLA: Poly-D,L-lactic acid



Figure 2. PDLLA filler injection sites at the 20th week. PDLLA filler was located in the subdermal tissue, and no abnormal findings, such as migration to surrounding tissues or inflammation, were apparent; A: skin reflection to show PDLLA filler mass; B: closer view of Figure 2A. PDLLA: Poly-D,L-lactic acid

Collection and observation of tissues

After the clinical observations of injection sites, tissues were harvested, immobilized in 10% neutral formalin solution, and then sliced into serial sections. Hematoxyline-eosin (H&E) and immunohistochemical (IHC) staining analyses were performed using antibodies against collagen (type I) and actin. The degrees of proliferation of normal tissues were estimated on the basis of the observations of cells, myofibroblasts, and collagen.

Safety of PDLLA filler

The developmental states of all treated animals were monitored by periodically measuring their body weights. The transfer of the microspheres to other organs was validated histologically in the liver, kidney, spleen, and lung tissues from treated rats.

RESULTS

Macroscopic findings

After injecting PDLLA filler into the dorsal subdermal tissues of SD rats, no significant skin color changes were observed in the injection sites compared with the untreated sites, and circular elevations were noted [Figure 1A-C]. The PDLLA filler mass was visually pale yellow compared with the subdermal tissues from the inner side after peeling off the muscle tissues [Figure 2A and B]. PDLLA filler masses that formed circular shapes at the subdermal tissues of injection sites and PDLLA microspheres did not infiltrate into neighboring tissues during the 20th week of the study period after injection. Moreover, the injection volumes were maintained without significant reductions for the entire 20-week study period [Figure 3].

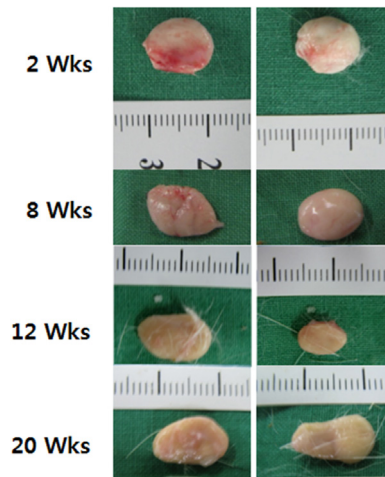


Figure 3. Changes in the sizes of poly-D,L-lactic acid filler masses over time. No significant reductions in volume were observed during the 20-week observation period after injection

Histological findings

Cell distributions in PDLLA filler masses

PDLLA filler masses were fixed in 10% neutral formalin solution, and serial sections were stained with H&E. As shown in [Figure 4A and B](#), PDLLA filler masses were localized to subdermal tissues and did not migrate to the surrounding tissues. Furthermore, although inflammatory cells were observed around PDLLA filler masses at the 2nd week after filler injections [[Figure 4A](#)], they tended to decrease at the 4th week [[Figure 4B](#)].

In the analyses of serial sections, cells were observed in PDLLA filler masses. However, cell densities were not uniform throughout these masses at the 2nd and 8th weeks. Cell densities were low in the centers of filler masses early in the study period, particularly at the 2nd week. At the 12th and 20th weeks, cell densities were uniform throughout the filler masses. The high magnification ($\times 400$) microscope observations show the foreign body giant cells in the spaces between and on the surfaces of the PDLLA microspheres at the 2nd week [[Figure 5A](#)]. However, empty spaces remain between the microspheres. At the 8th week [[Figure 5B](#)], these spaces were totally filled with giant cells; at the 12th and 20th weeks [[Figure 5C and D](#)], giant cells were visible in the spaces between the microspheres and within individual microspheres.

In [Figure 6A](#), the H&E stained section of an PDLLA filler mass at the 2nd week shows a vessel-like conduit. At the 12th and 20th weeks [[Figure 6B and C](#)], the vessel was increasingly evident and resembled a blood vessel.

New tissue formation (neotissue) in PDLLA filler masses

A. IHC staining for actin

To confirm the formation of neotissue in PDLLA filler masses, actin components were stained immunohistochemically in serial sections. Actin filaments are inside and the cytoskeleton of myofibroblasts. As shown in [Figure 7A](#), myofibroblasts were visible around and in the spaces between the microspheres at the outer and inner parts of the mass from the 2nd week after PDLLA filler injections. At the 8th week, myofibroblasts were present in the entire mass and filled most of the spaces between the microspheres [[Figure 7B](#)]. At the 12th week, myofibroblasts were additionally present within individual microspheres [[Figure 7C](#)]; at the 20th week, myofibroblasts were further increased [[Figure 7D](#)].

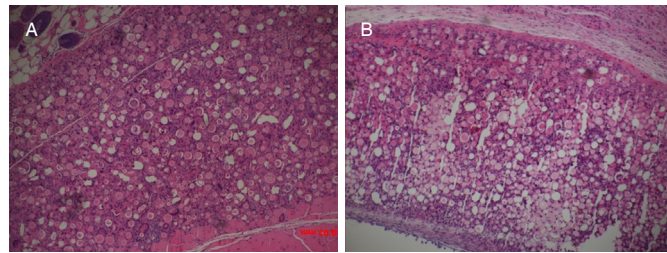


Figure 4. H&E staining ($\times 100$) after PDLLA filler injections. The injected PDLLA microspheres remained in the subdermal layer, and infiltration into surrounding tissues was not apparent. Inflammatory cells were visible around PDLLA microspheres. A: at the 2nd week; B: at the 4th week. PDLLA: poly-D,L-lactic acid

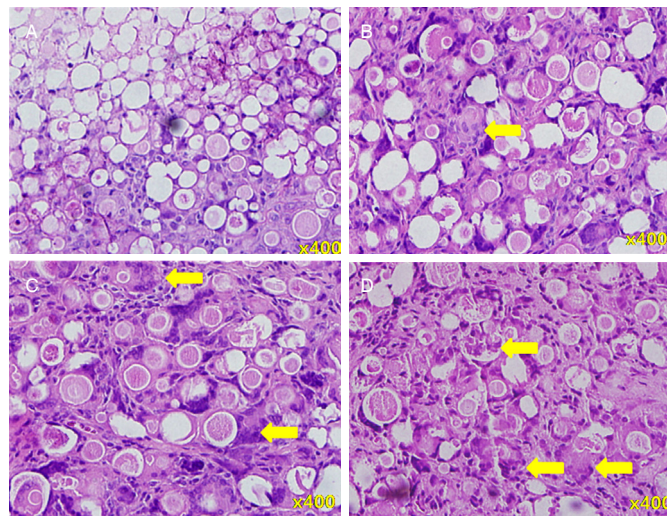


Figure 5. H&E staining ($\times 400$) at the 2nd to 20th week after poly-D,L-lactic acid filler injections. A: at the 2nd week; B: at the 8th week; C: at the 12th week; D: at the 20th week. Yellow arrows: foreign body giant cells, with increasing number from A to D

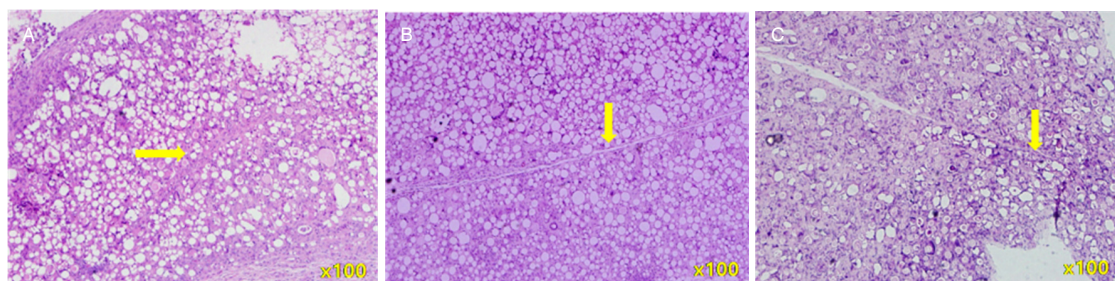


Figure 6. H&E staining ($\times 100$) pictures of a poly-D,L-lactic acid filler mass show a vessel-like conduit. A: at the 2nd week; B: at the 12th week; C: at the 20th week. Yellow arrows: vessel-like conduits

B. IHC staining for type I collagen

To confirm the formation of neotissue, we performed IHC analyses of filler mass sections by using antibodies against type I collagen. Unlike actin, collagen was expressed only in some parts between and on the surfaces of the microspheres at the 4th week [Figure 8A]. At the 8th week, the collagen expression between the microspheres was greater than that at the 4th week [Figure 8B].

At the 12th week after PDLLA filler injection, the appearance of collagen was increased [Figure 8C]. As indicated by the arrows, collagen was present inside the individual microspheres. Moreover, at the 20th week, collagen expression was increased inside the individual microspheres [Figure 8D].

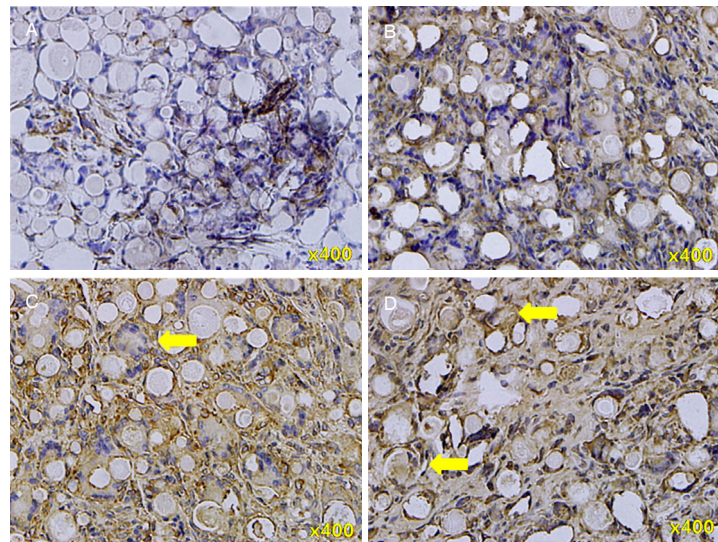


Figure 7. Immunohistochemical staining of actin ($\times 400$) in PDLLA filler mass sections at the 2nd to 20th weeks after PDLLA filler injections. A: at the 2nd week; B: at the 8th week; C: at the 12th week; D: at the 20th week. Actin filaments are inside and the cytoskeleton of myofibroblasts. Yellow arrows: myofibroblasts, with increasing number from A to D. PDLLA: poly-D,L-lactic acid

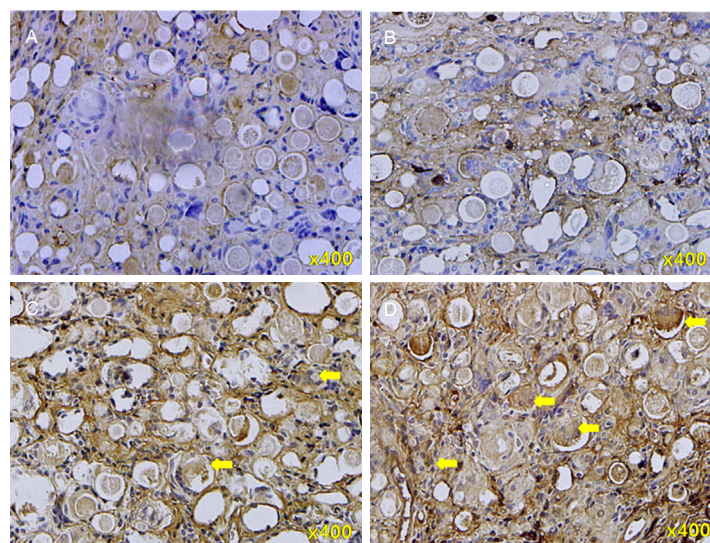


Figure 8. Immunohistochemical staining of type I collagen in neotissues ($\times 400$) at the 4th to 20th weeks after poly-D,L-lactic acid filler injections. A: at the 4th week; B: at the 8th week; C: at the 12th week; D: at the 20th week. Yellow arrows: type I collagen, with increasing number from A to D

Changes in body weight

No significant weight gains or losses were observed after the injection of the filler into experimental animals.

Transfer of PDLLA microspheres to other organs

After PDLLA filler was injected, liver, kidney, spleen, and lung tissues were harvested and fixed in 10% neutral formalin solution. H&E staining was then performed with serial sections. These analyses show that the microspheres did not migrate into distant organs [Figure 9A-D].

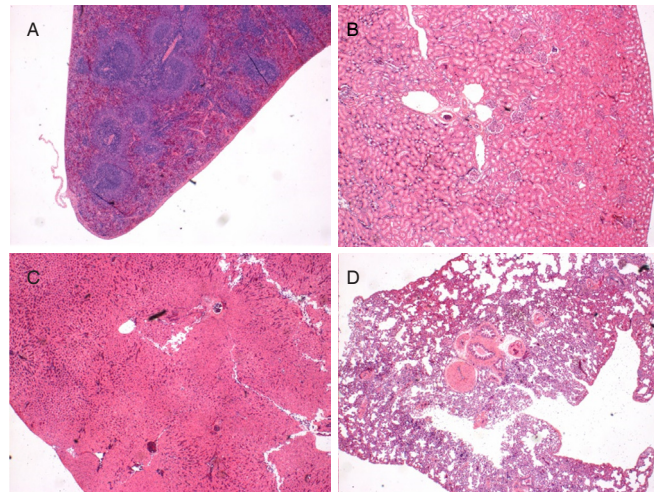


Figure 9. The migration of PDLLA microspheres to internal organs was not observed after PDLLA filler injections. A: lung; B: spleen; C: liver; D: kidney. PDLLA: poly-D,L-lactic acid

DISCUSSION

Injectable fillers offer simple and minimally invasive techniques for tissue volume expansion. Ideal materials for such interventions must be easily injectable, nonmigratory, noninflammatory, volume stable, biodegradable, and biocompatible. Many types of tissue fillers are currently used for cosmetic and medical indications in routine clinical practice^[14]. These tissue fillers can be classified as temporary, semipermanent, or permanent fillers depending on the duration of the injected product in tissues^[15]. These fillers are also classified according to their compositions, and collagen (bovine, porcine, and human), hyaluronic acid (HA), PLLA, calcium hydroxylapatite (CaHA), polymethyl methacrylate, polyacrylamide, and autologous fat cells have been investigated^[15]. Among these fillers, CaHA and PLLA are known as collagen stimulators^[16] and offer unique and effective ways to address tissue impediments with natural-appearing results and durability.

Poly-lactic-co-glycolic acid (PLGA) microspheres have been considered injectable bulking substances in previous studies^[17-19]. These studies show that PLGA is biodegradable and biocompatible and induces hybrid tissue formation upon implantation. However, PLGA microspheres fail to offer a long-term (more than six months) maintenance of hybrid tissue volumes because they degrade. Compared with PLGA, PLA microspheres have slower degradation rates owing to their relative hydrophobicity. Hence, injectable PLA microspheres maintain hybrid tissue volumes for longer periods. Kang *et al.*^[20] previously showed that volumes of implanted PLA in dorsum tissues of mice slowly decreased in volume to 52% after 12 months but maintained this residual volume until 18 months.

In this study, PDLLA filler affected the formation of neotissues around and inside injection areas, similar to PLLA demonstrations as a collagen stimulator. Moreover, during the test period, no clinical symptoms or changes in body weights were observed in our experimental animals. No migration of test substance to the lung, spleen, liver, or kidney tissues was observed, and the injected PDLLA filler volumes in the sub-dermis were maintained between the 2nd and 20th weeks after injection. We also observed no abnormal findings, such as inflammation around and inside the injection sites. Histopathological findings similarly showed the appropriate localization of injected PDLLA filler in subdermal tissues and confirmed that the substance did not migrate to surrounding tissues.

Cells that were distributed in the periphery of PDLLA filler injection sites moved into the spaces between PDLLA microspheres and then moved into the centers of the microspheres. Nutrient supply through

microvessels is necessary for the proliferation and migration of cells into injected masses. As shown in [Figure 5A-D](#), the spaces between PDLLA microspheres filled with cells over time, thus suggesting the formation of blood vessel-like pathways that may supply nutrients for cell proliferation inside the PDLLA filler mass.

To investigate the formation of neotissues, we performed IHC analyses on the actin and type I collagen in sections of the PDLLA filler masses. Myofibroblasts were found between the microspheres as early as two weeks after injection and continued to develop and eventually penetrated the PDLLA microspheres. Similarly, extracellular type I collagen was detected in spaces between and on the outer surfaces of the microspheres at the 4th week and was found inside the individual microspheres by the 20th week.

This animal study suggests that injected PDLLA filler mass maintains its volume by facilitating the formation of new tissues, which ultimately replace the volume of the PDLLA filler mass and presumably hydrolyze the PDLLA.

We can divide the volume maintenance into two stages. The first stage of the volume increase is from the volume of the injected PDLLA microspheres. The second stage is volume maintenance, and it is due to the formation of new tissues and collagen with cell inflow between and inside PDLLA microspheres. The volume of new tissues and collagen replaces the volume of PDLLA microspheres, which are eventually hydrolyzed.

In 2012, a clinical study was performed to determine the efficacy and safety of PDLLA filler injections for penile augmentation^[21]. The significant penile augmentation effect lasted for 18 months after injection and was well tolerated without serious adverse effects. Subsequently, 58 people were recruited into a randomized, evaluator-blinded, comparative study that was conducted on August 1, 2012 to March 6, 2013. In this study, the efficacy and safety of PDLLA microspheres injections for the correction of nasolabial folds were compared with those of HA. PDLLA microspheres were not inferior to HA^[22], and 30 subjects completed the 24-month long-term safety evaluation follow up, which showed that PDLLA microspheres are safe and effective for use as fillers for nasolabial fold correction^[23]. Complications such as granuloma formation^[24-27] and accidental vascular occlusion^[26-28] could occur, similar to other subdermal fillers, and need to be investigated further.

In this study, rat body weights did not change during the experimental period, and no evidence of test substance migration to other organs was found. The injected volumes were maintained for 20 weeks in part because of the inflow and growth of cells, actin, and type I collagen inside the microspheres. The formation of neotissues that replace the original volume of the PDLLA filler mass was further suggested by observations of microvessels inside PDLLA filler masses. Therefore, injectable PDLLA polymer is biodegradable and has efficacy and safety as a subdermal tissue filler.

DECLARATIONS

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Authors' contributions

Concept and design: Kim JY

Data acquisition, technical and material support: Kang M

Data analysis, manuscript preparation: Yang DY, Lee SH

Critical revision and completion of manuscript: Lin CY, Lin JY

Availability of data and materials

Not applicable.

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Conflicts of interest

Dr. Dae-Yeol Yang has no conflicts to disclose. Dr. Chuan-Yuan Lin is medical director for Regen. Dr. Jui-Yu Lin is chief medical director for Regen. Dr. Seong-Ho Lee has no conflicts to disclose. Miyeon Kang is director for Regen R&D center. Dr. Jeoung-Yong Kim is chief director for Regen R&D center.

Ethical approval and consent to participate

The study has been approved by relevant ethical committee and the whole research process complied with ethical guidelines.

Consent for publication

Not applicable.

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REFERENCES

1. Middleton JC, Tipton AJ. Synthetic biodegradable polymers as orthopedic devices. *Biomaterials* 2000;21:2335-46.
2. Kulkarni RK, Pani KC, Neuman C, Leonard F. Polylactic acid for surgical implants. *Arch Surg* 1966;93:839-43.
3. Achtnich A, Forkel P, Metzlauff S, Zantop T, Petersen W. Degradation of poly-D-L-lactide (PDLLA) interference screws (Megafix (R)). *Arch Orthop Trauma Surg* 2014;134:1147-53.
4. Farah S, Anderson DG, Langer R. Physical and mechanical properties of PLA, and their functions in widespread applications - a comprehensive review. *Adv Drug Deliv Rev* 2016 15;107:367-92.
5. Saini P, Arora M, Kumar M. Poly(lactic acid) blends in biomedical applications. *Adv Drug Deliv Rev* 2016;107:47-59.
6. Athanasiou KA, Niederauer GG, Agrawal CM. Sterilization, toxicity, biocompatibility and clinical applications of polylactic acid/polyglycolic acid copolymers. *Biomaterials* 1996;17:93-102.
7. Pretula J, Slomkowski S, Penczek S. Polylactides-Methods of synthesis and characterization. *Adv Drug Deliv Rev* 2016;107:3-16.
8. Grandfils C, Flandroy P, Nihant N, Barbette S, Jerome R, et al. Preparation of poly (D,L) lactide microspheres by emulsion-solvent evaporation, and their clinical applications as a convenient embolic material. *J Biomed Mater Res* 1992;26:467-79.
9. Robinson BP, Hollinger JO, Szachowicz EH, Brekke J. Calvarial bone repair with porous D,L-polylactide. *Otolaryngol Head Neck Surg* 1995;112:707-13.
10. Sherwood JK, Riley SL, Palazzolo R, Brown SC, Monkhouse DC, et al. A three-dimensional osteochondral composite scaffold for articular cartilage repair. *Biomaterials* 2002;23:4739-51.
11. Valantin MA, Aubron-Olivier C, Ghosn J, Laglenne E, Pauchard M, et al. Polylactic acid implants (New-Fill) to correct facial lipodystrophy in HIV-infected patients: results of the open-label study VEGA. *AIDS* 2003;17:2471-7.
12. Humble G, Mest D. Soft tissue augmentation using sculptra. *Facial Plast Surg* 2004;20:157-63.
13. Palm MD, Woodhall KE, Butterwick KJ, Goldman MP. Cosmetic use of poly-L-lactic acid: a retrospective study of 130 patients. *Dermatol Surg* 2010;36:161-70.
14. Attenello NH, Maas CS. Injectable fillers: review of material and properties. *Facial Plast Surg* 2015;31:29-34.
15. Sanchez-Carpintero I, Candelas D, Ruiz-Rodriguez R. Dermal fillers: types, indications, and complications. *Actas Dermosifiliogr* 2010;101:381-93.
16. Breithaupt A, Fitzgerald R. Collagen stimulators: poly-L-Lactic acid and calcium hydroxyl apatite. *Facial Plast Surg Clin North Am* 2015;23:459-69.
17. Cho ER, Kang SW, Kim BS. Poly(lactic-co-glycolic acid) microspheres as a potential bulking agent for urological injection therapy: preliminary results. *J Biomed Mater Res B Appl Biomater* 2005;72:166-72.
18. Kang SW, Cho ER, Kim BS. PLGA microspheres in hyaluronic acid gel as a potential bulking agent for urologic and dermatologic injection therapies. *J Microbiol Biotechnol* 2005;15:510-8.
19. Cho ER, Kang SW, Park HJ, Cho YS, Lee YS, et al. Submucosal injection of poly(lactic-co-glycolic acid) microspheres in rabbit bladder as a potential treatment for urinary incontinence and vesicoureteral reflux: preliminary results. *J Biomater Sci Polym Ed* 2005;16:1109-20.
20. Kang SW, Cho ER, Jeon O, Kim BS. The effect of microsphere degradation rate on the efficacy of polymeric microspheres as bulking

- agents: an 18-month follow-up study. *J Biomed Mater Res B Appl Biomater* 2007;80:253-9.
21. Yang DY, Ko K, Lee SH, Moon DG, Kim JW, et al. Efficacy and safety of a newly developed polylactic acid microsphere as an injectable bulking agent for penile augmentation: 18-months follow-up. *Int J Impot Res* 2017;29:136-41.
 22. Hyun MY, Lee Y, No YA, Yoo KH, Kim MN, et al. Efficacy and safety of injection with poly-L-lactic acid compared with hyaluronic acid for correction of nasolabial fold: a randomized, evaluator-blinded, comparative study. *Clin Exp Dermatol* 2015;40:129-35.
 23. No YA, Seok J, Hyun MY, Kwon TR, Oh CT, et al. Long-term (24-month) safety evaluation of poly-DL-lactic acid filler injection for the nasolabial fold: a multicenter, open, randomized, evaluator-blind, active-controlled design. *Plast Reconstr Surg* 2015;135:1074-5.
 24. Lee JM, Kim YJ. Foreign body granulomas after the use of dermal fillers: pathophysiology, clinical appearance, histologic features, and treatment. *Arch Plast Surg* 2015;42:232-39.
 25. Molina-Ruiz AM, Requena L. Foreign body granulomas. *Dermatol Clin* 2015;33:497-523.
 26. Woodward J, Khan T, Martin J. Facial filler complications. *Facial Plast Surg Clin North Am* 2015;23:447-58.
 27. Urdiales-Galvez F, Delgado NE, Figueiredo V, Lajo-Plaza JV, Mira M, et al. Treatment of soft tissue filler complications: Expert consensus recommendations. *Aesthetic Plast Surg* 2018;42:498-510.
 28. Ansari ZA, Choi CJ, Rong AJ, Erickson BP, Tse DT. Ocular and cerebral infarction from periocular filler injection. *Orbit* 2018;30:1-3.

Technical Note

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Endoscopic-assisted rib cartilage harvesting for revision rhinoplasty

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Abstract

We describe the endoscopic-assisted rib harvesting technique for secondary rhinoplasty as minimum - invasive and safe harvesting method. Endoscopic-assisted rib harvesting was performed on 52 patients for revision rhinoplasty in last two years (2017-2019). Adequate amount of cartilage was obtained through 1-2 cm incision. The 30 degrees angled endoscope was used for vision control. Fifty-two patients underwent rhinoplasty with costal cartilage harvested using endoscopic-assisted method. The length of the harvested cartilage blocks from the rib was 5 ± 1.5 cm in average. There were no associated intraoperative complications. Postoperative complications were less than by the conventional rib harvesting technique: in all cases, no signs of pneumothorax or excessive bleeding were detected after surgery. The wound healed without significant scarring in 50 (96%) cases. Two patients (4%) showed hypertrophic scar formation. Postoperative pain was evaluated by using Visual Pain Analog Scale retrospectively. Forty-eight patients (92%) scored 1.43 ± 0.7 experienced no significant postoperative pain. Only 4 patients (8%) scored 4.1 ± 0.8 and complained of slight postoperative pain. This technique provides an effective and less-invasive alternative for conventional costal cartilage harvesting with reduced complications risk and extended visualization. Patients benefit from an inconspicuous scar and reduced postoperative pain. Technique can be applied for revision and primary rhinoplasty and allows achieving reproducible aesthetically and functionally successful results with minimized risks.

Keywords: Rhinoplasty, rib, revision, costal cartilage



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INTRODUCTION

Nasal framework reconstruction in secondary and more rarely in primary rhinoplasty is often restricted by quantity and quality of cartilaginous framework. The most commonly used donor site for cartilage harvesting is considered to be septal cartilage, however surgeons frequently face such problems as: paucity of available graft material, especially in secondary cases and cartilaginous insufficiency in severe deformities cases. Both arguments are particularly true in secondary rhinoplasty when over resection of the osseocartilaginous framework is observed. Considering all these surgeons may often need an alternative source of grafting material in order to correct both aesthetic deformities and functional problems.

Satisfactory and consistent long-term results rely on using not only adequate quantity of cartilage, but also on graft quality: low resorption rate, sufficient strength for appropriate support, rejection and allergy safety. Thus, the most suitable and preferred graft material nowadays is considered to be autologous tissue. From all potential donor sites for autologous graft, the rib provides the most abundant cartilage source for graft fabrication and is the material of choice when reliable support is required^[1].

Conventional rib harvesting techniques included 3-5 cm incision and cutting the muscles^[2]. Nevertheless, autogenous graft harvesting is associated with several disadvantages such as postoperative pain, visible scar, risk of pleura perforation and often requires advanced surgical skills^[3,4]. With regard to above mentioned complexities, we suggest the method of endoscope-assisted rib cartilage harvesting. This technique is less invasive and enables reducing risks of bleeding and pleura perforation due to extended visualization and better remote access incision site.

In last two years we performed 52 endoscopic-assisted rib harvesting. We observed significant decrease in postoperative pain, bleeding and therefore faster recovery and better aesthetic result.

ENDOSCOPIC RIB HARVESTING OPERATIVE TECHNIQUE

Marking

Rib cartilage harvesting is preferentially performed on the patient's right side. Marking starts with palpating the sternomanubrial junction, which corresponds to the position of the second rib. The ribs are then numbered according to their position. We prefer to harvest 6th rib as it provides abundant cartilage supply and is straight and wide enough for future graft fabrication.

Placement of the incision line is determined by the sex of the patient. In female patients, the inframammary fold offers a good position for camouflage and the incision line is marked at approximately 5 mm above the inframammary fold^[5]. The incision should not extend beyond the medial border of the inframammary fold in order to avoid postoperative visibility. In male patients, the incision is placed right over the selected rib.

Incision

The main advantage of this method is short incision, about 1-2 cm [Figure 1]. Some experienced surgeons do harvest the rib through such small incision with direct vision without using endoscope, but usually it requires advanced surgical skills and is still associated with bad visualization and, therefore, higher risk of pneumothorax and bleeding for the not enough experienced surgeons.

When placement of the incision is chosen, harvesting procedure begins by incising the skin using 15th blade. The subcutaneous and fascial layers are transected using electrocautery or blade. The muscle itself was not cut, instead, it was divided bluntly by spreading following the direction of the muscle fibers. Dissection was concluded with Freer elevators. This step enables to reduce postoperative pain and possible intraoperative bleeding^[6] [Figure 2].



Figure 1. Incision 1.2 cm in length

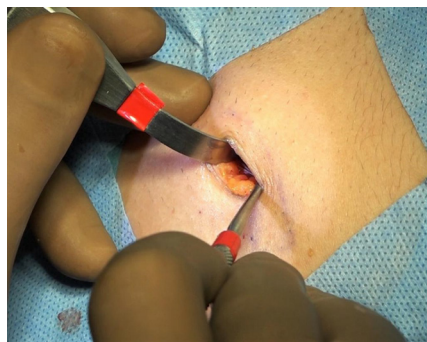


Figure 2. Separating the muscle fibers via blunt dissection

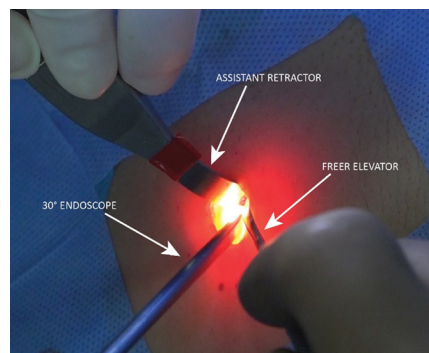


Figure 3. Using the endoscope - surgeon is holding the endoscope with left arm. Second arm is holding the elevator. Assistant is helping to open the wound with the retractor

Endoscopic-controlled harvesting

Once the muscles are separated, we are able to see the rib clearly. Assistant retract the wound upward to make room for endoscopic work. We use 30 degrees angled endoscope. Surgeon is holding endoscope with one hand, while using Freer elevator with the other hand. Other instrument may be used if needed [Figure 3].

Then we reach the rib with the help of endoscope, which gives us clear wound imaging. Now, one can see the perichondrium clearly [Figure 4]. It's crucial to know the position of both sided bony cartilaginous junctions for ensuring that the maximum possible length of the cartilage is harvested, thereby optimizing the efficiency of the procedure.

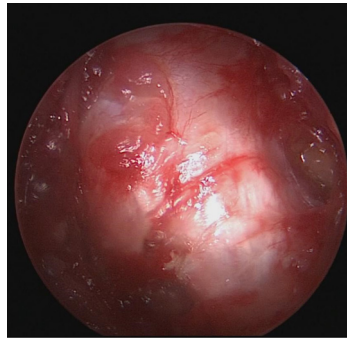


Figure 4. Clear visualization of the perichondrium with the help of endoscope

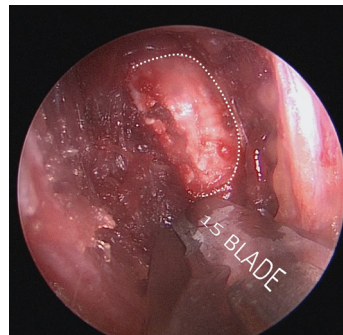


Figure 5. Perichondrial flap

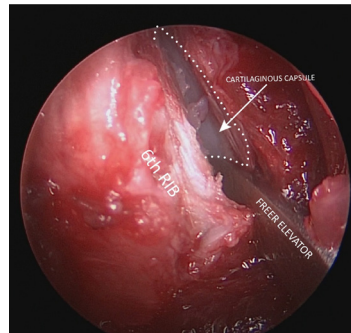


Figure 6. Elevation of the perichondrium

Then, we are making a so-called “window” incision to the perichondrium - creating a quadrangular perichondrial flap, with its 3 from 4 sides incised [Figure 5].

After perichondrium elevation one should pay attention to another tissue layer - under the perichondrium there is a thin layer of cartilaginous capsule. In order to perform the procedure safe in a bloodless plain, surgeon has to be under the capsule. Once the layer beneath is approached - one is safe for performing the dissection [Figure 6].

We perform the whole dissection using Freer elevator in my second hand, although it's not a must. Dissection is limited by the junction of the rib cartilage and the sternum medially, and by demarcated costochondral zone laterally. Both can be clearly seen via endoscope.

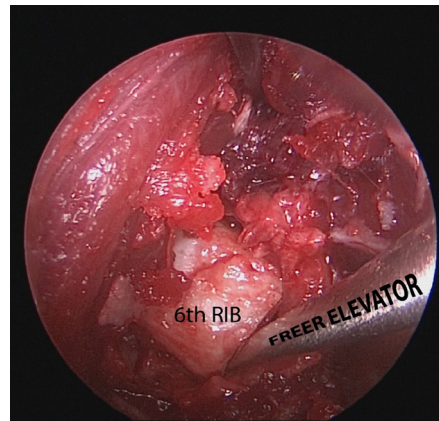


Figure 7. Disarticulation of the rib



Figure 8. Cartilage is easily removed from the wound after disarticulation

During capsule elevation care must be taken to not enter the cartilage, harm the cartilaginous surface or cause the fracture that may limit future graft fabrication.

When undermining is completed right-angled circular incision to the cartilage is performed using 15th blade. We make semi-circular incision on one side first, then we turn around the rib and finish the incision connecting both lines.

After incision is made the cartilage segment is released both medially and laterally by means of disarticulation using Freer elevator [Figure 7].

Cartilage is easily removed from the wound and placed in sterile saline solution until the graft fabrication [Figure 8].

Calcified cartilage

Despite appropriate preoperative screening, occasionally patients may present with premature calcification of the cartilaginous rib. Frequently, the main calcification area can be observed at the junction of the osseous and cartilaginous rib.

In most of cases, one can manage this problem using the elevator to gently lift the calcification for providing an adequate access to the underlying cartilage. But in some more severe cases, usually by elder patients, calcification is too strong and tightly welded to the rib. In such cases the use of Piezo electric device has

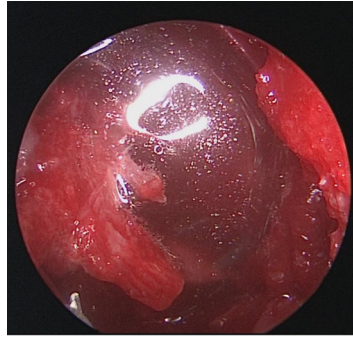


Figure 9. Insufflation test - filling the wound with saline solution



Figure 10. Closed wound. Separate skin sutures using 5.0 prolene

proven to be very helpful in contouring areas of calcification. In this situation, we prefer to enlarge the incision and use piezo electric instrument under direct vision because it's not easy to use piezo device with endoscopic view. As the Piezo electric device does not harm any soft tissue, one can be safely cut out the calcified area without injuring the perichondrium^[7].

Small calcifications may also be found within the body of the rib cartilage itself. This fact should be drawn to surgeon's attention as it can impair the preparation of individual grafts and act as a site of weakness, often having a tendency to fracture.

Safety check

After cartilage removal it's important to make sure that pleura is left intact. We perform insufflation test - filling the wound with saline solution and using positive thoracic pressure^[6]. If no bubbles observed- one is safe and pleura is intact. After the test we wash the cavity with rifampicin solution [Figure 9].

Wound closure

We close the wound layer by layer for faster healing and avoiding tension. Closure is initiated from perichondral layer by putting 2-3 stitches with 4.0 rapid vicryl. Then the subcutaneous layer is closed with 4.0 vicril.

Skin is closed with separate sutures using 5.0 prolene. We haven't used any drain application on any of our cases [Figure 10].

Graft fabrication

We suggest to use the rib according to the oblique split method, described by Dr. Eren Tastan [Figure 11]. As warping has been the main problem by costal cartilage grafting, oblique split method provides straight costal cartilage grafts of varying thicknesses without the risk of warping.

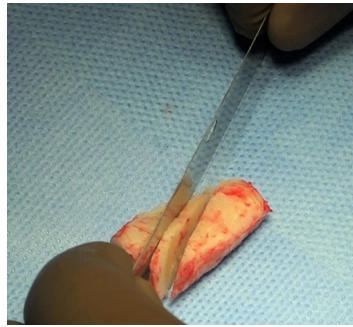


Figure 11. Cutting harvested cartilage according to oblique split method

Numerous clinical cases have shown that a cross-sectional graft obtained through an oblique cut to the long axis of the rib results in a graft with equal circumferential forces of contracture that have a decreased chance of warping^[8].

Postoperative pain

Usually the main patient's complain after conventional rib harvesting is postoperative pain. Due to the fact that thoracic muscles are used for such physiological process as breathing and many other everyday activities such as getting up, speaking, walking and so forth - the thorax cannot be immobilized completely in postoperative period. In the majority of cases these movements may cause pain conditioned by the cut muscle fibers.

On the contrary, one of the key advantages of the endoscopic rib harvesting is reduced postoperative pain. Significant decrease in pain is attained by means of delicate muscle undermining under endoscopic-assisted vision, which enables to preserve the majority of muscle fibers. The use of muscle-sparing technique contributes to faster healing with reduced postoperative pain [1.6 ± 0.9 Visual Pain Analog Scale (VAS)]. This benefit is more pronounced in the early postoperative period and is especially dramatic in reducing movement pain^[6].

OUR EXPERIENCE

The endoscopic-assisted rib harvesting was performed on 52 patients in last two years. In all cases no severe complications such as pneumothorax or excessive bleeding was observed. The incision length was 1.4 ± 0.3 cm in average. Fifty patients (96%) showed no problems with scar healing and 2 patients (4%) showed hypertrophic scar formation. Postoperative pain was evaluated by using VAS retrospectively. Forty-eight patients (92%), who scored 1.43 ± 0.7 experienced no significant postoperative pain. Only 4 patients who scored 4.1 ± 0.8 (8%) complained of slight postoperative pain for the first 2-3 days and it was manageable with Paracetamol 1000 mg i/v. In this cases pain was relieved with no additional painkillers or local anesthetic agent. Dissection was done with Freer elevators, which also enabled to reduce postoperative pain and possible intraoperative bleeding^[6]. Recovery to walk and breath normally was very short showing 1.2 ± 0.6 days. Patients did not need additional rehabilitation and recovery exercises and precautions. With regard to our clinical study this method allows achieving reproducible, aesthetically and functionally successful results with minimized risks.

CONCLUSION

Rib cartilage harvest is a common procedure in primary and secondary rhinoplasties. The main disadvantages of the conventional technique for autogenous graft harvesting are risks of potential complications such as bleeding, pneumothorax, and postoperative pain.

Using endoscopic system in harvesting the rib cartilage provides better visuality and safety with less chance for major complications by conventional methods although this method requires surgeon's experience in using endoscope and has limitations in overweight patients.

DECLARATIONS

Authors' contributions

Made substantial contributions to conception and design of the study and performed data analysis and interpretation: Göksel A

Provided technical, and material support: İlhan E

Availability of data and materials

Not applicable.

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All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

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Consent for publication

Written informed consent for publication was obtained from patients mentioned in article and added photos.

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REFERENCES

1. Parker Porter J. Grafts in rhinoplasty: alloplastic vs. autogenous. *Arch Otolaryngol Head Neck Surg* 2000;126:558-61.
2. Marin VP, Landecker A, Gunter JP. Harvesting Rib cartilage grafts for secondary rhinoplasty. *Plast Reconstr Surg* 2008;121:1442-8.
3. Wee JH, Park MH, Oh S, Jin HR. Complications associated with autologous rib cartilage use in rhinoplasty: ameta-analysis. *JAMA Facial Plast Surg* 2015;17:49-55.
4. Woo KJ, Kang BY, Min JJ, Park JW, Kim A, et al. Postoperative pain control by preventive intercostal nerve block under direct vision followed by catheter-based infusion of local analgesics in rib cartilage harvest for auricular reconstruction in children with microtia: a randomized controlled trial. *J Plast Reconstr Aesthet Surg* 2016;69:1203-10.
5. Toriumi DM. Dorsal augmentation using autologous costal cartilage or microfat-infused soft tissue augmentation. *Facial Plast Surg* 2017;33:162-78.
6. Özücer B, Dinç ME, Paltura C, Koçak I, Dizdar D, et al. Association of autologous costal cartilage harvesting technique with donor-site pain in patients undergoing rhinoplasty. *JAMA Facial Plast Surg* 2018;20:136-40.
7. Gerbault O, Daniel RK, Kosins AM. The role of piezoelectric instrumentation in rhinoplasty surgery. *Aesthet Surg J* 2016;36:21-34.
8. Taştan E, Yücel ÖT, Aydın E, Aydoğan F, Beriat K, et al. The oblique split method a novel technique for carving costal cartilage grafts. *JAMA Facial Plast Surg* 2013;15:198-203.

Original Article

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Review of the optimal timing and technique for extensor tendon reconstruction in composite dorsal hand wounds

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Abstract

Aim: The management of complex dorsal hand wounds with extensor tendon loss is controversial. Treatment has focused on soft tissue coverage, but there is limited evidence comparing immediate *vs.* staged tendon reconstruction. This review evaluates existing literature to determine the optimal management of composite hand defects.

Methods: A MEDLINE database review was performed including objective measurements such as number of operations, total active motion, grip strength, days to maximum range of motion (ROM), and return to work. Data extraction included demographics, surgical techniques, complications, and relative outcome. We compared primary and secondary staged reconstruction to correlate any significant differences in outcome and determine optimal timing and technique for extensor tendon reconstruction. We extracted information on flap types including regional and free tissue transfer with tendinous components *vs.* staged tendon grafts.

Results: Comparison of outcomes showed that patients with immediate reconstruction had fewer operations, faster return to maximum ROM, and greater chance of returning to work. The most successful single stage flaps include the radial forearm, suitable for reconstructing one to three tendons and the dorsalis pedis for three or four tendons; however, there were significantly more complications in immediate reconstruction particularly regarding donor site morbidity. Pedicled flaps had better total active motion. The two-stage approach resulted in acceptable functional outcomes without significant complications.



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Conclusion: Immediate cutaneous tendinous flaps have clear advantages over staged approaches for reconstruction of composite dorsal hand wounds. Benefits include less operations, faster time to maximum ROM, and higher percent of patients returning to work; however, significantly more flap related complications were seen. Immediate pedicled radial forearm provided the best total active motion with least complications. When patient circumstances dictate, a fascial perforator free flap offers a suitable environment for staged tendon grafts with good functional outcomes reported albeit longer time to achieve them.

Keywords: Composite dorsal hand wound flap extensor tendon reconstruction

INTRODUCTION

Complex dorsal hand wounds present a challenging problem for hand and reconstructive surgeons. The proximity to the surface makes open injury to extensor tendons relatively common^[1]. The surgical timing and flap choice for composite dorsal hand wounds are debated. Traditional management focuses on debridement, skeletal fixation, and soft tissue coverage. There is limited evidence on optimal extensor tendon reconstruction in a wound with tendinous defect. These injuries have been approached with a multitude of techniques with varying degrees of success.

The goal of extensor tendon treatment is to restore function while minimizing disability^[2]. Restoration of thin, pliable tissue with reliable vascularity and a gliding surface facilitates motion^[3]. Analysis of treatment options begins with assessment of the wound. The paratenon provides a well-vascularized compartment that minimizes adhesion to surrounding tissue. If paratenon is intact, skin graft or substitute matrix are viable options. When there is denuded tendon or exposed bone, reconstruction typically elevates to flap selection [Figure 1]. Numerous coverage options are available for these types of defects and are determined based on the extent of zone of injury and tissue match. An Allen's test is vital to ascertain competence of the palmar arch for deciding upon a reverse radial forearm flap with retrograde flow or an appropriate recipient for anastomosis. A decision must be made whether immediate or staged tendon reconstruction is preferable and which flaps best with the least complications.

Single-staged procedures include either composite pedicle forearm flaps or free tissue transfers with accompanying vascularized tendon graft. Alternatively, primary reconstruction with nonvascularized tendon grafts may be performed in conjunction with conventional flap coverage^[4]. Staged approaches include initial flap coverage and subsequent delayed tendon reconstruction with grafts or transfer [Figure 2]. Reid^[5] reported success using a multiple-staged approach with a primary abdominal flap and delayed tendon grafts to restore function in the hand. Taylor and Townsend^[6] described the single-stage dorsalis pedis cutaneotendinous free flap with positive results withstanding donor site morbidity. The dorsalis pedis flap can provide up to four vascularized tendons^[7-11]. Reid and Moss^[12] performed a one-stage flap repair using radial forearm flap containing palmaris longus and brachioradialis tendon. Modifications can provide palmaris longus, flexor carpi radialis, and/or brachioradialis with paddle location dependent on desired orientation when transposed^[13,14]. Pedicle flaps obviate the need for microsurgery when it is relatively contraindicated due to patient factors and status. Other flap choices including ulnar island^[15], posterior interosseous^[16,17], lateral arm^[18,19], and free anterolateral thigh^[20-22] have been described to incorporate strips of tendon or fascia for reconstitution. Latissimus, serratus, and gracilis are common muscle flaps. Consideration of positioning and availability of a two-team approach to expedite harvest and inset is warranted.

The goals of reconstruction are to provide adequate soft tissue coverage, enable tendons to glide with excursion, and provide adequate power for pull through^[23]. To determine whether a specific technique for management of cutaneous-tendinous hand defects provides superior outcomes, we performed a systematic

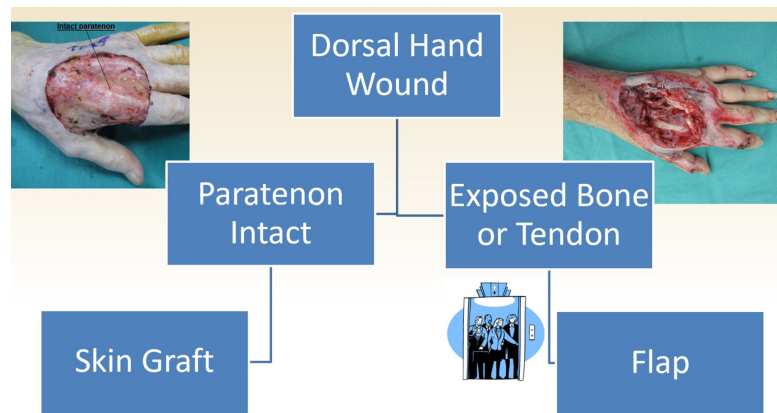


Figure 1. Analysis of defect and indicated reconstruction options

review of existing literature. We compared immediate *vs.* staged tendon reconstruction with evaluation of functional outcomes for evidence-based decision making.

METHODS

Identification of Relevant Literature - Database search: The authors performed a systematic search of the literature using the MEDLINE database (1969 through 2017) to identify articles that included the following keywords: “extensor tendon reconstruction”. To ensure adequate coverage, the authors utilized a Boolean search for keywords: [(hand OR extensor tendon) AND (“ROM” OR ROM OR grip strength OR patient outcome OR return to work OR disability)]. The abbreviation of ROM was used to assess and locate abstracts that included that term.

Search Limits: The pool of citations was then limited to those relevant to humans and published in English. The authors limited the results to exclude case reports. Inclusion criteria required objective measurements of data analysis including: ROM, grip strength, and patient outcomes related to return to work or disability. Amputation and arthrodesis were accounted for as a confounding factor and excluded when elucidated. The review of MEDLINE using these limits and search terms identified seven reliable studies, which represented 61 patients. Data points extracted were patient demographics, surgical technique, timing of tendon reconstruction, outcomes, and complications.

Flap types recorded included primary pedicle and free flaps with/without tendinous components *vs.* staged tendon grafts. Results of metacarpophalangeal total active motion, days to max ROM, grip strength, complication rate, number of operations, and percent returning to work were compared between immediate *vs.* staged techniques and pedicled *vs.* free flap repairs using a two-sample *t*-test assuming unequal variances. The authors adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines.

RESULTS

Sixty one patients analyzed in this review included males and females ranging in age from 13 to 70 who had undergone either an immediate 50 or staged 11 tendon reconstruction surgery. Of the fifty immediate (single) surgery group, 39 were free flaps and 11 were pedicled. In the eleven staged group, 6 were free and 5 were pedicled flaps [Table 1].

The most reported single-stage cutaneous tendinous flaps include radial forearm and the dorsalis pedis flap. Comparisons of outcomes [Table 2] showed immediate reconstruction had significantly fewer operations, 1.5 *vs.* 5.2 ($P < 0.001$) and led to faster return to maximum ROM 214 *vs.* 551 days ($P < 0.001$). Concurrently,

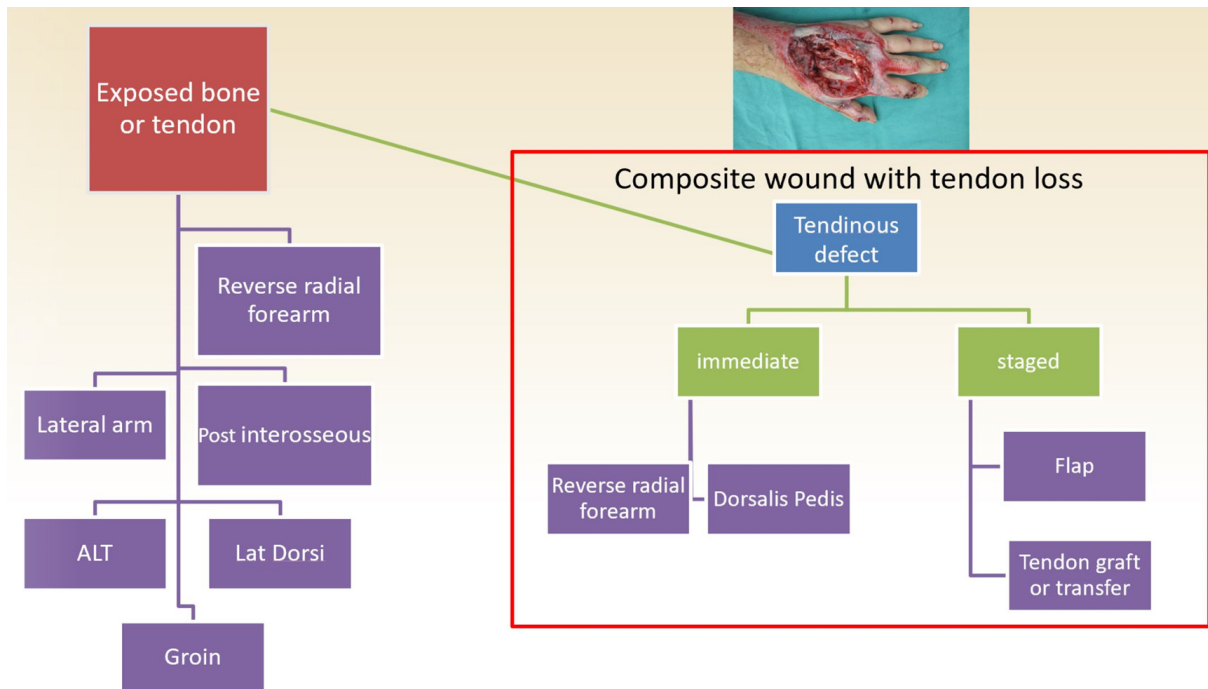


Figure 2. Flap choice for reconstruction of composite dorsal hand wound with tendinous defect, immediate vs. staged. ALT: anterolateral thigh flap

the patients tended to have a greater percentage of returning to work 88% vs. 43% ($P < 0.04$). Unplanned return to operating room for immediate reconstruction occurred in 20% whereas reoperation in addition to planned second stage occurred in ten of eleven staged reconstructions. Flap debulking was not reported as a complication in this review. Immediate reconstruction had significantly higher complication rate 36% ($P < 0.001$). Complications included: partial donor site graft loss, flap venous occlusion, tendon adhesions and joint contracture requiring tenolysis and capsulectomy.

Staged reconstruction resulted in significantly more operations 5.2 vs. 1.5 ($P < 0.001$), longer days to maximum ROM 551 vs. 214 ($P < 0.001$), and less percentage returning to work 43% vs. 88% ($P < 0.04$). The staged approach nonetheless resulted in acceptable functional outcomes with no significant difference in total active motion 61 vs. 57 degrees ($P < 0.3$) or grip strength 50% vs. 57% ($P < 0.3$), and no significant complications reported.

Of the immediate single surgery group, 39 were free flaps and 11 were pedicled. In the staged group, 6 were free and 5 were pedicled. When comparing the pedicled vs. free flap surgeries, the pedicled group had a significantly higher metacarpophalangeal total active motion 75 vs. 55 ($P < 0.007$). Differences in the days to maximum ROM, complication rate, and number of operations were not significant however, and there was not enough data to compare grip strength or percent of patients who returned to work in these groups.

DISCUSSION

Our results are concordant with Sundine and Schecker^[24] who found that immediate reconstruction allowed for faster return to maximum ROM, fewer operations, and a greater chance of adequate recovery for vocation. Taylor and Townsend^[6] used a vascularized single-stage reconstruction utilizing a dorsalis pedis free flap, which allows for a one-stage reconstruction for most dorsal hand extensor injuries. The proposed benefit of this technique is transferring tendons with an intact vascular supply and within their tendon sheath which may facilitate faster tendon repair healing, thus allowing for rehabilitation

Table 1. Overview of articles

Author	Adani <i>et al.</i> ^[26,27]	Koul <i>et al.</i> ^[33]	Ulusal <i>et al.</i> ^[19]	Sundine <i>et al.</i> ^[24]	Scheker <i>et al.</i> ^[25]	Al-Qattan ^[29]	Lu <i>et al.</i> ^[17]
# of Patients	12	8	8	14	9	4	6
Type of Surgery	single composite, 7 dorsalis pedis free flap, 5 radial forearm island flap	single, 7 free flap with palmaris longus graft, 1 posterior interosseous artery with palmaris longus graft	single lateral arm composite free flap triceps	7 staged vs. 7 single	single tendon graftstaged, groin flaps	single, posterior interosseous artery	
Average Patient Age	33	29	32	25 vs. 33	38	21	No Data
Average Time to Surgery Post-Injury	14 days	2.3 days	11 days	No Data	Within 24 hours	7 months	No Data
ROM	full MP ROM stiff IPJ case 2	192 at 8 weeks, 237 at 12 weeks, combined 268 at 12 weeks, 274 at 6 months	No Data	51 vs. 56	48	Average 82	No Data
Complications	tenolysis 1/12, hypertrophic scar, donor partial skin graft loss 6/12	no extension lag	two rays, three tenolysis	None	2 complications recorded	None	no tenolysis
Grip Strength	No Data	average 54 at 12 weeks	No Data	Average 50% vs. 53%	Average 60%	No Data	No Data
Follow-up Timing	No Data	No Data	15 months	No Data	No Data	8 months	No Data
Time to Max ROM	No Data	No Data	No Data	630 vs. 214 days	3 months	430 days	No Data
% Returned to Work	No Data	No Data	No Data	43 vs. 86	89	No Data	No Data
Average # of Operations	1.33	1	1.75	6 vs. 2	1.22	4	No Data

ROM: range of motion

Table 2. Comparison of surgical outcomes

Flap Type °	MP TAM (°) (<i>P</i> = 0.3123)	Days to Max ROM * (<i>P</i> < 0.001)	Grip Strength (<i>P</i> = 0.2713)	Complication rate * (<i>P</i> < 0.001)	#Operations * (<i>P</i> < 0.001)	Return to work * (<i>P</i> = 0.0381)
Immediate n 50	56.99	213.86	57%	36%	1.45	88%
Staged n 11	61.39	551.18	50%	0%	5.18	43%
°	*(<i>P</i> = 0.0067)	(<i>P</i> = 0.1610)	°	(<i>P</i> = 0.4740)	(<i>P</i> = 0.0604)	°
Pedicled n 16	75.25	522.4	NR	30%	3.4	NR
Free n 45	55.4	380.62	NR	29%	1.93	NR

ROM: range of motion; #: number of operations; *: *P* < 0.05 considered significant; TAM: total active motion; NR: not recorded

to be initiated earlier. Scheker *et al.* ^[25] reported better function with primary reconstruction, with fewer operations, a shorter hospital stay, minimal complications, and a shorter period of disability. Adani *et al.* ^[26,27] reviewed completely vascularized single stage reconstruction using dorsalis pedis and radial forearm cutaneoutendinous flaps. Our study confirmed that there is significantly less operations required, an earlier return to maximum ROM, and greater chance of returning to work; in contrast to some reports, there was no significant difference in total active motion and significantly more complications reported in immediate reconstruction. Obvious advantages to a single stage technique include avoidings need to re-elevate the flap for tendon graft and the ability to start earlier active ROM rehabilitation. With potential expedition however comes more risk. Considering the significantly higher rate of complications mostly relating to donor site graft loss and delayed healing of foot wounds, the radial forearm flap lends to less donor site morbidity for immediate composite reconstruction.

Multiple staged reconstruction is commonly utilized for large composite defects ^[28]. The procedure allows for wound closure and fracture union while tendon reconstruction is commonly delayed to subsequent procedures. The staged approach resulted in acceptable functional outcomes with no significant difference in total active motion or grip strength and no significant complications. Good to excellent total active motion has previously been reported in two stage technique with rod placement for extensor zone six ^[29].

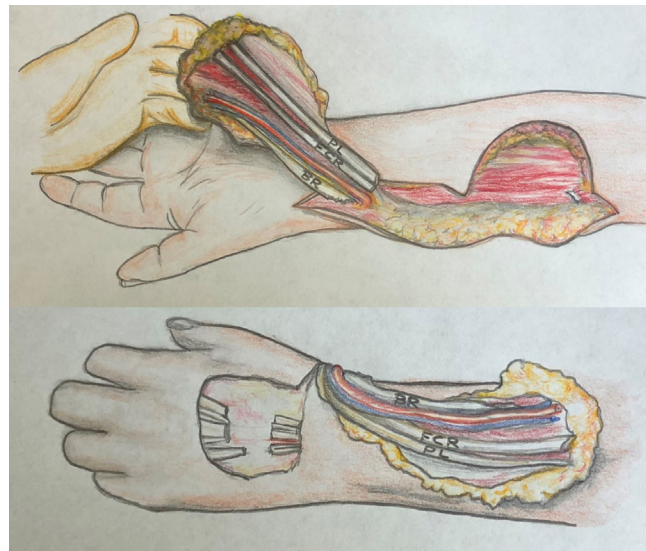


Figure 3. Pedicled composite radial forearm flap with tendon orientation upon transposition

Anterior lateral thigh and lateral arm perforator flaps are considered ideal for coverage of dorsal hand soft tissue defects with minimal donor site morbidity^[30,31]. Due to the varying presentation and degree of severity of these complex injuries, there is vast heterogeneity in the surgical management depicted. Lack of structured data collection and inconsistency in reporting outcomes limits the conclusiveness of retrospective literature review.

Tendon graft is the most common reported staged reconstruction technique; if significantly delayed, myostatic contracture may necessitate a tendon transfer for adequate power. We do acknowledge the variable postoperative protocols and compliance with therapy regimens with retrospective reviews. Early active motion is favored with the lowest rate of extensor lag, averting the need for tenolysis after static splinting. Fortunately, tendon rupture is rare^[32,33]. Available evidence suggests better outcomes with dynamic over static splinting after repair of extensor tendons in Zone V-VIII of the hand^[34,35]. Early mobilization after tendon transfers is also safe and beneficial in the initial rehabilitation phase^[36].

Review of the literature for reconstruction of extensor hand defects provides us with a myriad of different procedural modalities to choose from. The present review was limited by lack of consistent objective measurements. Scrutiny in criteria of data collection refined the specificity and increased the reliability of evidence to draw from. Decreased sensitivity lowered the power of the study; particularly lacking data on staged reconstruction and elicitation of complications. The significantly less operations and earlier time to maximum ROM provide a basis to support and favor the use of single-stage reconstruction. By effect, immediate cutaneous tendinous reconstruction allows for expedited recovery and quicker return to work. These factors correlate with significant decreases in cost and saved productivity for quality of life. Pedicled composite radial forearm flap showed the best potential for total active motions, earlier recovery, and least complications and can include modifications of slips for tendon repair coaptation [Figure 3].

The staged approach nonetheless resulted in acceptable functional outcomes. Choice of staging tendon reconstruction can be justified in certain cases dependent on patient condition and preference.

The algorithm in Figure 4 provides some guidance in choosing the best individualized plan for this challenging problem.

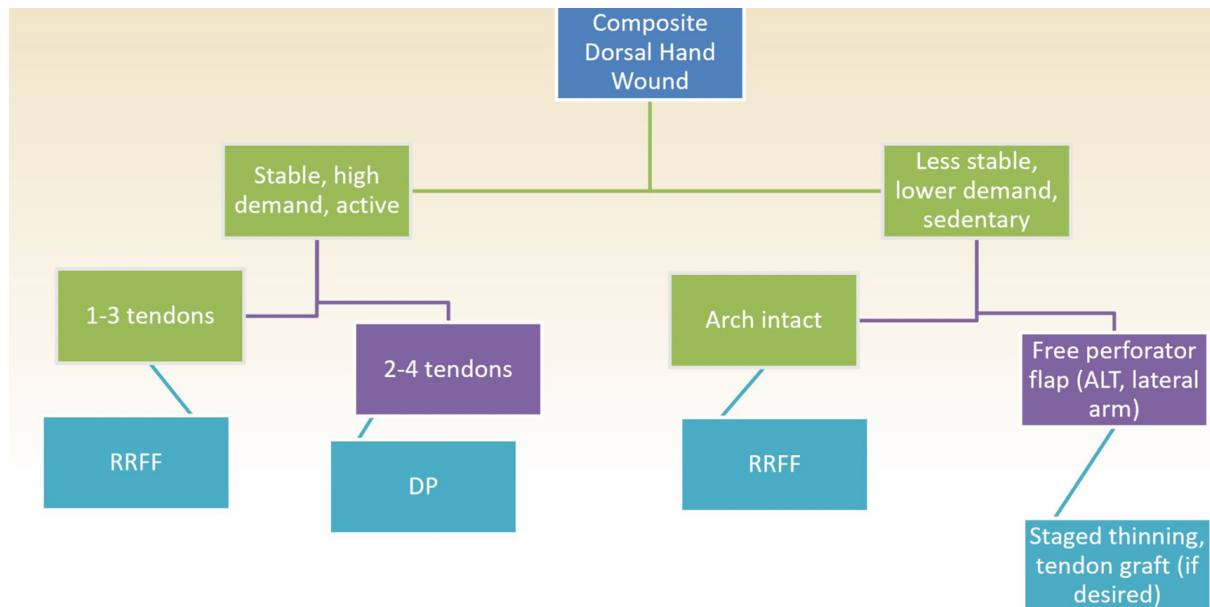


Figure 4. Algorithm for composite dorsal hand wound reconstruction. RRFF: reverse radial forearm flap; DP: dorsalis pedis; ALT: anterolateral thigh

In conclusion, while this study does provide a foundation, further multi-center studies are needed to improve power. Limitations of review include retrospective recall bias, inability to stratify cohorts, variable compliance postoperative rehab regimens, and the lack of objective functional data measurements for comparison between tendon graft and transfers and the need for hunter rod pseudosheath creation. When no extensor tendon reconstruction is performed, compensatory tenodesis effect from scar contracture may be functionally tolerable to the patient. The results of total active motion in these cases are likely not followed. Future studies will look at prospective comparison risk/benefit Hunter rod placement, critical lengths of nonvascularized tendon grafts, as well as a cost analysis to compute the comparative efficacy of immediate reconstruction, particularly factoring in gain of productivity and quality of life factors.

DECLARATIONS

Acknowledgments

Paul J. Weatherby, BS and Pablo L. Padilla, MD University of Texas Medical Branch, 301 University Blvd. Galveston, TX 77555. Paul J. Weatherby and Pablo L. Padilla, assisted with literature review data collection and compilation.

Authors' contributions

Primary author interpretation of results and summarization: Lies S
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 Reviewed manuscript: Lee G
 Edited manuscript: Zhang AY

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Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

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REFERENCES

1. Amirtharajah M, Lattanza L. Open extensor tendon injuries. *J Hand Surg Am* 2015;40:391-7.
2. Lutz K, Pipicelli J, Grewal R. Management of complications of extensor tendon injuries. *Hand Clin* 2015;31:301-10.
3. Carty MJ, Blazar PE. Complex Flexor and Extensor Tendon Injuries. *Hand Clin* 2013;29:283-93.
4. Dessai SS, Chuang DC, Levine SL. Microsurgical reconstruction of the extensor system. *Hand Clin* 1995;11:471-82.
5. Reid DA. Hand Injuries requiring skin-replacement and restoration of tendon function. *Br J Plast Surg* 1974;27:5-18.
6. Taylor GI, Townsend P. Composite free flap and tendon transfer: an anatomical study and clinical technique. *Br J Plast Surg* 1979;6:31-7.
7. Vila-Rovira R, Ferreira BJ, Guinot A. Transfer of vascularized extensor tendons from the foot to the hand with a dorsalis pedis flap. *Plast Reconstr Surg* 1985;76:421-5.
8. Hentz VR, Pearl RM. Hand reconstruction following avulsion of all dorsal soft tissues. A cutaneo-tendinous free tissue transfer. *Ann Chir Main* 1987;6:31-7.
9. Caroli A, Adani R, Castagnetti C, Pancaldi G, Squarzina PB. Dorsalis pedis flap with vascularized extensor tendons for dorsal hand reconstruction. *Plast Reconstr Surg* 1993;92:1326-30.
10. Lee KS, Park SW, Kim HY. Tendocutaneous free flap transfer from the dorsum of the foot. *Microsurgery* 1994;15:882-5.
11. Cho BC, Lee JH, Weinsweig N, Baik BS. Use of free innervated dorsalis pedis tendocutaneous flap in composite hand reconstruction. *Ann Plast Surg* 1998;40:268-76.
12. Reid CD, Moss LH. One-stage flap repair with vascularized tendon grafts in a dorsal hand injury using the "Chinese" forearm flap. *Br J Plast Surg* 1983;36:473-9.
13. Foucher G, Van Genechten F, Merle M, Michon J. A compound radial artery forearm flap in hand surgery: an original modification of the Chinese forearm flap. *Br J Plast Surg* 1984;37:139-148.
14. Yajima H, Inada Y, Shono M, Tamai S. Radial forearm flap with vascularized tendons for hand reconstruction. *Plast Reconstr Surg* 1996;98:328-33.
15. Glasson DW, Lovie MJ. The ulnar island flap in hand and forearm reconstruction. *Br J Plast Surg* 1988;41:349-353.
16. Costa H, Comba S, Martins A, Rodrigues J, Reis J, et al. Further experience with the posterior interosseous flap. *Br J Plast Surg* 1991;44:449-55.
17. Lu LJ, Gong X, Lu XM, Wang KL. The reverse posterior interosseous flap and its composite flap: experience with 201 flaps. *J Plast Reconstr Aesthet Surg* 2007;60:876-82.
18. Gosain AK, Matloub HS, Yousif NJ, Sanger JR. The composite lateral arm free flap: vascular relationship to triceps tendon and muscle. *Ann Plast Surg* 1992;29:496-507.
19. Ulusal BG, Lin YT, Ulusal AE, Lin CH. Free lateral arm flap for 1-stage reconstruction of soft tissue and composite defects of the hand: A retrospective analysis of 118 cases. *Ann Plast Surg* 2007;58:173-8.
20. Zhang WF, Liang F, Li JY, Wang AW, Zhang XF, et al. Repair of tissue defects with free composite anterolateral femoral fascia lata perforator tissue flaps. *Zhonghua Shao Shang Za Zhi* 2013;29:427-31.
21. Cui MY, Shen H. Anterolateral thigh free flap for simultaneous reconstruction of digital extensor tendon and defect of the dorsal hand: A case report. *Chin J Traumatol* 2016;19:309-10.
22. Yazar S, Gideroglu K, Kilic B, Gokkaya A. Use of composite anterolateral thigh flap as double-vascularised layers for reconstruction of complex hand dorsum defect. *J Plast Reconstr Aesthet Surg* 2008;61:1549-50.
23. Schubert CD, Giunta RE. Extensor tendon repair and reconstruction. *Clin Plastic Surg* 2014;41:525-531.
24. Sundine M, Scheker LR. A comparison of immediate and staged reconstruction of the dorsum of the hand. *J Hand Surg Br* 1996;21:216-21.
25. Scheker LR, Langley SJ, Martin DL, Julliard KN. Primary extensor tendon reconstruction in dorsal hand defects requiring free flaps. *J Hand Surg Br* 1993;18:568-75.
26. Adani R, Tarallo L, Castagnetti C, Pancaldi G, Marcoccio I. Tendinous cutaneous dorsal hand injuries. One-stage reconstruction. *Chir Organi Mov* 2002;87:87-95.
27. Adani R, Marcoccio I, Tarallo L. Flap coverage of dorsum of hand associated with extensor tendons injuries: a completely vascularized single-stage reconstruction. *Microsurgery* 2003;23:32-9.
28. Cautilli D, Schneider LH. Extensor tendon grafting on the dorsum of hand in massive tendon loss. *Hand Clin* 1995;11:423-9.
29. Al-Qattan MM. Two-staged extensor tendon reconstruction for zone 6 extensor tendon loss of the fingers: indications, technique and

- results. *J Hand Surg Eur Vol* 2015;40:276-80.
30. Benhaim T, Perignon D, Qassemyar Q, David E, Robbe M, et al. Reconstruction of hand dorsum soft tissue defect using anterolateral thigh perforator flap: description, case study and review of literature. *Chir Main* 2011;30:56-61.
31. Lukas B, Hartl P, BÄcker K. [Soft-tissue reconstruction of the dorsum of the hand and finger to cover the extender tendons]. *Handchir Mikrochir Plast Chir.* 2008;40:110-4.
32. Hammond K, Starr H, Katz D, Seiler J. Effect of aftercare regimen with extensor tendon repair: a systematic review of the literature. *J Surg Orthop Adv* 2012;21:246-52.
33. Koul AR, Patil RK, Philip V. Complex extensor tendon injuries: early active motion following single-stage reconstruction. *J Hand Surg (European Volume)* 2008;33:753-9.
34. Kitis A, Ozcan RH, Bagdatli D, Buker N, Kara IG. Comparison of static and dynamic splinting regimens for extensor tendon repairs in zones V to VII. *J Plast Surg Hand Surg* 2012;46:267-71.
35. Sameem M, Wood T, Ignacy T, Thoma A, Strumas N. A systematic review of rehabilitation protocols after surgical repair of the extensor tendons in zones V-VIII of the hand. *J Hand Ther* 2011;24:365-72.
36. Sultana SS, MacDermid JC, Grewal R, Rath S. The effectiveness of early mobilization after tendon transfers in the hand: a systematic review. *J Hand Ther* 2013;26:1-20.

Editorial

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The key to costal cartilage in rhinoplasty

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Autologous costal cartilage is an excellent source of graft in rhinoplasty due to its rich supply, durability, versatility, and functionality. For a long time, rhinoplasty surgeons have been critical of using autologous costal cartilage based on the potential for associated complications including donor site morbidities, postoperative pain, warping, and long operation time.

Even with this criticism, costal cartilage is still a graft material of choice in cartilage depleting revision rhinoplasty. Recently, there has been a steady increase in costal cartilage use even in primary augmentation rhinoplasty, especially in Asian. This is attributed to the increased awareness of alloplast-associated complications and continuously developed techniques to minimize potential complications and maximize the benefits of costal cartilage.

In this special issue, world-renowned rhinoplasty experts discuss a variety of aspects of costal cartilage use in rhinoplasty. These include preoperative considerations, harvesting and carving techniques, diverse clinical applications, and management of complications in costal cartilage use. As veterans in the field of rhinoplasty, these experts share in great detail invaluable knowledge that can only be attained through extensive clinical experience and continuous effort toward innovation and mastery of their craft.

First, a national survey of current trends in costal cartilage use in rhinoplasty by Clara M. Olcott and Steve J. Pearlman will give us a glimpse of the common practice patterns of using costal cartilage in US facial plastic surgeons. Preoperative considerations focus on determining the availability of the costal cartilage and the site of harvesting. Costal cartilage calcification is not infrequent even in young patients



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and size, shape, and length of straight cartilaginous portion differs greatly from patient to patient. Tips on evaluating and analyzing preoperatively and postoperative care considerations delivered by Jong-Sook Yi will be of great help to the beginning rhinoplasty surgeons.

Recent advances in harvesting techniques focus on the minimal incision and minimal pain. Most surgeons use 3.0 cm or more incision considering the depth of dissection and the size of harvesting cartilage. Minimizing the size of the incision in harvesting was pioneered by Dean Toriumi and he reduced incision size up to 1 cm. Although it is fascinating, it needs experience, skill, and patience, and it is not for all rhinoplasty surgeons. As an alternative, an endoscope harvesting technique by Abdulkadir Goksel also helps to minimize scar and pain.

Reducing the chest pain after harvesting was facilitated by several technical modifications: keeping the underlying perichondrium intact, dissecting and retracting the covering muscles instead of cutting, and harvesting cartilage partially leaving a thin layer of cartilage at the superior and inferior margins. Experts will elaborate in great detail their techniques in terms of reducing postoperative pain.

The carving technique of costal cartilage was the main concern for rhinoplasty surgeons. Warping has been the most criticized point, and the chances increase even more when using the rib for major dorsal augmentation, which is quite common in Asian. A few key techniques to prevent warping including the oblique splitting method by Fazil Apaydin has been introduced in this issue. I hope readers can modify their techniques according to their situation by referring to these articles. Diced cartilage wrapped in temporalis fascia has been popularized by Rollin Daniel. It has been introduced as a solution for warping and its use is slowly increasing. Techniques to avoid drawbacks of dicing method are introduced by young, talented surgeon Donald Yoo.

The final aspect of using costal cartilage is an application of the above-mentioned techniques in diverse patients. Septal application includes splinting, replacement, extension, and spreader grafts. Dorsum and tip applications include augmentation, reinforcement, camouflage, onlay, and strut grafts. Each application has points to be addressed and these are also covered in many case series with illustrative patient photos by Tae-Bin Won and Chuan-Hsiang Kao.

I am confident that this special issue will provide meaningful insight into the diverse aspects of using costal cartilage in rhinoplasty. It is my sincere hope that readers will be able to enhance their skills and integrate this cutting-edge knowledge into their practice to provide patients with the best experience possible.

DECLARATIONS

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Original Article

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Limb preservation with suprafascial and thin perforator flaps: salvaging osteomyelitis, Charcot collapse and critical limb ischemia

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Abstract

Aim: There are limited reports in the United States demonstrating outcomes of primarily thinned fasciocutaneous flaps in the setting of critical limb ischemia, Charcot collapse and osteomyelitis. We hope to determine patient and flap related outcomes in advanced lower extremity disease.

Methods: The authors conducted a retrospective review of fasciocutaneous free flaps of variable thickness for lower extremity salvage. Osteomyelitis and non-osteomyelitis patients were compared according to our primary outcome measures: functional ambulation, bone healing and complications to flap and patient. Subgroups with critical limb ischemia, Charcot collapse and diabetic foot were analyzed separately.

Results: Fifty-nine patients underwent free flap reconstruction: osteomyelitis ($n = 20$, 34%), Charcot collapse ($n = 22$, 37%), and/or critical limb ischemia ($n = 12$, 20%). All patients underwent anterolateral thigh flaps tailored for defect-specific thicknesses: 17 superthin, 25 suprafascial, 17 subfascial. There were no significant differences between groups in terms of partial and complete flap loss ($P = 1.000$ and $P = 0.108$). Ninety-one percent of patients were ambulatory at follow up. Eighty-five percent of individuals with osteomyelitis cleared their infection demonstrating radiographic bone healing. Two patients developed recalcitrant deep space infections ultimately requiring amputation. Subgroup analysis did not show any differences in flap related complications within the diabetic Charcot population. In multivariate regression, preoperative revascularization was independently associated with failure of limb salvage.



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Conclusion: Primarily thinned perforator flaps performed well in the setting of lower extremity limb salvage, critical limb ischemia, osteomyelitis, and the Charcot foot - expanding their role in the armamentarium for lower extremity care.

Keywords: Perforator flap, diabetic foot, limb salvage

INTRODUCTION

Free microvascular tissue transfer in combination with aggressive debridement, targeted antimicrobial therapy, optimization of distal perfusion and boney stabilization remains a powerful tool to heal lower extremity wounds with osteomyelitis - restoring functional ambulation^[1-3]. Godina along with Mathes described the role of muscle-flap coverage for high-energy wounds with infected bone almost 40 years ago. They achieved an 89% infection clearance rate^[4]. Numerous authors have demonstrated similar results^[1-7]. Lower extremity salvage in the setting of high-energy trauma, critical limb ischemia and the diabetic foot often includes management of denuded and dysvascular bone with variable degrees of osteomyelitis ranging from superficial contamination, to deeper medullary involvement, from localized to diffuse infections described by the four-tiered Cierny-Mader classification^[8,9]. Traditionally muscle-bearing flaps were used to create a local tissue environment conducive to healing and fill-in tissue dead-space. Muscle has been thought of as more effective than fasciocutaneous flaps in overcoming bacterial colonization and infection due to improved oxygen delivery and restoration of wound bed perfusion^[2,3,6,10]. However this has been refuted over the past decade by a number of authors^[3,5,7,11].

Over time, a deeper understanding of perforator anatomy^[12], microsurgical technical refinements^[13-16], perioperative protocols and improved instrumentation has empowered reconstructive surgeons to reliably utilize skin-only and fasciocutaneous flaps for coverage of lower extremity defects^[17]. Nonetheless, challenges remain as traditional perforator-based flap thickness can interfere with post-operative function, particularly in the lower extremity, wherein bulky, thick, flaps can interfere with footwear, contour across joints, irregular weight bearing surface and can lead to flap breakdown^[2,13,14]. Technical refinements in anterolateral thigh (ALT) harvest offer reliable methods to achieve thinner flaps, minimizing debulking procedures, improving contour and decreasing donor morbidity.

Recent reports consistently demonstrate that elevation of the ALT flap in different planes allow for the possibility of safe, consistent, and definitive distal extremity reconstruction in a single stage^[15,18,19]. However, limited data exists for successful limb salvage with use of thin fasciocutaneous flaps in the setting of osteomyelitis, limb ischemia and the Charcot foot. Our goal is to describe the routine use of the primarily thinned ALT flap in varying thicknesses for lower limb salvage surgery, and to assess outcomes in patients at high risk for failure.

METHODS

Patient data

All lower extremity free flaps performed at a single, Level 1 medical center were entered into a prospectively maintained registry including patient demographic information, clinical history, radiographic imaging, procedural data, operative reports, postoperative care and long-term complications across 116 unique variables. A REDCap database was utilized as a secure web-based application for data maintenance. A trained member of the research team uploads data once monthly. Follow up radiographic reports and clinic visits are specifically analyzed to identify limb salvage failure, nonunion, malunion, osteomyelitis, flap failure, wound recurrence, patient ambulation, use of assistive devices, patient disposition and rates of amputation. The database is maintained via institutional review board approval.



Figure 1. Superficial osteomyelitis managed with suprafascial anterolateral thigh. A patient with Cierny-Mader Class 2 osteomyelitis of the calcaneus. A: A preoperative photo; B: immediate post flap photo; C: pre flap radiography with osteomyelitis; D: six-month follow up photo with clearance of osteomyelitis. The patient was weight bearing at time of follow up

For the purposes of this study, the database was queried in June 2018 for cases performed from January 2015 to December 2017. We excluded muscle flaps and skin-only or fasciocutaneous flaps other than ALT's. Of 84 patients who underwent lower extremity free-tissue with ALT flaps, we excluded 25 individuals without high risk factors. This left 59 patients selected for at least one of the following features: osteomyelitis, Charcot collapse, and critical limb ischemia.

For each patient, relevant demographic information, comorbidities, presence of peripheral vascular disease, revascularization, antibiotic use, anticoagulant use, wound etiology, pre-operative imaging, anatomical wound location, skeletal fixation, flap thickness, operative characteristics, complications and follow-up were reviewed.

Osteomyelitis was defined as tissue-proven bony infection via histological analysis and bony tissue culture obtained at the time of flap coverage in the case of single-staged reconstructions and or prior to reconstruction from bone biopsy. Clinical, radiographic, microbiological information was gathered.

Patients were separated based on the Cierny-Mader classification system defining the depth as well as diffusion of osteomyelitis^[8,9,20]. Patients with Charcot collapse, critical limb ischemia (defined by vascular imaging proven: single vessel run-off, multi-level or multivessel arterial disease) and diabetes mellitus were separated into a subgroup for analysis of their unique pathophysiology.

Reconstructive technique

Patients were separated for analysis into groups based on flap thickness: periscarpal (superthin), suprafascial and subfascial (thick). During the period of study, no muscle-flaps were utilized. We relied uniformly on skin-only and fasciocutaneous flaps. Flap thickness was tailored to match defect surface contour and volume of dead space.

Figures 1-3 demonstrate case based examples of our reconstructive technique. ALT flap thickness for each case was determined by defect thickness, need to fill deadspace and correlates with Cierny classification of Osteomyelitis.

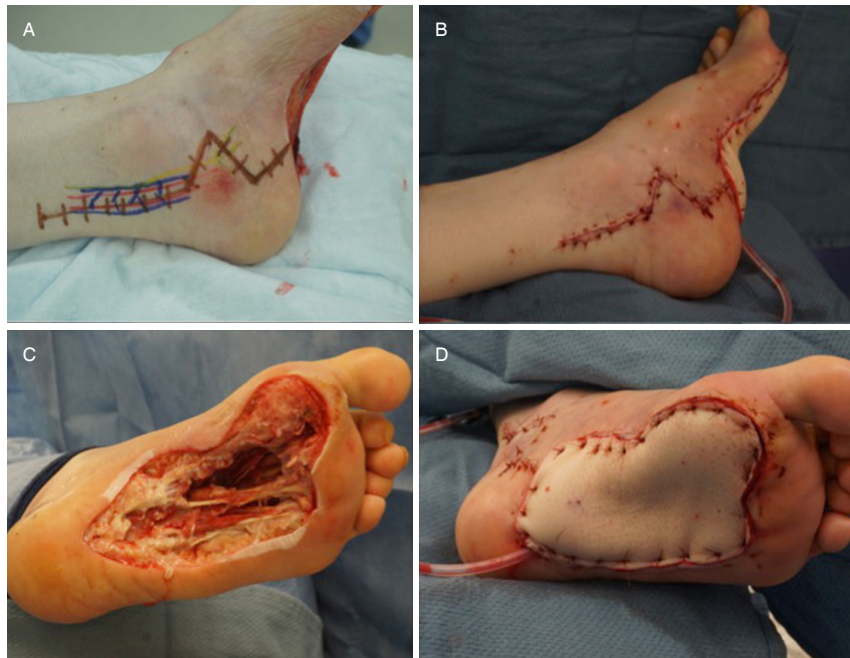


Figure 2. Deep Space Infection and Charcot Foot treated with Subfascial anterolateral thigh (ALT). A patient with plantar weight bearing soft tissue loss after deep space diabetic foot infection. A: Preoperative lateral view showing Bruner incision for tarsal tunnel release, vessel harvest and tibial neurolysis; B: lateral clinical photography after inset and closure of Bruner incision with mid-foot plantar arch contouring; C: preoperative view of the plantar surface; D: after subfascial ALT for coverage and lateral femoral cutaneous nerve coaptation to plantar branch of the tibial nerve. The crural fascia was inset well beyond the skin incision margin. The patient was successfully weight bearing 11 weeks post-operatively

Our technique for elevation in the desired plane has been previously described^[15,16]. Superthin flaps were defined as those elevated at the superficial scarpal fascia within the subcutaneous fat. Suprafascial flaps were defined as flaps elevated just above the crural fascia and subfascial flaps were those elevated below the crural fascia and/or deep muscular fascia^[2]. Defects with bone-loss requiring spacer placement and or bone grafting for management of later stage III, IV Cierny-Mader osteomyelitis often required thicker flaps to fill-in dead space. As such, subfascial ALT flaps were harvested to assist filling dead-space and or to contour deeper defects. However, we preferentially utilized a superthin elevation for reconstruction of weight bearing surfaces along the heel, mid-foot, dorsal-foot and ankle region. Earlier stage Cierny-Mader Osteomyelitis being cortical, focal medullary involvement resulted in superficial boney defects often amenable to coverage with super-thin flaps.

The major tenets of lower extremity salvage were regarded as appropriate debridement to perfused tissue, preservation of vital structure, muscle, nerve and tendon along with isolation and control of major vascular inflow. Wounds amenable to local tissue reconstruction with advancement flaps, skin-graft, regional pedicle flaps, freestyle propeller flaps were utilized when-able but were excluded from this study.

During free tissue transfer, we preferentially performed end-end anastomosis in patients with adequate runoff and normal vascular supply. However, in patients with peripheral vascular disease, single-vessel runoff, multi-vessel or multi-level flow limiting lesions, end to side anastomosis was performed to maintain in-line perfusion distal to the reconstruction. Venous outflow was preferentially based on the deep venous system with emphasis on vessel quality, size-match, lack of back-bleeding, avoidance of venous hypertension over absolute number of venous anastomosis.

An enhanced recovery protocol was utilized for the majority of our patients including the use of regional anesthetic block achieved via continuous peripheral nerve catheter placed in the popliteal region



Figure 3. A case of Calcaneal Osteomyelitis treated with superthin anterolateral thigh (ALT) flap. A patient with Cierny-Mader class 3 osteomyelitis with calcaneal and proximal mid-foot erosions seen on (A) preoperative radiography. This required bony debridement and soft tissue coverage with superthin ALT in single-stage; (B) shows postoperative radiography with clearance of osteomyelitis; (C) demonstrating superthin (periscapal) ALT; (D) after final inset and small skin graft for coverage of the vascular pedicle. This resulted in full-ambulation in normal shoe gear

targeting the sciatic, tibial and peroneal nerves when appropriate. This achieved decreased rates of post-operative narcotic use and shorter post-anesthesia unit stays^[21]. Additionally an early limb dependency program^[22] helped patients dangle early in their post-operative course expediting hospital stay, discharge to rehabilitation facilities, and return toward functional ambulation.

Outcome measures

Outcomes pertaining to flap specific morbidity such as partial flap loss, microvascular collapse, vessel thrombosis, site infection and dehiscence were analyzed in addition to systemic complications.

With regard to osteomyelitis, discontinuation of antibiotic, achievement of bony union, return to weight bearing, exchange of external for internal hardware and radiography were analyzed. Return to functional ambulation, weight bearing and avoidance of amputation were compared across all groups.

Statistical analysis

Descriptive statistics were utilized to compare patient demographic information in regard to number, frequency, mean and standard deviation. Student *t*-test for continuous data and Fischer's exact test for categorical data were used for univariate analysis to determine significant differences in wound and flap characteristics along with donor site and flap complications between groups of patients. Those variables achieving significance P -value < 0.05 were entered into a multivariable regression model to identify independent risk factors associated with limb loss and osteomyelitis recurrence. Statistical significance was defined as a P -value < 0.05 . The analysis was performed using IBM SPSS software by members of our research group within the institution (Version 3.154).

RESULTS

A total of 59 ALT flaps were performed from January 2015 to December 2017 for lower extremity salvage reconstruction. The mean follow-up time of our population was 13.8 months (2.24-39.2 months). Flaps

Table 1. Patient characteristics and univariate comparison based on the presence of osteomyelitis

	Osteomyelitis <i>n</i> = 20	No osteomyelitis <i>n</i> = 39	<i>P</i> -value
Age	51.95 ± 13.65	52.3 ± 13.44	0.918
Sex (%)			0.192
Male	18 (90)	29 (74.4)	
Female	2 (10)	10 (25.6)	
BMI	31.53 ± 6.80	28.10 ± 4.71	0.026
Smoking history (%)	6 (30.0)	17 (43.6)	0.311
Hypertension (%)	9 (45.0)	10 (25.6)	0.132
Diabetes (%)	9 (45.0)	13 (33.3)	0.380
Coronary artery disease (%)	5 (25.0)	3 (7.7)	0.106
Peripheral artery disease (%)	6 (30.0)	9 (23.1)	0.563
Renal disease (%)	1 (5.0)	3 (7.07)	1.000
Malnourished (Albumin < 3.5 g/dL) (%)	6 (30.0)	5 (12.8)	0.159
Multiple comorbidities (%)	10 (50.0)	23 (59.0)	0.511
Preoperative antithrombotic use (%)	20 (100.0)	38 (97.4)	1.000
Preoperative antiplatelet use (%)	12 (60.0)	27 (69.2)	0.478
Chemotherapy (%)	1 (5.0)	3 (7.7)	1.000
Radiation (%)	1 (5.0)	3 (7.7)	1.000
Prior revascularization (open or endovascular) (%)	6 (30.0)	3 (7.7)	0.050
Vascular imaging (%)	13 (65.0)	22 (56.4)	0.525
Prior amputation level (%)	2 (10.0)	0 (0.0)	0.111

Table 2. Wound, flap and anastomotic characteristics with univariate comparison between groups of patients based on the presence of osteomyelitis

	No.	%	Osteomyelitis (<i>n</i> = 20)	No osteomyelitis (<i>n</i> = 39)	<i>P</i> -value
Type of wound (%)					
Traumatic	30	50.8	7 (35.0)	23 (59.0)	0.081
Malignant	5	8.5	0 (0.0)	5 (12.8)	0.156
Chronic (> 90-day)	24	40.7	13 (65.0)	11 (28.2)	0.006
Wound location					
Foot	24	40.7	8 (40.0)	16 (41.0)	0.939
Ankle	14	23.7	5 (25.0)	9 (23.1)	1.000
Calf	13	22.0	4 (20.0)	9 (23.1)	1.000
Shin	3	5.1	1 (5.0)	2 (5.1)	1.000
Knee	4	6.8	2 (10.0)	2 (5.1)	0.598
Thigh	1	1.7	0 (0.0)	1 (2.55)	0.544
Flap type					
Superthin	17	28.8	8 (40.0)	9 (23.1)	0.174
Suprafascial	25	42.4	8 (40.0)	17 (43.6)	0.792
Subfascial	17	28.8	4 (20.0)	13 (33.3)	0.284
Anastomosis					
End to End	42	76.4	15 (75.0)	27 (77.1)	1.000
End to Side	13	23.6	5 (25.0)	8 (22.9)	1.000

were elevated in three major planes: superthin (17 patients, 29%), suprafascial (25 patients, 42%) and subfascial (17 patients, 29%). Twenty patients (34%) had tissue-proven osteomyelitis. When separated into groups based on the presence of osteomyelitis, patients were well-matched across 116 variables. Select comparisons are shown in Table 1. Individuals with osteomyelitis had higher average BMI ($P = 0.03$) and a greater incidence of previous vascular interventions ($P = 0.05$).

Table 2 describes wound characteristics and locations. Traumatic injury was the most common type of wound etiology in both osteomyelitis and non-osteomyelitis groups (51%) followed by chronic wound and malignant wounds (40% and 9%, respectively). Chronic wounds were defined as an established wound despite attempts at local or surgical wound care, offloading, and medical comorbidity management past 90-days. The foot and ankle were the most common recipient site for the ALT flaps. The distributions of ALT thickness type across osteomyelitis as well as non-osteomyelitis groups were comparable.

Table 3. Flap complication and reported Limb salvage rates

	Total N N.59 = 59	Osteomyelitis N.20N = 20	CLI ¹ N.12 = 12	Charcot N.22	P-value ²
Ambulatory	54 (91%)	17 (85%)	10 (83%)	20 (90%)	0.110
Non-ambulatory	5 (9%)	3 (15%)	2 (17%)	2 (9.1%)	0.217
Amputation	2 (3.4%)	2 (10%)	2 (17%)	2 (9.1%)	0.252
Amputation free	57 (96.6%)	18 (90%)	10 (83%)	20 (90%)	
Osteomyelitis clearance		18 (90%)	10 (83%)	18 (81%)	
Flap complication	18 (30%)	8 (40%)	5 (42%)	7 (31.8%)	0.260
Complete flap loss	4 (6.8%)	1 (5%)	0 (0%)	0 (0%)	0.699
Partial flap loss	3 (5.1%)	1 (5%)	2 (17%)	2 (9.1%)	0.983
Flap infection	4 (6.8%)	2 (10%)	1 (8.3%)	1 (4.5%)	0.598
Dehiscence	6 (10.2%)	1 (5%)	1 (8.3%)	4 (18.2%)	0.653
Flap revision	9 (15%)	1 (5%)	1 (8.3%)	0 (0%)	0.841

¹CLI: critical limb ischemia, defined as patients with at least one of the following: single-vessel runoff, severe peripheral vascular disease, multi-vessel arterial disease, multi-level arterial disease; ²P-values reported after univariate comparison of patients with Osteomyelitis to those without across all outcomes

Overall donor site complication rates were as follows: seroma, 5% ($n = 3$); neuropathy, 5% ($n = 3$); contour irregularity, 3.4% ($n = 2$); and site infection, 3.8% ($n = 2$). No differences in donor site complication rates were noted between groups. Flap complication rates including complete flap loss, partial flap loss, wound dehiscence and flap infection were 6.8%, 5.1%, 10.2%, and 6.8%, respectively. Again, no significant differences between groups were noted. Table 3 demonstrates complication rates across high-risk individuals harboring critical limb ischemia, Charcot foot, and osteomyelitis. Eight flap revisions were needed, none of which were related to an osteomyelitis recurrence.

Sub-group analysis in the diabetic population revealed no cases of complete flap loss, two cases of partial flap loss, four cases of wound dehiscence and one of flap infection, complication rates of 0.0%, 9.1%, 18.2% and 4.5%, respectively [Table 3]. No differences between the osteomyelitis and non-osteomyelitis groups within the diabetic population were noted. Our sub-group analysis demonstrated comparable outcomes amongst a group of diabetic patients with osteomyelitis and Charcot foot.

Table 4 describes variegations in the osteomyelitis group and associated salvage rates. Cierny-Mader osteomyelitis class, flap type and presence of comorbidity did not significantly alter osteomyelitis clearance ($P > 0.05$) for each univariate comparison.

A multivariable regression was performed after stepwise entry of variables associated with limb-loss and amputation with ($P < 0.1$). Preoperative revascularization was independently associated with limb loss OR 6.1 ($P < 0.05$). Osteomyelitis, Charcot foot, diabetes, the presence of critical limb ischemia, and flap elevation plane were not in and of themselves independently associated with limb loss.

DISCUSSION

In this study of lower extremity free tissue transfers with ALT flaps, we compared complication rates and outcomes across three elevation planes in settings of osteomyelitis, charcot collapse and critical limb ischemia. We did not find any significant differences between the groups using either one of the three planes of elevation in terms of major complication as flap revision, flap infection; wound dehiscence, partial and complete flap loss. Important to note, the distribution of flap types between groups harboring osteomyelitis was comparable (superthin: $P = 0.174$; suprafascial: $P = 0.792$; and subfascial: $P = 0.284$). Interestingly, there were no differences between major flap complications within the diabetic population and Charcot foot. These findings further support the use of skin-only and fasciocutaneous flaps in the setting of osteomyelitis. We demonstrate that thin flaps can assist in boney healing and clearance of infection despite a lower metabolic demand compared to muscle flaps.

Table 4. Characteristics of 20 patients who underwent perforator based flaps for treatment of lower extremity osteomyelitis

	No.	(%)	Clearance ^a
Soft tissue defect location			
Calf/Knee	7	35	7 (100%)
Ankle	5	25	4 (80%)
Foot	8	40	7 (87.5%)
Bone involved			
Tibia	5	25	5 (100%)
Fibula	2	10	2 (100%)
Calcaneus	5	25	4 (80%)
Ankle mortis/carpus	6	30	6 (100%)
Metatarsal/phalangeal	2	10	1 (50%)
Tissue based diagnosis	20	100	
Ciernes-Mader classification			
I - Superficial	12	60	12 (100%)
II - Medullary	3	15	2 (67%)
III - Isolated (Sequestrum)	1	5	1 (100%)
IV - Diffuse	4	20	1 (75%)
Hardware present and kept in place	(4/4)	100	4 (100%)
External fixator present	2	10	2 (100%)
Microorganism			
Staph epidermidis, coagulase negative staph. MSSA	13	65	12 (92%)
MRSA	1	5	1 (100%)
Enterobacter	2	10	2 (100%)
Streptococcal	1	5	1 (100%)
Corynebacterium	1	5	1 (100%)
Proteus sp.	1	5	0 (0%)
Stenotrophomonas	1	5	1 (100%)
Flap thickness			
Subfascial (Thick)	4	20	4 (100%)
Suprafascial	6	30	5 (83%)
Superthin (Periscapal)	10	50	9 (90%)
Bone union achieved across fracture line	(8/9)	89%	
External fixator exchanged for internal hardware or removed	(2/2)	100%	
Amputation	2	10	
Radiographically healed compared to preoperative	(7/9)	78%	
Osteomyelitis recurrence	2	10%	

^aOsteomyelitis clearance as defined by lack of local recurrence of bony osteomyelitis, discontinuation of antibiotic, healed soft-tissue envelope, clearance of deep-space infection

In subgroup analysis of our highest risk populations nine diabetic patients had osteomyelitis and three more had critical limb ischemia. Although this is a small sample size, outcomes in this population are mixed: none experienced recurrence of osteomyelitis defined as clinical evidence of bone infection by clinical exam, radiography or tissue pathology within the surgical site; five of our patients were fully weight-bearing in less than four months while three of them never fully ambulated due to conservative management of secondary ulcers in the same extremity, and one patient went on to amputation due to severe peripheral artery disease. Only one flap loss occurred due to extensive arterial thrombosis despite early intervention within the osteomyelitis group [Table 3].

Microvascular tissue transfer in high-risk individuals harboring vascular disease, osteomyelitis and the Charcot foot improves upon outcomes achieved with alternative standard of care pathways. Revascularization alone as demonstrated in the “Bypass versus Angioplasty in Severe Ischemia of the Leg Trial” (BASIL Trial) [23] offers limited salvage rates with shortened up overall amputation-free survival and mortality when compared to revascularization plus wound directed reconstructive surgery. Of 250 patients

enrolled and randomized with critical limb ischemia to either open or endovascular revascularization at a mean 3.1 year follow-up: the trial showed a 56% mortality rate, 38% amputation-free survival and thirty patients and (7%) living with an amputation. This of course represents a morbid group of individuals meeting particular selection criteria of the trial, many of whom may be precluded from the surgical stress of free tissue transfer. However, when wound-directed therapy with Integra Bilayer Wound Matrix (Integra Lifesciences, Plainsboro NJ) and skin graft was added to a similar group of individuals, Iorio *et al.*^[24] improved limb salvage rates. Limb survival was compared across 105 individuals with 121 foot/ankle wounds according to tissue type exposed and presence of high-risk factors: 61% of those with bone exposure and osteomyelitis were salvaged, 71% of diabetic wounds were salvaged and 59% of diabetics with bone involvement avoided amputation. When provided with thin perforator flaps at our center (18/20) 90% of individuals avoided amputation with osteomyelitis, (21/22) 92%, of diabetics were salvaged, all of whom were high-risk for amputation, and 89% (8/9) of individuals with both diabetes and osteomyelitis avoided amputation.

Hong *et al.*^[2] demonstrated a survival benefit over time in 2016 while utilizing the “Angiosome and Supermicrosurgery Concept” principle and techniques for the management of diabetic foot wounds. Hong *et al.*^[2] salvaged 84.9% of individuals over five-year follow-up. However, Dr. Hong also noted limited success in those individuals requiring preoperative revascularization. During a regression analysis, revascularization was associated with limb-loss independent of other high-risk features similar to our findings. We came to similar findings as Dr. Hong’s with regard to limb ischemia requiring revascularization-lending caution to future patient selection.

With regard to osteomyelitis, flap coverage has been widely studied by several groups over the last four decades^[25,26]. In 1982, Chang and Mathes^[10] described 21 patients with chronic osteomyelitis who underwent muscle flap coverage with a success rate of 90%, two patients (10%) developed recurrent infection postoperatively^[11]. Then, in 1991 James *et al.* demonstrated the long term effect of muscle flap coverage in the management of 34 patients with chronic osteomyelitis with 89% of success rate over a long-term follow up (> 5 years, mean 7.4 years). Reconstructive surgeons readily accepted muscle flaps as a standard for management of Gustillo IIIB defects with osteomyelitis in the 1990’s. Eventually fasciocutaneous flaps started to make a presence in the early 2000’s. Salgado *et al.*^[1] demonstrated in animal model that both muscle and non-muscle flaps provide a viable option for wound coverage of osteomyelitis defects. A recent publication by Hong *et al.*^[3] assessed the efficacy of perforator flaps in the treatment of chronic osteomyelitis in a retrospective study including 120 patients who underwent reconstruction for chronic osteomyelitis of the lower extremity; their flap loss rate was 4.2% and partial flap loss rate of 8.3% with remission rate of 91.6% in one-stage reconstruction. These findings in line with ours in terms of 6.8% rate of flap loss overall and 5% rate of partial flap loss in the osteomyelitis group. Hong *et al.*^[2] utilized 30 superficial circumflex iliac (SCIP) flaps, 1 thoracodorsal artery perforator (TDAP), and 41 ALT flaps but did not describe the plane of elevation. With our contribution of 16 superthin (N. 10) and suprafascial (N. 6) ALT’s utilized for osteomyelitis, we estimate the number of published reports of utilizing superthin (periscapal) and suprafascial flaps for the management of osteomyelitis is in the range of 50-100 worldwide to date.

Notable limitations of this study include our small sample size lending to type 1 error in the comparison of moderate-sized groups of patients with low overall complication rates - necessitating larger numbers to strongly power our conclusions over time. We uniformly relied on the ALT flap at our institution for wounds necessitating coverage by free tissue transfer, which assists in limiting selection biases but is of course a unique practice. The unique referral pattern from foot and ankle surgery, podiatry and vascular surgery along with availability to perform free-tissue transfer in this setting may also be difficult to repeat across centers. This study does not include a number of patients managed by local pedicled flaps, skin grafts, dermal substitutes and local tissue rearrangement. Our limited mean follow-up of 13.8 months

does not fully capture limb salvage rates particularly in individuals with osteomyelitis who can go on to recur after one year and or those with critical limb ischemia whose disease is not reversed by flap coverage. We also have not explored basic laboratory, animal research or clinical pathologic review facets of fasciocutaneous flaps that promote wound healing. Thus we can comment very little the physiologic basis of our findings. This certainly will be an avenue of further pursuit. Further, this nonrandomized single-site study carries potential selection and treatment biases inherent in unique to the surgeon and institutions practices. However, it is our hope that with further multi-institutional participation, presentation and publication, particularly to our podiatry, vascular surgery and orthopedic colleagues that we can expand our practice and move from small scale low-power studies to larger powered research - working toward prospective trial. This will be particularly helpful in those patients requiring revascularization by either open or endovascular means to delineate selection of patients fit for free tissue transfer and the timing of such interventions.

The superthin, suprafascial and subfascial variations of the ALT flap, are reliable, safe and effective options for lower limb salvage surgery in the setting of osteomyelitis, limb preservation and Charcot collapse. Incorporating these flaps widens the reconstructive surgeon's armamentarium to replace like tissue, avoid a muscle-flap donor, improve contour, shoe gear and allow bony healing - translating to healthy weight bearing limbs and restoring ambulation^[27]. Limb ischemia necessitating revascularization prior to flap reconstruction remains a major risk factor for limb loss, particularly in the patient with concomitant osteomyelitis.

DECLARATIONS

Authors' contributions

Study design: Diamond S, Doval AF, Iorio ML

Manuscript preparation: Diamond S, Iorio ML

Data acquisition: Diamond S, Doval AF, Scott B

Data analysis: Scott B

Availability of data and materials

IRB approved retrospective study based on BIDMC hospital charted data.

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Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

IRB approval prior to data acquisition and study design.

Consent for publication

An informed consent for publication has been taken from the patients.

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REFERENCES

1. Salgado CJ, Mardini S, Jamali AA, Ortiz J, Gonzales R, et al. Muscle versus nonmuscle flaps in the reconstruction of chronic osteomyelitis defects. *Plast Reconstr Surg* 2006;118:1401-11.

2. Hong JP. Reconstruction of the diabetic foot using the anterolateral thigh perforator flap. *Plast Reconstr Surg* 2006;117:1599-608.
3. Hong JPJ, Goh TLH, Choi DH, Kim JJ, Suh HS. The efficacy of perforator flaps in the treatment of chronic osteomyelitis. *Plast Reconstr Surg* 2017;140:179-88.
4. Anthony JP, Mathes SJ, Alpert BS. The muscle flap in the treatment of chronic lower extremity osteomyelitis: results in patients over 5 years after treatment. *Plast Reconstr Surg* 1991;88:311-8.
5. Sofiadellis F, Liu DS, Webb A, Macgill K, Rozen WM, et al. Fasciocutaneous free flaps are more reliable than muscle free flaps in lower limb trauma reconstruction: experience in a single trauma center. *J Reconstr Microsurg* 2012;28:333-40.
6. Suh HS, Oh TS, Lee HS, Lee SH, Cho YP, et al. A new approach for reconstruction of diabetic foot wounds using the angiosome and supermicrosurgery concept. *Plast Reconstr Surg* 2016;138:702e-9.
7. Yazar S, Lin CH, Lin YT, Ulusal AE, Wei FC. Outcome comparison between free muscle and free fasciocutaneous flaps for reconstruction of distal third and ankle traumatic open tibial fractures. *Plast Reconstr Surg* 2006;117:2468-75; discussion 2476-7.
8. Lazzarini L, Mader JT, Calhoun JH. Osteomyelitis in long bones. *J Bone Joint Surg Am* 2004;86:2305-18.
9. Schmitt SK. Osteomyelitis. *Infect Dis Clin North Am* 2017;31:325-38.
10. Chang N, Mathes SJ. Comparison of the effect of bacterial inoculation in musculocutaneous and random-pattern flaps. *Plast Reconstr Surg* 1982;70:1-10.
11. Paro J, Chiou G, Sen SK. Comparing muscle and fasciocutaneous free flaps in lower extremity reconstruction--does it matter? *Ann Plast Surg* 2016;76 Suppl 3:S213-5.
12. Saint-Cyr M, Wong C, Schaverien M, Mojallal A, Rohrich RJ. The perforasome theory: vascular anatomy and clinical implications. *Plast Reconstr Surg* 2009;124:1529-44.
13. Hong JP, Chung IW. The superficial fascia as a new plane of elevation for anterolateral thigh flaps. *Ann Plast Surg* 2013;70:192-5.
14. Hong JP, Choi DH, Suh H, Mukarramah DA, Tashti T, et al. A new plane of elevation: the superficial fascial plane for perforator flap elevation. *J Reconstr Microsurg* 2014;30:491-6.
15. Diamond S, Seth AK, Chattha AS, Iorio ML. Outcomes of subfascial, suprafascial, and super-thin anterolateral thigh flaps: tailoring thickness without added morbidity. *J Reconstr Microsurg* 2018;34:176-84.
16. Seth AK, Iorio ML. Super-thin and suprafascial anterolateral thigh perforator flaps for extremity reconstruction. *J Reconstr Microsurg* 2017;33:466-73.
17. Demirtas Y, Kelahmetoglu O, Cifci M, Tayfur V, Demir A, et al. Comparison of free anterolateral thigh flaps and free muscle-musculocutaneous flaps in soft tissue reconstruction of lower extremity. *Microsurgery* 2010;30:24-31.
18. Chen YC. Reply: suprafascial anterolateral thigh flap dissection: limits and advantages. *Plast Reconstr Surg* 2016.
19. Chen YC, Scaglioni MF, Carrillo Jimenez LE, Yang JC, Huang EY, et al. Suprafascial anterolateral thigh flap harvest: a better way to minimize donor-site morbidity in head and neck reconstruction. *Plast Reconstr Surg* 2016;138:689-98.
20. Giurato L, Meloni M, Izzo V, Uccioli L. Osteomyelitis in diabetic foot: a comprehensive overview. *World J Diabetes* 2017;8:135-42.
21. Ruan QZ, Diamond S, Zimmer S, Iorio ML. Assessing the safety and efficacy of regional anesthesia for lower extremity microvascular reconstruction: enhancing recovery. *J Reconstr Microsurg* 2018;34:293-9.
22. Seth AK, Diamond S, Iorio ML. Outcomes of an early protocol for dependent conditioning in lower extremity microsurgical free flaps. *J Reconstr Microsurg* 2017;33:670-8.
23. Bradbury AW, Adam DJ, Bell J, Forbes JF, Fowkes FG, et al. Bypass versus angioplasty in severe ischaemia of the leg (BASIL) trial: analysis of amputation free and overall survival by treatment received. *J Vasc Surg* 2010;51(5 Suppl):18S-31.
24. Iorio ML, Goldstein J, Adams M, Steinberg J, Attinger C. Functional limb salvage in the diabetic patient: the use of a collagen bilayer matrix and risk factors for amputation. *Plast Reconstr Surg* 2011;127:260-7.
25. Hallock GG. A paradigm shift in flap selection protocols for zones of the lower extremity using perforator flaps. *J Reconstr Microsurg* 2013;29:233-40.
26. Sisti A, D'Aniello C, Fortezza L, Tassinari J, Cuomo R, et al. Propeller Flaps: a literature review. *In Vivo* 2016;30:351-73.
27. Maruccia M, Fallico N, Cigna E, Ciudad P, Nicoli F, et al. Suprafascial versus traditional harvesting technique for free antero lateral thigh flap: a case-control study to assess the best functional and aesthetic result in extremity reconstruction. *Microsurgery* 2017;37:851-7.

Review

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Tissue engineering in mandibular reconstruction: osteogenesis-inducing scaffolds

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Abstract

Currently, the gold standard for aesthetic and functional reconstruction of critical mandibular defects is an autologous fibular flap; however, this carries risk of donor site morbidity, and is not a promising option in patients with depleted donor sites due to previous surgeries. Tissue engineering presents a potential solution in the design of a biomimetic scaffold that must be osteoconductive, osteoinductive, and support osseointegration. These osteogenesis-inducing scaffolds are most successful when they mimic and interact with the surrounding native macro- and micro-environment of the mandible. This is accomplished via the regeneration triad: (1) a biomimetic, bioactive osteointegrative scaffold, most likely a resorbable composite of collagen or a synthetic polymer with collagen-like properties combined with beta-tri calcium phosphate that is 3D printed according to defect morphology; (2) growth factor, most frequently bone morphogenetic protein 2 (BMP-2); and (3) stem cells, most commonly bone marrow mesenchymal stem cells. Novel techniques for scaffold modification include the use of nano-hydroxyapatite, or combining a vector with a biomaterial to create a gene activated matrix that produces proteins of interest (typically BMP-2) to support osteogenesis. Here, we review the current literature in tissue engineering in order to discuss the success of varying use and combinations of scaffolding materials (i.e., ceramics, biological polymers, and synthetic polymers) with stem cells and growth factors, and will examine their success *in vitro* and *in vivo* to induce and guide osteogenesis in mandibular defects.

Keywords: Osteogenic scaffolds, mandibular reconstruction, tissue engineering, regeneration triad, bone morphogenetic protein, bone marrow mesenchymal stem cells, beta-tri calcium phosphate, gene activated matrix



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INTRODUCTION

A mandibular defect is the loss of a lower jaw bone segment that produces a gap within the bone of 2 cm or more, resulting in a continuity or non-continuity mandibular defect^[1]. These defects primarily arise from tumor resection, infection, physical trauma, and osteomyelitis^[2]. Such a critical defect will not heal on its own or regenerate more than 10% of the lost bone within the lifetime of the patient^[3]. Not only is mandibular bone important for craniofacial aesthetics, but also for the support of muscles of mastication, facial expression and speech^[4]. Therefore, the choice of scaffold to repair the defect must allow for sufficient muscle attachment to restore oral and maxillofacial function, which has been shown to have significant impact on the patient's quality of life^[5]. Thus, to achieve successful reconstruction, care must be taken to restore both aesthetics and functional capacity^[6].

The autologous fibular free flap is currently the workhorse for mandibular defect repair which, along with other autologous free vascularized tissue transfer, is considered the "gold standard" for mandibular reconstruction because of their osteogenic, osteoinductive, and osteoconductive properties, in combination with the avoidance of an immune reaction^[7,8]. These grafts also contain live stem or osteoprogenitor cells that themselves migrate, proliferate, and potentiate bone healing^[9]. The major concern with using a fibular free flap is donor site morbidity, which has been reported to occur in 31.2% of patients^[10]. These complications include wound-healing disturbance, paresthesias, cold intolerance, motor weakness of the lower leg muscles, pain, edema, poor aesthetics, and gait disturbance, and has been reported to lead to long term morbidities in 17% of patients, and severe disability in 4% of patients^[11]. To circumvent this problem, cadaver grafts may be an attractive option, however, osteoclastic resorption, risk of disease transmission (viral) and immune reaction make this a less than ideal alternative^[12-14]. Additionally, synthetic grafts designed from metals or polymers are not bioactive and do not bond to bone or support bone cell function, and can also induce the formation of fibrous tissue at the interface between the implant and bone, which can interfere with bone healing and cause bone resorption, fracture, and eventual failure of the implant^[15-17].

If advancement is to be made beyond these methods in an effort to prevent such suffering to the patient, the following factors seem to be important in the design of a biotechnology capable of adequately closing a critical osseous defect: (1) a scaffold to allow bone growth on its surface (osteoconduction); (2) growth factors that induce osteogenesis (osteoiduction); (3) cells that will support osteogenesis; and (4) vascular supply and integration for the delivery of oxygen and nutrients to developing and native tissue^[14,18]. Of these, vascularization has been a limiting factor for the use of scaffolds in mandibular repair, since both *in vitro* and *in vivo* construct implantation lack pre-existing vasculature^[19]. Because of these multifactorial considerations, tissue engineering might provide the solution to this problem^[20].

The critical focus of first-generation biomaterial design was passive biocompatibility; it was not until second-generation biomaterials that biointeractivity for the stimulation of active tissue regeneration emerged^[21]. Third-generation biomaterials are bioresponsive, e.g., they can activate genes to influence all aspects of proliferation and differentiation of cells^[22,23]. This assembly of scaffold material, scaffold structure (i.e., pore size), cells and growth factors reveals the multidisciplinary nature of tissue engineering, which is the intersection of material science, mechanical engineering, clinical medicine, and genetics^[21]. In mandibular reconstruction, the primary goals of tissue engineering include reducing donor site morbidity, operative time, and operative complexity^[24]. If non-vascularized flaps can be used (i.e., patients who have not been and are not planned to undergo radiation), favorable results have been reported with the adjunct use of tissue engineering for mandibular reconstruction^[25,26]. Furthermore, modern regenerative medicine builds on tissue engineering designs to direct the surrounding native cellular environment toward a healing process, thereby making use of foreign biological material to recreate cells and rebuild tissues.

In order to accomplish this, an effective bone scaffold must satisfy the following requirements: osteoconductivity, osteoinductivity and osseointegration^[27]. Osteoinductivity is the ability of a material to recruit multipotent cells and encourage their differentiation into an osteoblastic lineage^[28]. This is typically accomplished adding both growth factors and stem cells, such that growth factors signal to surrounding mesenchymal stem cells to differentiate into chondroblasts and osteoblasts to form new bone^[29,30]. In the context of mandibular reconstruction, stem cells have potential to regenerate oral and dental tissues, such as bone, dentin, cementum, periodontal ligaments, mucosa, and salivary glands^[22]. Mesenchymal stem cells are the most common source of osteoprogenitor cell used, and may be derived from bone marrow, adipose tissue, and dental and periodontal tissue, and their differentiation is guided by growth factors [such as bone morphogenic protein (BMP)]. Such involvement and interaction between growth factors are essential to the process of native bone healing, including vascular endothelial growth factor (VEGF), fibroblastic growth factors, insulin-like growth factors, platelet-derived growth factor, and BMP, to name a few^[31]. During osteogenesis, an osteoconductive material will allow the growth of bone not only on the scaffold surface, but also into pores and channels, such that both cortical and cancellous bone are formed around and within the framework^[32]. Such materials may also be designed to be resorbed in order to encourage growth of native bone. Osseointegration is the degree to which the native bone and the implant favorably interact, and such incorporation of a graft is influenced by many factors, such as the type of bone scaffold used and the site of implantation^[33]. Thus, the general principle underlying third generation biomaterials is the regeneration triad: (1) an extracellular matrix (ECM) scaffold, which can be made of varying material to create a porous 3D structure that may be seeded with; (2) growth factors; and (3) stem cells^[34,35]. Ideally, scaffolds should be designed to provide regenerative signals to surrounding cells, while simultaneously improving cell adhesion, proliferation, and differentiation^[36], and mechanical rigidity or flexibility^[37].

Thus, there is extensive flexibility in assembling a scaffold. The choice of scaffold material itself can be varied, and sometimes may be used successfully on its own or in combination with other materials. Furthermore, modification of the scaffold material by coating its surface with nanoparticles, an ECM molecule (such as collagen), or a growth factor (such as BMP-2) has been shown to improve tissue properties^[38]. In this review, we will explore the success of varying combinations of the above scaffolding materials, and will examine their success *in vivo* and *in vitro* in inducing and guiding osteogenesis in mandibular defects.

SCAFFOLD MATERIALS AND STRUCTURE

Beyond the biocompatibility of a scaffold, as has been argued by Chocholata *et al.*^[21], the most important aspect of scaffold design is its three dimensional structure, namely the degree of pore interconnectivity and pore size, both of which effect the degree of cell attachment and three dimensional regeneration of tissue, as well as cell growth, proliferation, and differentiation, diffusion of waste and the degradation products of scaffolds. The goal of these materials is to initiate or enhance bone formation - if pore size is too small, it can hinder cell migration, and if too large will result in suboptimal binding of cells to the scaffold^[18,39]. For maximal osteoconductivity, the ideal pore size as described by Ghayor and Weber^[40] based on *in vivo* data is 0.7-1.2 mm, and the size of connections between pores should be between 0.5-1.2 mm; sizes larger than this are detrimental to osteoconductivity. During osteointegration, these porous spaces are initially populated by capillaries, perivascular tissues, and osteoprogenitor cells, followed by incorporation of the porous structure within the newly formed bone^[41]. Additionally, the scaffold must be designed to degrade at an appropriate rate so that there is enough time for bone regeneration^[42]. This is especially relevant in pediatric patients, where the future growth of the mandible must be considered. In this case, fixation of the mandible using titanium locking reconstruction plates does not allow for mandibular growth over time, and might result in facial asymmetry and problems with occlusion as the patient grows^[24]. Resorbable plates have been developed in order to address this, but their drawbacks include postoperative plate

fracture and the development of delayed foreign-body reactions, and this potential harm to the patient's well-being might discourage their use; consequently, the focus on "resorbable" material has consequently shifted to "bioabsorbable" scaffolding, which combines biodegradation with osteoconduction^[43,44]. Lastly, the mechanical properties of the material must sufficiently mimic the native tissue at the implantation site in order to support functionality^[45]. These factors will vary with scaffolding material, and will be described below.

A key requirement of effective tissue engineering is constructing a cellular environment that mimics critical aspects of the *in vivo* setting through proper control of the materials and mechanical setting as well as the chemical environment. The macroscopic structure of bone consists of a cortical outer layer encasing porous trabecular bone^[29]. However, it is the nanoscopic structure of bone that yields its mechanical, biological and chemical properties, and this heterogenous structure is importantly irregular and anisotropic^[46,47]. The ECM of bone is comprised of 60% mineral [hydroxyapatite (HA)] and 30% organic matrix^[48]. The organic components give bone tissue its flexibility, and mainly consist of collagen (type I collagen, type III and type IV collagen), and together with fibrin and over 200 types of noncollagenous matrix proteins (glycoproteins, proteoglycans, sialoproteins, *etc.*), collagen forms the native scaffold for mineral deposition^[15,48]. These HA $\text{Ca}_3(\text{PO}_4)_2(\text{OH})_2$ nanocrystals, inlaid between individual collagen fibers, give bone its mechanical strength and rigidity^[49]. Due to this structure, bone tissue can be treated as a ceramic-organic bio-nanocomposite complex^[48].

In an effort to design biomimetic material, natural (some authors also called these biological) scaffolds use existing ECM materials, and may be protein-based (e.g., collagen, fibrin) and polysaccharide-based (e.g., chitosan, alginate, glycosaminoglycans, hyaluronic acid)^[50-52]. Such material also contains cross-linking agents (e.g., glutaraldehyde, water-soluble carbodiimide), which can be adjusted to modify degradation rates^[37]. One method to achieve both porosity and biocompatibility is to mimic the collagen network of the ECM of bone using nanofibrous scaffolds^[53]. This can be constructed using electrospun (PLLA) scaffolds, which when coated with HA has been shown to induce calcium deposition and mineralization and the formation of higher order bone structures such as trabeculi and bone marrow, when combined with stem cells^[54]. It has also been shown that electrospun PLLA can be combined with a porous collagen membrane to guide bone regeneration^[55].

Single material scaffolds have shown promise in reconstructing mandibular defects. These materials include: biological polymers (collagen, chitosan), ceramics [beta-tri calcium phosphate (β -TCP), calcium HA, biphasic calcium phosphate (BCP)], and synthetic polymers [polycaprolactone (PCL), PLA, PGA, PLGA]^[56]. The advantages to ceramics are that they are osteoconductive and biocompatible. Herford *et al.*^[57] generated a ceramic compression resistant osteoconductive matrix that was 15% HA and 85% β -TCP that showed a significantly higher bone density and space maintenance than BMP2 combined with resorbable collagen sponge. However, one of the main concerns in the application of HA bone grafts is poor resorption, and several studies have reported fibrous encapsulation around HA ceramic particles inside alveolar bone^[58-60]. In a 12 mm full thickness mandibular defect in a rabbit model using β -TCP ceramic, Lopez *et al.*^[61] found that new bone accounted for half of the defect site repair at 8 weeks post-scaffold implantation, although no stem cell seeding or BMP signaling was used to direct osteoblast differentiation, instead using the properties of the biomaterial itself to direct endogenous healing mechanisms. Such calcium phosphate ceramics (β -TCP and BCP) are promising because of their biocompatibility and drug delivery potential, and they have been shown to be osteoconductive with sufficient mechanical strength, and they can be reliably used in 3D printing methodology^[62,63]. However, calcium phosphate is insufficiently osteoinductive and requires supplementation with growth factors to induce new bone formation^[64]. These scaffolds do have lower mechanical strength compared to allografts because they are designed to be degradable such that it can be replaced by new bone; however, the extent of new bone formation, lack of

host-host bridging, and engraftment is similar^[65]. In preclinical animal studies, autogenous bone precursor cells seeded onto calcium phosphate ceramic scaffolds, pyrolyzed bovine bone, or calcium carbonate has been comparable to autograft bone in mandibular reconstruction in terms of biomechanical testing, bone bridging, and bone ingrowth^[64-66].

The second major category is the synthetic polymer (PCL, PLLA, PLA-PEG, PGA, PLGA, PLGA-PEG, *etc.*). This material is promising because it allows 3D printing of complex structures that are biodegradable, bioactive, and undergo controlled degradation^[67]. However, PCL is not ideal for mandible tissue engineering due to inferior mechanical properties such as a low compressive strength^[68].

The third category of material is the natural polymer (collagen, chitosan, silk fibroin, alginate, gelatin, *etc.*)^[69]. Although biocompatibility with natural scaffolds is obviously excellent, there remain issues with potential immunogenicity in some cases. Because they do not induce antigen-antibody reactions, decellularized tissue matrices obtained from processing discarded donor tissue is an attractive solution. When bone matrix is demineralized via removal of HA, the remaining bony matrix is comprised mainly of collagen - this biocompatible, bioactive biomaterial has the ability to induce bone morphogenesis via BMP signaling, particularly in stem cells, and can be used as a film, gel, or sponge^[70,71]. Although they have similar osteoinductive and osteoconductive properties as autologous grafts, they lack the corresponding osteogenic properties^[71]. Additional major downsides are sourcing, processing, immunogenicity, and disease transmission, as well as lack of mechanical strength to withstand the forces exerted by the muscles of mastication^[72,32].

In order to address this, Kakabadze *et al.*^[73] reports development of a novel biologically active bone graft using decellularized cancellous bovine femur seeded with human bone marrow mesenchymal stem cells (BMSCs) and growth factors, which was applied clinically to repair a large mandibular defect following primary tumor resection that successfully repaired the defect and showed maintained mandibular bone volume at 5 months post-op. Importantly, like the use of autologous bone, this graft construction requires use of a barrier membrane to prevent fibrous tissue invasion, and decellularized human amnion/chorion membrane was chosen by the authors due to its osseointegrative properties^[73].

However, the shortcomings of using a single material in scaffold construction include: poor strength for biologically-derived materials, brittleness for inorganic materials, and poor cell compatibility and insufficient mechanical strength for synthetic polymers^[56]. Because of this, combining two or more materials to create a composite scaffold has shown improvement in material properties and biocompatibility. Most often, the polymer of choice is type I collagen, which is most often coated on scaffolds made from PCL, HA, and TCP in order to aim to mimic the structure of native bone^[38]. Additionally, biomimetic Mg-MgHA/collagen-based scaffolds have been shown to greatly improve osteoblast differentiation^[74]. When choosing between ceramics to add compressive strength, it should be noted that compared to β -TCP, HA has low absorption kinetics *in vivo* (1%-2% per year at 5 years postimplantation)^[75]. An HA-collagen or β -TCP-collagen scaffold can be 3D printed, and the combination of biocompatibility, compressive strength, and resorption rate *in vivo* and *in vitro* allows for bone replacement over time, and the degradation rate of the material can be altered by increasing the macroscopic surface area by decreasing the strut diameter or altering micro/nano porosity^[61].

The scaffold surface may also be modified by the addition of nanoparticles. Most commonly, nano-HA is combined with PCL and chitosan scaffolding^[38]. Nano-HA is of interest because it has been shown to increase the mechanical properties and improve the protein adsorption capacity of the polymer, while also acting as a substrate for cell attachment and migration during bone regeneration^[76]. Polyamide66 is a synthetic polymer chosen by Cai *et al.*^[77] to combine with HA due to its biocompatibility, high tensile

strength, and its similarity to collagen in chemical structure and functional groups^[78]. When combined with BMSCs in a mandibular defect, this scaffold showed greater biocompatibility and osteoconductivity with the surrounding host bone compared with commercial porous polyethylene (MEDPOR) constructs seeded with BMSCs^[77].

One of the fundamental hurdles of bone-tissue engineering is vascularization of tissue. Zhu *et al.*^[79] fabricated pre-vascularized tissues using a method derived from rapid 3D printing, termed microscale continuous optical bioprinting, in which two types of biocompatible and photopolymerizable hydrogels-glycidyl methacrylate-HAp and gelatin methacrylate scaffolds - were pre-designed with vascular channels into which endothelial cells and mesenchymal cells were printed, which resulted in the spontaneous formation of a functional endothelial network both *in vitro* and *in vivo*.

Graphene and its derivatives, such as graphene oxide and reduced graphene oxide, is also a promising scaffold material because it is not only biocompatible, but also has been shown to regulate cell behavior, help in differentiation, and improve adhesion, growth and proliferation of cells^[21]. Graphene is built by layering SP2 bonded carbon atoms with atomic graphite in a honeycomb lattice structure^[80]. When combined with natural and synthetic biomaterials, graphene has been shown to increase osteogenic potential and mechanical strength of the scaffold^[80,81]. However, graphene has been shown to be toxic at higher concentrations and is not reliably biodegradable, warranting further investigation before clinical trials^[80,81].

STEM CELLS AND GROWTH FACTORS

Most tissue engineering utilizes living cells, and supplying enough cells is obviously a critically important issue. Cells are typically derived from: (1) donor tissue, which is often in very limited supply; (2) stem or progenitor cells. Stem cells possess two major properties that make them attractive for deriving large cell quantities: (1) their high proliferative capacity; (2) their multipotency, or ability to differentiate into cells of multiple lineages^[37]. Bone marrow stroma contains progenitor cells with osteogenic potential, which are referred to as bone marrow stromal cells, or BMSCs^[82]. BMSCs are a major seed cell source for bone tissue engineering due to their well-known capability of self-renewal (which is an outcome of asymmetric division), and differentiation into the osteoblastic lineage *in vitro* and *in vivo*^[83-85]. Scaffolding has been shown to be capable to support ectopic bone formation when seeded with BMSCs in a mouse model, and the repair of large segmental defects^[86,87]. Moreover, many previous studies have succeeded in repairing bone defects by using BMSCs in animal models as well as in humans^[88].

The procedure to extract autologous BMSCs is painful and associated with potential complications, so effort has been made to explore the use of adipose derived stem cells (ADSCs). Although ADSCs have a higher cell yield, the literature suggests they possess an inferior osteogenic capacity compared to BMSCs, so they are not as desirable in mandibular reconstruction^[88]. Dental pulp stem cells are also of interest due to their ease of access, low donor site morbidity, and ability to differentiate into fibroblasts, nerve cells, endothelial cells, and odontoblasts in order to facilitate creation of new connective tissue^[89]. Raspini *et al.*^[90] showed that dental pulp stem cells combined with bioactive glass scaffold that was treated with osteogenic medium *in vitro* showed good biocompatibility and osteogenic induction, making it a promising combination for hard tissue regeneration in the cranio-maxillofacial skeleton. However, the comparative efficacy of these cells between laboratory study and patient intervention remains to be seen^[91].

When bone is transplanted, it is degraded and replaced through a process termed “creeping substitution”, and this degradation process releases calcium phosphates and osteoinductive proteins that amplify bone regeneration^[41]. BMPs are a member of the transforming growth factor-beta (TGF- β) superfamily that

induces the formation of bone and cartilage. In order to mimic this endogenous microenvironment, BMPs are often combined with MSCs in order to amplify their bone-forming potential. This use of MSCs with BMPs to repair mandibular bony defects has shown its effectiveness in animal models^[72,92]. Jiang *et al.*^[93] showed that transfection of BMSCs with hBMP-4 enhances their inherent osteogenic capacity in mandibular defect repair. Zhou *et al.*^[94] showed rhBMP-2 combined with prefabricated tissue engineered vascularized bone flaps produced *in vivo* induced successful reconstruction of the mandibular defect. Chen *et al.*^[95] found that loading a demineralized bone matrix with a formulated collagen-targeting BMP-2 induced better bone formation compared to rhBMP-2, and the authors note remarkable osteoinductive properties with homogenous bone formation. Additionally, BMPs may be combined with non-vascularized bone grafts, such as cadaveric fibula or other non-vascularized bone grafts, to stimulate osteogenesis^[24]. Such a design has shown capability to reconstruct mandibular defects up to 12 cm^[25]. It should be noted that BMP is contraindicated in cancer, because it is thought to stimulate cancer growth (shown *in vivo*)^[96].

The importance of scaffold selection when using BMP-2 and BMP-7 has been well documented. The material must allow sustained diffusion of BMPs throughout the environment and provide matrix for in-growth of osteoprogenitor cells and blood vessels, and the properties of scaffolds constructed with BMP and ceramics, synthetic polymers, or biological polymers differ^[69]. Currently, collagen is the gold standard delivery system for BMPs. Composite scaffolds are also promising for BMP use, such as PLA/PEG/HAP which is osteoconductive, or a PLGA-collagen hybrid, which has osteoinductive activity and long stimulation effect^[97,98]. In terms of novel carriers, nanoparticles and microparticles are becoming increasingly popular due to localized and sustained delivery of BMPs, which can be designed with natural polymers, synthetic polymers, or ceramics. Quinlan *et al.*^[99] loaded alginate and PLGA MPs with rhBMP-2 in order to incorporate the polymer into porous HAP-collagen scaffold for bone regeneration, which showed new bone formation in a rat model *in vivo*. Dual-interacting polymeric nanoparticles were prepared by Seo *et al.*^[100] to form nanocomplexes with BMP-2, which resulted in sustained BMP-2 release and significant bone generation.

BMPs combined with biomaterial appears equivalent to autogenous osteogenic tissue. In humans, native human BMPs, xenogeneic BMPs, rhBMP-2, or rhBMP-7 were reported to yield complete mandibular bony defect bridging without simultaneous use of autogenous osteogenic tissue in 29 out of 34 patients^[85]. It has long been thought that bone growth cytokines could be reliably used in lieu of traditional bone grafting^[57]. While tissue-engineered autogenous osteogenic tissues without application of osteoinductive BMPs has been reported to restore mandibular continuity ($n = 16$ patients), osteoinductive rhBMP-2 loaded onto various scaffolding materials without concomitant transplantation of autogenous osteogenic tissue has also been shown to restore mandibular continuity^[4,101-103].

Other growth factors that have been explored for promoting osteogenesis include recombinant human platelet-derived growth factor, TGF- β , fibroblast growth factor, recombinant human growth/differentiation factor-5, VEGF, and insulin-like growth factor^[85]. However, BMPs remain the most frequently used compared to other growth factors^[38]. Beside their ability to induce osteogenic differentiation in stem cells, BMPs can accelerate the healing process^[104]. However, it should be noted that in a calvaria defect model, BMP-2 and VEGFA had similar bone healing capacities, with FGF-2 displaying a significantly higher bone regeneration capacity; however, the healing rate was lower than with BMP-2 and VEGFA^[105]. BMP-2 and VEGFA also showed increased angiogenic response upon healing^[105]. It should also be noted that undesirable clinical outcomes with BMPs have been shown, namely extreme bone proliferation (albeit in a calvarial model), ectopic bone formation, radiculitis, and potential stimulation of neoplasms^[106-108]. Because of this, investigation into β -TCP ceramic scaffold coated with an adenosine A2 receptor indirect agonist augmented bone growth as effectively as rhBMP-2 in a 3 mm defect^[109]. Adenosine A2A receptor signaling appears to be important for osteoclast differentiation both *in vitro* and *in vivo*, and has been shown to promote bone regeneration^[110].

GENE THERAPY

Gene therapy makes use of native nuclear machinery in order to synthesize a protein of interest via the process of transduction, in which a viral vector is typically used^[111]. In this way, growth factor can be produced in the region of the defect, and has been reported to support mineralized tissue formation^[112]. Therefore, expression in the host cell lasts longer (weeks to years) compared to pharmaceutical compounds or recombinant protein, which ranges from several hours to days. This allows continuous production of biologically active molecules, thereby mimicking the endogenous physiological healing response in the microenvironment of the defect^[113,114]. Viral vectors remain preferred to non-viral vectors because they have been rendered replication-incompetent, and non-viral vectors have insufficient transfection efficiencies^[115,116].

In order to induce *de novo* bone formation in the maxillofacial region *in vivo*, the genes of interest range from soluble growth factors (PDGF, FGFs), morphogens (BMPs), angiogenic factors (VEGF), intracellular regulators (LIM mineralization protein-1), transcription factors (Runx2) associated with bone and cartilage-related gene expression^[117,118]. Due to their ability to initiate and sustain the entirety of the bone formation process, BMPs are the preferred candidates for local gene therapy for bone regeneration^[119].

Although gene therapy can be administered via systemic or local injection, gene therapy may be delivered with a biomaterial. This combination of a vector and biomaterial is referred to as a gene activated matrix that acts as a scaffold for delivery of the vector to the area of interest^[120]. This method may be especially attractive in the repair of mandibular defects, in which cells may be removed from the donor site, be genetically modified and implanted onto the scaffold of choice, and re-implanted into the defect^[121]. Interestingly, BMSCs have been successfully transfected by various vector systems in order to improve their proliferation and differentiation capacities^[117]. A meta-analysis by Fliefel *et al.*^[115] which considered majority animal-model studies found evidence that gene therapy improves bone formation in maxillofacial defects. These results have not yet been confirmed in human subjects; thus, it remains an exciting approach to mandibular defect repair that warrants future research and randomized clinical trials^[115].

CONCLUSION

Tissue engineering for mandibular reconstruction is most successful when it can mimic and interact with the surrounding native macro- and micro-environment in order to induce and support osteogenesis. Based on the current literature, an optimal mandibular scaffold is comprised of three elements: (1) a biomimetic, bioactive osteointegrative scaffold, most likely a resorbable composite of collagen or a synthetic polymer with collagen-like properties with β -TCP that is 3D printed according to defect morphology; (2) growth factor, most frequently BMP; and (3) stem cells, most commonly BMSCs. Overall, the use of a tissue engineered scaffold may prevent common complications of mandibular defect repair with fibular free flap, such as donor site morbidity, and may provide an approach for patients with depleted donor sites due to previous surgeries.

DECLARATIONS

Authors' contributions

Made substantial contributions to conception and design, analysis, interpretation, and preparation of the review and manuscript: Nelms L

Assisted with manuscript preparation, as well as provided administrative, technical, and material support: Palmer WJ

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Conflicts of interest

Both authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

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REFERENCES

1. Akinbami BO. Reconstruction of Continuity Defects of the Mandible with Non-vascularized Bone Grafts. Systematic Literature Review. *Craniomaxillofac Trauma Reconstr* 2016;9:195-205.
2. Rana M, Warraich R, Kokemüller H, Lemound J, Essig H, et al. Reconstruction of mandibular defects - clinical retrospective research over a 10-year period. *Head Neck Oncol* 2011;3:23.
3. Brierly GI, Tredinnick S, Lynham A, Woodruff MA. Critical sized mandibular defect regeneration in preclinical in vivo models. *Curr Molecular Bio Rep* 2016;2:83-9.
4. Nuttegg CM, Hidalgo-Bastida AL. Scaffolds for Mandibular Reconstruction. In: Mozafari M, Sefat F, Atala A, editors. *Handbook of Tissue Engineering Scaffolds: Volume One*. Woodhead Publishing; 2019. pp. 347-68.
5. Murphy C, Kearns G, Sleeman D, Cronin M, Allen P. The clinical relevance of orthognathic surgery on quality of life. *Int J Oral Maxillofac Surg* 2011;40:926-30.
6. Wong R, Tideman H, Kin L, Merckx M. Biomechanics of mandibular reconstruction: a review. *Int J Oral Maxillofac Surg* 2010;39:313-9.
7. Zou W, Chen X. Osteogenesis and Ototoxicity of a Novel Preparation of Autogenous Bone Cement. *Otolaryngol Head Neck Surg* 2014;151:1020-7.
8. Miles BA, Goldstein DP, Gilbert RW, Gullane PJ. Mandible reconstruction. *Curr Opin Otolaryngol Head Neck Surg* 2010;18:317-22.
9. Pandit N, Pandit I. Autogenous bone grafts in periodontal practice: a literature review. *J Int Clin Dent Res Organ* 2016;8:27-33.
10. Kumar G, Narayan B. Morbidity at Bone Graft Donor Sites. In: Banaszkiewicz P, Kader D, editors. *Classic Papers in Orthopaedics*. Springer, London; 2014. pp. 503-5.
11. Momoh AO, Yu P, Skoracki RJ, Liu S, Feng L, et al. A prospective cohort study of fibula free flap donor-site morbidity in 157 consecutive patients. *Plast Reconstr Surg* 2011;128:714-20.
12. De Long WG Jr, Einhorn TA, Koval K, McKee M, Smith W, et al. Bone grafts and bone graft substitutes in orthopaedic trauma surgery. A critical analysis. *J Bone Joint Surg Am* 2007;89:649-58.
13. Wang W, Yeung KWK. Bone Grafts and Bone Substitutes for Bone Defect Management. *Orthopedic Biomater* 2017:495-545.
14. Stevenson S, Horowitz M. The response to bone allografts. *J Bone Joint Surg Am* 1992;74:939-50.
15. Wu SH, Li Y, Zhang YQ, Li XK, Yuan CF, et al. Porous titanium-6 aluminum-4 vanadium cage has better osseointegration and less micromotion than a poly-ether-ether-ketone cage in sheep vertebral fusion. *Artif Organs* 2013;37:E191-201.
16. Decking R, Reuter P, Huttner M, Puhl W, Claes LE, et al. Surface composition analysis of failed cementless CoCr- and Ti-base-alloy total hip implants. *J Biomed Mater Res B Appl Biomater* 2003;64:99-106.
17. Meneghini RM, Daluga A, Soliman M. Mechanical stability of cementless tibial components in normal and osteoporotic bone. *J Knee Surg* 2011;24:191-6.
18. Vaccaro AR. The role of the osteoconductive scaffold in synthetic bone graft. *Orthopedics* 2002;25:S571-8.
19. Ikada Y. Challenges in tissue engineering. *J R Soc Interface* 2006;3:589-601.
20. Wang KH, Inman JC, Hayden RE. Modern concepts in mandibular reconstruction in oral and oropharyngeal cancer. *Curr Opin Otolaryngol Head Neck Surg* 2011;19:119-24.
21. Chocholata P, Kulda V, Babuska V. Fabrication of scaffolds for bone-tissue regeneration. *Materials* 2019;12:E568.
22. Rahman S, Nagrath M, Ponnusamy S, Arany P. Nanoscale and macroscale scaffolds with controlled-release polymeric systems for dental craniomaxillofacial tissue engineering. *Materials* 2018;11:1478.
23. Hench LL, Polak JM. Third-generation biomedical materials. *Science* 2002;295:1014-7.
24. Kakarala K, Shnyder Y, Tsue TT, Girod DA. Mandibular reconstruction. *Oral Oncol* 2018;77:111-7.
25. Desai SC, Sclaroff A, Nussenbaum B. Use of recombinant human bone morphogenetic protein 2 for mandible reconstruction. *JAMA Facial Plast Surg* 2013;15:204-9.

26. Schlieve T, Hull W, Miloro M, Kolokythas A. Is immediate reconstruction of the mandible with nonvascularized bone graft following resection of benign pathology a viable treatment option? *J Oral Maxillofac Surg* 2015;73:541-9.
27. Albrektsson T, Johansson C. Osteoinduction, osteoconduction and osseointegration. *Eur Spine J* 2001;10:S96-101.
28. Melville JC, Tursun R, Green JM, Marx RE. Reconstruction of a post-traumatic maxillary ridge using a radial forearm free flap and immediate tissue engineering (bone morphogenetic protein, bone marrow aspirate concentrate, and cortical-cancellous bone): case report. *J Oral Maxillofac Surg* 2017;75:438.e1-6.
29. Stevens MM. Biomaterials for bone tissue engineering. *Mater Today* 2008;11:18-25.
30. Roberts TT, Rosenbaum AJ. Bone grafts, bone substitutes and orthobiologics: the bridge between basic science and clinical advancements in fracture healing. *Organogenesis* 2012;8:114-24.
31. Devescovi V, Leonardi E, Ciapetti G, Cenni E. Growth factors in bone repair. *Chir Organi Mov* 2008;92:161-8.
32. Dawson DR, El-Ghannam A, Van Sickels JE, Naung NY. Tissue Engineering: What is New? *Dental Clinics* 2019;63:433-45.
33. Khan SN, Cammisa Jr FP, Sandhu HS, Diwan AD, Girardi FP, et al. The biology of bone grafting. *J Am Acad Orthop Surg* 2005;13:77-86.
34. O'Brien FJ. Biomaterials & scaffolds for tissue engineering. *Mater Today* 2011;14:88-95.
35. Tabatabaei FS, Motamedian SR, Gholipour F, Khosraviani K, Khojasteh A. Craniomaxillofacial Bone Engineering by Scaffolds Loaded with Stem Cells: A Systematic Review. *J Den Sch* 2012;30:113-30.
36. Dhandayuthapani B, Yoshida Y, Maekawa T, Kumar DS. Polymeric scaffolds in tissue engineering application: a review. *Int J Polym Sci* 2011; DOI:10.1155/2011/290602.
37. Berthiaume F, Maguire TJ, Yarmush ML. Tissue engineering and regenerative medicine: history, progress, and challenges. *Annu Rev Chem Biomol* 2011;2:403-30.
38. Motamedian SR, Hosseinpour S, Ahsaie MG, Khojasteh A. Smart scaffolds in bone tissue engineering: A systematic review of literature. *World J Stem Cells* 2015;7:657-68.
39. Yu J, Xia H, Ni QQ. A three-dimensional porous hydroxyapatite nanocomposite scaffold with shape memory effect for bone tissue engineering. *J Mater Sci* 2018;53:4734-44.
40. Ghayor C, Weber FE. Osteoconductive microarchitecture of bone substitutes for bone regeneration revisited. *Front Physiol* 2018;9:960.
41. Cornell CN, Lane JM. Current understanding of osteoconduction in bone regeneration. *Clin Orthop Relat Res* 1998;355:S267-73.
42. Ge Z, Jin Z, Cao T. Manufacture of degradable polymeric scaffolds for bone regeneration. *Biomed Mater* 2008;3:022001.
43. Stanton DC, Liu F, Yu JW, Mistretta MC. Use of bioresorbable plating systems in paediatric mandible fractures. *J Craniomaxillofac Surg* 2014;42:1305-9.
44. Park YW. Bioabsorbable osteofixation for orthognathic surgery. *Maxillofac Plast Reconstr Surg* 2015;37:6.
45. Hutmacher DW. Scaffolds in tissue engineering bone and cartilage. In: Williams DF, editor. *The Biomaterials: Silver Jubilee Compendium* 2000; pp. 175-89.
46. Wang X, Xu S, Zhou S, Xu W, Leary M, et al. Topological design and additive manufacturing of porous metals for bone scaffolds and orthopaedic implants: A review. *Biomaterials* 2016;83:127-41.
47. Rho JY, Kuhn-Spearing L, Zioupos P. Mechanical properties and the hierarchical structure of bone. *Med Eng Phys* 1998;20:92-102.
48. Kattimani VS, Kondaka S, Lingamaneni KP. Hydroxyapatite - Past, present, and future in bone regeneration. *Bone Tissue Regenerat Insights* 2016;7:BTRI-S36138.
49. Walmsley GG, Ransom RC, Zielins ER, Leavitt T, Flacco JS, et al. Stem cells in bone regeneration. *Stem Cell Rev Rep* 2016;12:524-9.
50. Baier Leach J, Bivens KA, Patrick Jr CW, Schmidt CE. Photocrosslinked hyaluronic acid hydrogels: natural, biodegradable tissue engineering scaffolds. *Biotechnol Bioeng* 2003;82:578-89.
51. Chevally B, Herbage D. Collagen-based biomaterials as 3D scaffold for cell cultures: applications for tissue engineering and gene therapy. *Med Biol Eng Comput* 2000;38:211-8.
52. Zhang R, Ma PX. Poly (α -hydroxyl acids)/hydroxyapatite porous composites for bone-tissue engineering. I. Preparation and morphology. *J Biomed Mater Res* 1999;44:446-55.
53. Holzwarth JM, Ma PX. Biomimetic nanofibrous scaffolds for bone tissue engineering. *Biomaterials* 2011;32:9622-9.
54. Seyedjafari E, Soleimani M, Ghaemi N, Shabani I. Nanohydroxyapatite-coated electrospun poly (l-lactide) nanofibers enhance osteogenic differentiation of stem cells and induce ectopic bone formation. *Biomacromolecules* 2010;11:3118-25.
55. Cai YZ, Wang LL, Cai HX, Qi YY, Zou XH, et al. Electrospun nanofibrous matrix improves the regeneration of dense cortical bone. *J Biomed Mater Res A* 2010;95:49-57.
56. Jahan K, Tabrizian M. Composite biopolymers for bone regeneration enhancement in bony defects. *Biomater Sci* 2015;4: 25-39.
57. Herford AS, Lu M, Buxton AN, Kim J, Henkin J, et al. Recombinant Human Bone Morphogenetic Protein 2 Combined With an Osteoconductive Bulking Agent for Mandibular Continuity Defects in Nonhuman Primates. *Journal of Oral and Maxillofacial Surgery* 2012;70:703-16.
58. Lindhe J, Cecchinato D, Donati M, Tomasi C, Liljenberg B. Ridge preservation with the use of deproteinized bovine bone mineral. *Clin Oral Implants Res* 2014;25:786-90.
59. Stavropoulos A, Kostopoulos L, Mardas N, Nyengaard JR, Karring T. Deproteinized bovine bone used as an adjunct to guided bone augmentation: an experimental study in the rat. *Clin Implant Dent Relat Res* 2001;3:156-65.
60. Piattelli M, Favero GA, Scarano A, Orsini G, Piattelli A. Bone reactions to anorganic bovine bone (Bio-Oss) used in sinus augmentation procedures: a histologic long-term report of 20 cases in humans. *Int J Oral Maxillofac Implants* 1999;14:835-40.
61. Lopez CD, Diaz-Siso JR, Witek L, Bekisz JM, Cronstein BN, et al. Three dimensionally printed bioactive ceramic scaffold osseointegration across critical-sized mandibular defects. *J Surg Res* 2018;223:115-22.

62. Bose S, Tarafder S. Calcium phosphate ceramic systems in growth factor and drug delivery for bone tissue engineering: a review. *Acta Biomater* 2012;8:1401-21.
63. Inzana JA, Olvera D, Fuller SM, Kelly JP, Graeve OA, et al. 3D printing of composite calcium phosphate and collagen scaffolds for bone regeneration. *Biomaterials* 2014;35:4026-34.
64. Yuan J, Zhang WJ, Liu G, Wei M, Qi ZL, et al. Repair of canine mandibular bone defects with bone marrow stromal cells and coral. *Tissue Eng Part A* 2010;16:1385-94.
65. Nollf MC, Gellrich NC, Hauschild G, Fehr M, Bormann KH, et al. Comparison of two β -tricalcium phosphate composite grafts used for reconstruction of mandibular critical size bone defects. *Vet Comp Orthopaed* 2009;22:96-102.
66. Schliephake H, Knebel JW, Aufderheide M, Tauscher M. Use of cultivated osteoprogenitor cells to increase bone formation in segmental mandibular defects: an experimental pilot study in sheep. *Int J Oral Maxillofac Surg* 2001;30:531-7.
67. Hart LR, Li S, Sturgess C, Wildman R, Jones JR, et al. 3D printing of biocompatible supramolecular polymers and their composites. *ACS Appl Mater Inter* 2016;8:3115-22.
68. Sheikh Z, Najeeb S, Khurshid Z, Verma V, Rashid H, et al. Biodegradable materials for bone repair and tissue engineering applications. *Materials (Basel)* 2015;8:5744-94.
69. Begam H, Nandi SK, Kundu B, Chanda A. Strategies for delivering bone morphogenetic protein for bone healing. *Mat Sci Eng C* 2017;70:856-69.
70. Nakashima M, Reddi AH. The application of bone morphogenetic proteins to dental tissue engineering. *Nat Biotechnol* 2003;21:1025-32.
71. Gardin C, Ricci S, Ferroni L, Guazzo R, Sbricoli L, et al. Decellularization and Delipidation Protocols of Bovine Bone and Pericardium for Bone Grafting and Guided Bone Regeneration Procedures. *PLoS One* 2015;10:e0132344.
72. Seeherman H, Wozney JM. Delivery of bone morphogenetic proteins for orthopedic tissue regeneration. *Cytokine Growth Factor Rev* 2005;16:329-45.
73. Kakabadze A, Mardaleishvili K, Loladze G, Karalashvili L, Chutkerashvili G, et al. Reconstruction of mandibular defects with autogenous bone and decellularized bovine bone grafts with freeze-dried bone marrow stem cell paracrine factors. *Oncol Lett* 2017;13:1811-8.
74. Scarano, Antonio, Felice Lorusso, Giorgio Staiti, Bruna Sinjari, et al. "Sinus augmentation with biomimetic nanostructured matrix: tomographic, radiological, histological and histomorphometrical results after 6 months in humans." *Front Physiol* 2017;8:565.
75. Moore WR, Graves SE, Bain GI. Synthetic bone graft substitutes. *ANZ J Surg* 2001;71:354-61.
76. Wei G, Ma PX. Structure and properties of nano-hydroxyapatite/polymer composite scaffolds for bone tissue engineering. *Biomaterials* 2004;25:4749-57.
77. Cai B, Jiang N, Zhang L, Huang J, Wang D, et al. Nano-hydroxyapatite/polyamide66 composite scaffold conducting osteogenesis to repair mandible defect. *J Bioact Compat Pol* 2019;34:72-82.
78. Xiong Y, Ren C, Zhang B, Yang H, Lang Y, et al. Analyzing the behavior of a porous nano-hydroxyapatite/polyamide 66 (n-HA/PA66) composite for healing of bone defects. *Int J Nanomed* 2014;9:485-94.
79. Zhu W, Qu X, Zhu J, Ma X, Patel S, et al. Direct 3D bioprinting of prevascularized tissue constructs with complex microarchitecture. *Biomaterials* 2017;124:106-15.
80. Bai, Renu Geetha, Kasturi Muthoosamy, Sivakumar Manickam, and Ali Hilal-Alnaqbi. "Graphene-based 3D scaffolds in tissue engineering: fabrication, applications, and future scope in liver tissue engineering." *Int J Nanomed* 2019;14:5753.
81. Prasad S, Suresh S, Wong R. Osteogenic potential of graphene in bone tissue engineering scaffolds. *Materials* 2018;11:1430.
82. Bianco P, Gehron RP. Marrow stromal stem cells. *J Clin Invest* 2000;105:1663-8.
83. Jaquière C, Schaeren S, Farhadi J, Mainil-Varlet P, Kunz C, et al. In vitro osteogenic differentiation and in vivo bone-forming capacity of human isogenic jaw periosteal cells and bone marrow stromal cells. *Ann Surg* 2005;242:859.
84. Frank O, Heim M, Jakob M, Barbero A, Schäfer D, et al. Real-time quantitative RT-PCR analysis of human bone marrow stromal cells during osteogenic differentiation in vitro. *J Cell Biochem* 2002;85:737-46.
85. Chanchareonsook N, Junker R, Jongpaiboonkit L, Jansen JA. Tissue-engineered mandibular bone reconstruction for continuity defects: a systematic approach to the literature. *Tissue Eng Part B Rev* 2013;20:147-62.
86. Martin I, Muraglia A, Campanile G, Cancedda R, Quarto R. Fibroblast growth factor-2 supports ex vivo expansion and maintenance of osteogenic precursors from human bone marrow. *Endocrinology* 1997;138:4456-62.
87. Quarto R, Mastrogiacomo M, Cancedda R, Kutepov SM, Mukhachev V, et al. Repair of large bone defects with the use of autologous bone marrow stromal cells. *N Engl J Med* 2001;344:385-6.
88. Liao HT, Chen CT. Osteogenic potential: comparison between bone marrow and adipose-derived mesenchymal stem cells. *World J Stem Cells* 2014;6:288-95.
89. Bakhtiar H, Mazidi A, Asl SM, Ellini MR, Moshiri A, et al. The role of stem cell therapy in regeneration of dentine-pulp complex: a systematic review. *Prog Biomater* 2018;7:249-68.
90. Raspini G, Wolff J, Helminen M, Raspini G, Raspini M, et al. Dental stem cells harvested from third molars combined with bioactive glass can induce signs of bone formation in vitro. *J Oral Maxillofac Res* 2018;9:e2.
91. Spagnuolo G, Codispoti B, Marrelli M, Rengo C, Rengo S, et al. Commitment of oral-derived stem cells in dental and maxillofacial applications. *Dent J (Basel)* 2018;6:E72.
92. Marukawa E, Asahina I, Oda M, Seto I, Alam MI, et al. Bone regeneration using recombinant human bone morphogenetic protein-2 (rhBMP-2) in alveolar defects of primate mandibles. *British J Oral Maxil Surg* 2001;39:452-9.
93. Jiang X, Gittens SA, Chang Q, Zhang X, Chen C, et al. The use of tissue-engineered bone with human bone morphogenetic protein-4-

- modified bone-marrow stromal cells in repairing mandibular defects in rabbits. *Int J Oral Maxillofac Surg* 2006;35:1133-9.
94. Zhou M, Peng X, Mao C, Xu F, Hu M, et al. Primate mandibular reconstruction with prefabricated, vascularized tissue-engineered bone flaps and recombinant human bone morphogenetic protein-2 implanted in situ. *Biomaterials* 2010;31:4935-43.
 95. Chen B, Lin H, Wang J, Zhao Y, Wang B, et al. Homogeneous osteogenesis and bone regeneration by demineralized bone matrix loading with collagen-targeting bone morphogenetic protein-2. *Biomaterials* 2007;28:1027-35.
 96. Kokorina NA, Lewis Jr JS, Zakharkin SO, Krebsbach PH, Nussenbaum B. rhBMP-2 has adverse effects on human oral carcinoma cell lines in vivo. *The Laryngoscope* 2012;122:95-102.
 97. Lee EJ, Kim HE. Accelerated bony defect healing by chitosan/silica hybrid membrane with localized bone morphogenetic protein-2 delivery. *Mat Sci Eng C* 2016;59:339-45.
 98. Lu H, Kawazoe N, Kitajima T, Myoken Y, Tomita M, et al. Spatial immobilization of bone morphogenetic protein-4 in a collagen-PLGA hybrid scaffold for enhanced osteoinductivity. *Biomaterials* 2012;33:6140-6.
 99. Quinlan E, López-Noriega A, Thompson E, Kelly HM, Cryan SA, et al. Development of collagen-hydroxyapatite scaffolds incorporating PLGA and alginate microparticles for the controlled delivery of rhBMP-2 for bone tissue engineering. *J Control Release* 2015;198:71-9.
 100. Seo BB, Choi H, Koh JT, Song SC. Sustained BMP-2 delivery and injectable bone regeneration using thermosensitive polymeric nanoparticle hydrogel bearing dual interactions with BMP-2. *J Control Release* 2015;209:67-76.
 101. Herford AS, Boyne PJ, Williams RP. Clinical applications of rhBMP-2 in maxillofacial surgery. *J Calif Dent Assoc* 2007;35:335-41.
 102. Herford AS, Boyne PJ. Reconstruction of mandibular continuity defects with bone morphogenetic protein-2 (rhBMP-2). *J Oral Maxil Surg* 2008;66:616-24.
 103. Cicciù M, Herford AS, Stoffella E, Cervino G, Cicciù D. Protein-signaled guided bone regeneration using titanium mesh and Rh-BMP2 in oral surgery: a case report involving left mandibular reconstruction after tumor resection. *Open Dent J* 2012;6:51.
 104. Jansen JA, Vehof JW, Ruhe PQ, Kroeze-Deutman H, Kuboki Y, et al. Growth factor-loaded scaffolds for bone engineering. *J Control Release* 2005;101:127-36.
 105. Behr B, Sorkin M, Lehnhardt M, Renda A, Longaker MT, et al. A comparative analysis of the osteogenic effects of BMP-2, FGF-2, and VEGFA in a calvarial defect model. *Tissue Eng Part A* 2012;18:1079-86.
 106. Kinsella CR, Cray JJ, Durham EL, Burrows AM, Vecchione L, et al. Recombinant human bone morphogenetic protein-2-induced craniosynostosis and growth restriction in the immature skeleton. *Plast Reconstr Surg* 2011;127:1173-81.
 107. Carragee EJ, Hurwitz EL, Weiner BK. A critical review of recombinant human bone morphogenetic protein-2 trials in spinal surgery: emerging safety concerns and lessons learned. *Spine J* 2011;11:471-91.
 108. Spiro AS, Timo Beil F, Baranowsky A, Barvencik F, Schilling AF, et al. BMP-7-induced ectopic bone formation and fracture healing is impaired by systemic NSAID application in C57BL/6-mice. *J Orthop Res* 2010;28:785-91.
 109. Mediero A, Wilder T, Perez-Aso M, Cronstein BN. Direct or indirect stimulation of adenosine A2A receptors enhances bone regeneration as well as bone morphogenetic protein-2. *FASEB J* 2015;29:1577-90.
 110. Mediero A, Kara FM, Wilder T, Cronstein BN. Adenosine A2A receptor ligation inhibits osteoclast formation. *Am J Pathol* 2012;180:775-86.
 111. Scheller EL, Villa-Diaz LG, Krebsbach PH. Gene therapy: implications for craniofacial regeneration. *J Craniofac Surg* 2012;23:333.
 112. Rabie AB, Dai J, Xu R. Recombinant AAV-mediated VEGF gene therapy induces mandibular condylar growth. *Gene Ther* 2007;14:972.
 113. Rios HF, Lin Z, Oh B, Park CH, Giannobile WV. Cell-and gene-based therapeutic strategies for periodontal regenerative medicine. *J Periodontol* 2011;82:1223-37.
 114. Chatterjee A, Singh N, Saluja M. Gene therapy in periodontics. *J Indian Soc Periodontol* 2013;17:156.
 115. Fliefel R, Kühnisch J, Ehrenfeld M, Otto S. Gene therapy for bone defects in oral and maxillofacial surgery: a systematic review and meta-analysis of animal studies. *Stem Cells Dev* 2017;26:215-30.
 116. Mali S. Delivery systems for gene therapy. *Indian J Hum Genet* 2013;19:3-8.
 117. Fischer J, Kolk A, Pautke C, Warnke PH, Plank C, et al. Future of local bone regeneration-protein versus gene therapy. *J Cranio Maxill Surg* 2011;39:54-64.
 118. Franceschi RT, Yang S, Rutherford RB, Krebsbach PH, Zhao M, et al. Gene therapy approaches for bone regeneration. *Cells Tissues Organs* 2004;176:95-108.
 119. Luo J, Sun MH, Kang Q, Peng Y, Jiang W, et al. Gene therapy for bone regeneration. *Curr Gene Ther* 2005;5:167-79.
 120. Balmayor ER, van Griensven M. Gene therapy for bone engineering. *Front Bioeng Biotechnol* 2015;3:9.
 121. Tarassoli P, S Khan W, Hughes A, Heidari N. A review of techniques for gene therapy in bone healing. *Curr Stem Cell Res Ther* 2013;8:201-9.

Review

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Advances in microsurgery for upper and lower extremity reconstruction and limb preservation

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Abstract

In the recent decades, microsurgical reconstruction has evolved from simple survival of the affected extremity to the improvement of functional and aesthetic outcome. This review retraces the main contributions to the advances of microsurgery for reconstruction of upper and lower extremities and limb preservation. In the upper extremity, it is important to restore fine motility, together with allowing prompt mobilization. In the lower limb, care must be taken in the reconstruction of weight-bearing areas and the aim must be proper ambulation and shoe wearing. Local perforator flaps can be considered for medium size defects. They provide thin coverage and can be performed in short operating time. Their use, though, is often limited by tissue availability. Free flaps allow to overcome this problem and, thanks to the recent development in the study of perforator vessels, the microsurgeon can choose the flap with the most appropriate characteristics. Chimeric flaps can accomplish simultaneous reconstruction of different tissue components and large bone defects often require vascularized bone reconstruction. When dealing with limb preservation it is very important to consider residual functionality. Functioning muscle transfer and targeted muscle re-innervation can be performed in these cases. A useful reconstructive tool in severely damaged limbs with limited blood supply is the use of cross-leg free flaps. In conclusion, extremity reconstruction and limb preservation are reaching new heights thanks, not only to the work of plastic surgeons, but also to the new developments in other fields of study such as oncology, traumatology, radiology and medical engineering.

Keywords: Extremity reconstruction, functional and aesthetic outcome, limb salvage, perforator flaps, free flaps, weight-bearing areas, cross-leg flaps



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INTRODUCTION

Nowadays, the development of both trauma care and oncological treatments increased the number of situations in which plastic surgeons are called to perform difficult limb salvage and complex, tridimensional reconstructions. Fortunately, sophistication of microsurgical techniques and improvements in the comprehension of the blood supply to tissues in different areas of the body allow the ongoing evolution of reconstructive tissue transfer^[1]. This enables surgeons, not only to extend the indication for limb preservation but also to obtain better results, in terms of both aesthetic and function recovery. Due to their highly specific characteristics, the techniques and goals of reconstruction are different in the upper and lower extremity. The upper limb represents the area responsible for fine movements essential in everyday life, but it is also often exposed and involved in social relations. Therefore, both functional and aesthetical reconstruction should be achieved. In the lower extremity, reaching a functional reconstruction that allows the patient to walk properly without pain is the primary goal, even though, nowadays, reaching an aesthetic reconstruction is always desirable, when possible^[2-4]. Today, many have come to agree that a microsurgical approach is the standard of care in most cases of extremity reconstruction and limb preservation^[5]. Many different flaps can be used in order to reconstruct bone defects, muscular function and soft tissue coverage. Advances in microsurgery allows to overstep Levin's reconstructive ladder with specific and patient-customized reconstructive approaches^[6-9].

Upper extremity

Defects of the upper extremity may involve different tissue types with specific functions (i.e., muscles or tendons involved in hand and finger mobility) and large coverage area that allows secondary procedures, if needed^[10]. It would be preferable to avoid flaps that need to sacrifice the radial or ulnar artery, in order not to alter and diminish the vascular inflow and outflow from the already damaged limb, causing not only sensory alteration and cold intolerance but also chronic edema and tissue ischemia^[11-13]. If the function of flexors or extensors of fingers or other joints (i.e., wrist or elbow) is damaged, a functioning muscle transfer may be used^[14,15]. Goal of upper limb reconstruction is to restore fine functions of the hand, together with aesthetic coverage that allows prompt mobilization of the hand and joints in order to avoid stiffness from prolonged immobilization.

Lower extremity

When planning a microsurgical reconstruction, it has to be taken into account that the lower limb presents greater risks compared to other districts^[16]. These are represented by the status of the vascular network in the lower extremity, which may be affected by many conditions such as peripheral vascular disease or diabetes, and also by the fact that the area is responsible for weight bearing. The skin coverage in most of the lower leg is thin and tight over muscles and sometimes directly over the bone^[17,18]. Sometimes circumferential coverage is needed and post-operative edema and scarring have to be taken into consideration^[18]. Therefore, lower limb reconstruction is one of the most challenging, with a higher incidence of free flap loss compared to microsurgical reconstructions performed in other districts^[19-23]. Patients in need of lower extremity reconstruction also include various number of traumatic injuries. For this reason, it is extremely important, in evaluating the patient and developing the reconstructive strategy, to assess the condition of vessels in the extremity^[20]. When Gustilo classification system was firstly introduced, it already highlighted the fact that limb perfusion was essential in determining reconstructive options. In fact, type IIIC describes devascularized limbs needing vascular repair as having the worst prognosis^[24,25]. Goal of lower limb reconstruction is to restore the fundamental functions, the possibility to walk and wear shoes, together with proper coverage in order to avoid recurrent ulceration and acceptable aesthetic result.

SOFT TISSUE COVERAGE

Local perforator flaps

Over the past two decades the indications for perforator flaps reconstruction have increased due to the better understanding of the anatomy and distribution of perforator vessels^[5,26]. These flaps can be used as local flaps and transposed to the defect through a wide range of movements (i.e., V-Y advancement, rotation, *etc.*)^[27-30]. A propeller perforator flap is, according to Tokyo consensus, “a perforator flap with a skin island made of two paddles, one larger and one smaller, separated by the nourishing perforating vessel that corresponds to the pivot point”^[31]. Propeller perforator flaps have a low donor-site morbidity due to conservation of source vessels and muscles and provide like-with-like tissue coverage in terms of color match, thickness and texture. These flaps can be raised in a short time and can be designed almost in every location. Local flaps can be contraindicated in trauma patients, when the extent and the characteristics of the injury affect the viability of the surrounding tissues, for example in degloving injuries. Another questionable fact is that the vessel chosen for these flaps is usually close to the injured area but, if the perforator is not directly damaged, it usually does not undermine the flap survival^[32]. In patients with compromised general conditions, the time and cost saving procedures, sparing multiple surgical sites, can be a first choice^[33-37]. It is also true, though, that propeller perforator flaps have been related to higher rates of complications, such as partial flap necrosis and venous congestion. Such complications appear to be related to two main topics, still objects of debate, regarding propeller flaps: dimensional limit and arc of rotation. The limit in terms of size of these flaps is hard to determine due to the dynamicity of adjacent perforasomes recruitment which depends on many different factors^[38]. The arc of rotation, instead, has been determined to be related to the length of the pedicle and its proper and wide dissection^[39-41].

In limb reconstruction, local propeller perforator flaps can be considered as an important tool for the reconstruction of small and medium size defects. Due to the lack of tissues in the limbs, attention has to be paid to donor site morbidity. In the upper limb, direct donor site closure can be achieved for flaps with 4 cm of width or less in the forearm, and 2 cm in the dorsum of the hand. Partial donor site closure can be performed in greater defects, and total closure attained with skin grafting^[32].

Useful propeller perforator flaps of the upper limb are the one based on radial artery perforators and ulnar artery perforators. They are both pliable, thin, have a very good texture match, and can be used as sensate flaps, which is very important in upper limb reconstructions. If multiple tissue types are needed their harvest can incorporate bone and portions of tendons and muscles. If these flaps are based on proximal perforators they can be used for proximal defects, such as the elbow region, whereas, if they are based on distal perforators they can provide tissue coverage for the wrist area and the hand. In terms of donor site morbidity, the ulnar artery propeller perforator flaps have the advantage of a minor tendon exposure, especially if raised in the proximal forearm^[42]. Posterior and anterior interosseous artery propeller perforator flap can be used for the dorsum of the hand because of their characteristics very similar to the hand structure^[43]. For small defects of the hand and fingers, both volar and dorsal, another good option is the dorsal metacarpal artery perforator flap.

In the lower extremity, according to 2016 Bekara's meta-analysis, the most used propeller perforator flaps are posterior tibial artery perforator (58.6%), peroneal artery perforator (30.1%), sural artery perforator (medial or lateral, 5.6%), metatarsal artery perforator (2.0%) and anterior tibial artery perforator (1.6%)^[44]. Flap selection is usually based on the location of the defect and on the study of the perforators in the nearby area. Preoperative color Doppler ultrasound can be used to detect adjacent perforator vessels with suitable caliber and blood flow. Usually vessel selection includes vessels in a 2-10 cm range from the defect, with caliber greater than 0.6 mm. After the choice of the perforator, the design of the propeller flap is performed^[45]. In terms of complication rates of propeller perforator flaps in the lower limb, two recent review articles by Gir and Nelson reported analogous results (11% of partial flap necrosis in both studies,

and 1% and 5% of total necrosis)^[46,47]. Bekara *et al.*^[44] in 2016 presented a comparison between free flaps and pedicled propeller flaps in the distal third of the lower extremity by performing a systematic review with meta-analysis of all published data. In order to analyze the data, they included under “coverage failure” both partial and total flap necrosis needing a second reconstructive procedure. They did not find a statistical significance in the difference of coverage failure between the two groups, even though it was rather more frequent in the free flaps group. On the other hand, partial necrosis affected more the propeller flaps group, but not undermining their overall success rates. By showing that complication rates were comparable in the two groups, they suggested that the flap of choice may be decided depending on defect size, using pedicled-propeller flaps for smaller defects and free flaps for larger ones.

Free flaps

Despite all the stated above on pedicled perforator flaps, it is true that free flaps present many advantages which makes them an irreplaceable tool in extremity reconstruction. Pedicled flaps are inevitably limited by restricted tissue accessibility and characteristics^[48]. On the other hand, free flaps can be chosen and custom designed according to the defect^[1]. Characteristics of an ideal free flap are similarity with defect area and tissue reliability to allow secondary surgeries. Donor-site morbidity should be minimal. A long pedicle is always an advantage because it allows safer microanastomosis, further away from the wounded area^[49,50]. In upper extremity reconstruction, it is advisable to perform end-to-side anastomosis in order to spare main vascular axis and avoid reducing hand perfusion^[51]. Muscular, fasciocutaneous and cutaneous flaps can all be used in extremity reconstruction.

Muscle flaps

For many years muscle flaps have been the first choice for the lower limb reconstruction and are still a reliable option in many cases. Muscular flaps were preferred because of their usually long pedicle, relatively easy harvest, capability of obliterating dead space in large defects and better conforming to the irregular surface of the wound or plates used for bone fixation^[52]. Due to their capacity of improving blood supply, their use have also been indicated when dealing with wounds with high infection risk^[53,54]. Even in the upper extremity they have been used for large defects, in particular in the proximal arm, where they are still bulky at the beginning, but, thanks to progressive atrophy and revisions it is possible to obtain acceptable results^[10,55]. However, muscle flaps have downsides such as sacrificing a functioning muscle and requiring coverage, often with skin grafts. This affects the aesthetic appearance of the reconstruction. Moreover, muscle flaps may limit tendon gliding and their elevation for secondary surgeries (i.e., tenolysis) is harder^[51]. Most commonly used muscle flaps are, according to many authors, latissimus dorsi, serratus anterior, rectus abdominis and gracilis^[56-58]. The latissimus dorsi presents many advantages and it is a considered a “workhorse” flap. It is the largest muscle available and is a very good option for covering large areas, including exposed tendons, nerves and bone. Its dissection is quite easy and its pedicle has reasonable length and caliber, making it a reliable flap^[52,59]. It may be necessary, depending on the defect, to change the position of the patient for flap harvesting and this can be time and effort consuming. The same disadvantage has to be considered for serratus anterior muscle flap, together with the difficulties in sparing the long thoracic nerve during pedicle dissection, in order to avoid winged scapula^[60-63]. The serratus anterior flap can be raised as a small muscle flap with a long pedicle, and it is usually indicated in smaller defects without close recipient vessels. Portion of a rib can be raised with the flap if a bone component is needed for reconstruction. The rectus abdominis muscle flap is a bulky flap suitable for obliterating space in deep, moderate-size wounds. Donor site morbidity is its major concern, with abdominal bulge and hernia formation^[11,64-66]. Free muscle flaps are also used for functioning muscle transfer in upper and lower extremity. The latissimus dorsi flap can be used by harvesting the thoracodorsal nerve, which is responsible for its motor function, but, in many cases gracilis flap is preferred. The gracilis muscle has similar characteristics to the muscles of the forearm and a tendinous portion suitable for digits tendon attachment. For these reasons, gracilis flap is a very useful flap in finger function restoration with very little donor site morbidity^[1].

Cutaneous and fasciocutaneous flaps

Compared to muscle flaps, fasciocutaneous flaps allow supple and thin coverage with ideal surfacing, without needing skin grafting. They are also better re-elevated in case of secondary surgeries^[17,56,57]. Due to the many different perforator flaps described, it is often possible to choose a flap with suitable characteristics without needing to change the patient's position, and often allowing a two-team approach in order to reduce operative time. If the deep fascial layer is not needed for reconstructive purposes, cutaneous flaps can be elevated above it, including suprafascial components nourished by the perforator vessel. Preserving the deep fascia reduces donor site morbidity and chances of muscle herniation. It also allows harvesting thinner and more pliable flaps, which can be designed in order to better match the characteristics of the defect. Sensory nerves can be included for reinnervation and superficial veins to increase the venous outflow^[67]. The flap can be thinned during or immediately after harvesting, hence maximizing aesthetic results with a reduced need for surgical revisions^[68]. Obviously, the perforator dissection of these flaps is technically demanding and it may result in small caliber vessels anastomosis, requiring high surgical skills and knowledge of vascular anatomy^[69,70]. The characteristics of these flaps have increased their use as first option in difficult upper limb reconstructions, where it is extremely important to achieve optimal coverage and early rehabilitation.

Wang *et al.*^[51] in 2017 reviewed the evidence for application of different important perforator flaps in upper extremity reconstruction, such as the anterolateral thigh (ALT), superficial circumflex iliac perforator (SCIP), deep inferior epigastric perforator (DIEP) and superficial inferior epigastric artery (SIEA) flaps. The ALT resulted in being the most versatile flap, due to the possibility of harvesting it thicker or thinner, therefore functional both in larger defects of the proximal arm and distally, where a thin and supple flap is needed. The SCIP flap finds its indication in the hand and wrist area [Figure 1] whereas the DIEP and SIEA flaps are better suited for the proximal arm. Many authors have reported the use of free fasciocutaneous flaps in the lower extremity, even in complicated cases with open fractures, chronic osteomyelitis, diabetic complications and limb salvage^[56,57,71-75]. The ALT is the flap of choice in many cases, especially in open traumatic wounds, with fractures of the tibia, ankle and foot^[57,58,72]. It can be utilized with a portion of the fascia lata to reconstruct tendons as well (i.e., the Achilles)^[76]. Abdelfattah *et al.*^[5] evaluated free perforator flaps, other than ALT, for the reconstruction of lower limb defects, including superficial circumflex iliac perforator (SCIP), gluteal artery perforator (GAP), thoracodorsal artery perforator (TDAP), deep inferior epigastric perforator (DIEP), posterior interosseous artery perforator (PIAP), upper medial thigh perforator, and medial sural artery perforator (MSAP) flaps in their 563 cases experience. They propose an algorithm for flap selection based on the characteristics of each flap^[5]. Other than the already described ALT, SCIP and DIEP flaps, GAP flaps appeared to be indicated in moderate size defects located in the posterior body surface but, as a drawback, they have a short pedicle and may require supermicrosurgical technique^[77,78]. TDAP flap on the other hand have a long pedicle and can be utilized as a composite flap by harvesting it with scapular bone^[79,80]. PIAP and MSAP flaps provide excellent single-stage coverage for small defects in the lower leg and foot^[81]. This study suggests the reliability of free perforator flap reconstruction for lower extremity defects. Their series of 552 patients had a high success rate (96.2%), even though they treated a large number of diabetic limb salvage cases. Previous works reported achieving similar rates of success in using perforator flaps in complicated lower extremity reconstructions^[17,56,57,74,75].

WEIGHT-BEARING ISSUE IN THE LOWER LIMB

In lower limb reconstruction weight-bearing areas may be involved, where the epidermal-dermal layer is thicker and attached, through fibrous connective tissue, to the plantar aponeurosis. Fat lobules are located within these fibrous septa. This structure provides shock-absorbing function and prevents shear^[82]. In order to reconstruct this area like-with-like, the medial plantar flap was introduced. It was initially described as a cross-leg flap but it has been used since, both as pedicled, for ipsilateral defects, and as a

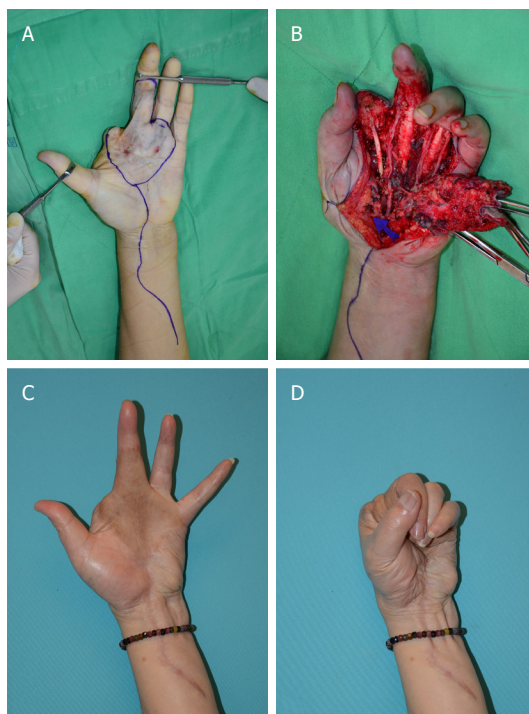


Figure 1. A: The 45-year-old woman was affected by arteriovenous malformation of the left hand. The index finger had been previously amputated due to recurrent and excessive bleeding. Before surgery, the residual lesion was marked according to angiography study; B: the arteriovenous malformation was excised, after delicate dissection, under the aid of tourniquet; C: the defect was covered with a thin SCIP flap. It provided good coverage of the tendons and nerves. Postoperatively, the range of movement was satisfactory. This picture shows complete extension of fingers; D: good dexterity of fingers was achieved with thin flap coverage. As shown, the patient can completely flex the fingers and good sensation of the finger tips was preserved

free flap^[83-85]. It can be used as a sensate flap, offering ideal tissue for medium-sized defects with low donor site morbidity, therefore an excellent option for coverage of the heel or the forefoot^[86]. In reconstruction of larger weight bearing areas free flaps are needed and the choice between muscle or fasciocutaneous flaps can be difficult. Fasciocutaneous flaps have the advantage of providing supple tissue that allows aesthetical and, if innervated, sensate reconstruction. On the other hand, they present high shear modulus in the subcutaneous tissue, therefore determining instability^[87,88]. The same problem affects muscle flaps, but it seems to reduce with progressive muscle fibrosis due to atrophy. Over time, also the appearance of skin grafted muscle flaps improves. They may still, though, incur in ulceration due to lack of sensation^[89]. Fox *et al.*^[90] in 2015 performed a systematic review in order to evaluate the outcomes of heel reconstruction with fasciocutaneous or muscle free flaps. They analyzed outcomes in terms of complication rate, revision surgeries, time to mobilization and requirement for specialized footwear. Their work reported no significant differences between the two groups, even though they admit that “the current evidence is largely limited to small cohort studies (level IV evidence)”^[90].

BONE RECONSTRUCTION

In the upper extremity, bone defects greater than 6 cm, both resulting from oncological resections or traumatic injuries usually require a vascularized bone transfer, especially if there is risk of infection. The free fibula flap is ideal for reconstruction of the long bones of the arm, due to its characteristics and shape^[91-93]. Its harvest presents low donor site morbidity, mostly represented by flexion contracture of the great toe and ankle pain^[94-96]. The medial femoral condyle is a valuable option in smaller upper extremity bone defects, in particular in the carpal region. This vascularized cancellous bone can be used to treat non-union and avascular necrosis of the scaphoid^[97,98]. Donor site morbidity is represented by knee pain and seroma formation^[99].



Figure 2. A: 32-year-old woman with necrosis of the skin of the right heel and part of the calcaneus secondary to crush injury due to motorcycle accident; B: an iliac osteocutaneous flap designed from the right groin area; C: the flap provided simultaneous skin coverage and bone reconstruction for the defect of calcaneus. The soft tissue of the flap was trimmed to fit the contour of the heel; D: the postoperative contour was good and the patient could wear regular shoes

In the lower limb, the loss of a significant portion of the tibia, both traumatic or due to oncological resections, can be difficult to treat. Even though critical-sized tibial bone defects are common, their treatment still represents a challenge. A strategy frequently used in orthopedic surgery is bone transport, which consists of the gradual and progressive translocation of a section of bone to the defect from an healthy area in proximity^[100]. Traumatic injuries though, often present with open fractures and soft tissue defects, increasing the risk of infections. A microvascular bone flap transfer is usually indicated in bone gaps greater than 6 cm. Again the “workhorse” is considered the free fibula flap^[101]. For coverage and monitoring purposes, a skin paddle is often harvested with the flap. Even though bone stabilization is needed, it is important to minimize it in order to avoid compromising the blood supply to the transferred bone^[102]. Weight-bearing need to be progressive and complete healing may take up to 6 months^[103]. If the bone defect affects the calcaneus, for example after total calcanectomy, the reconstruction needs to focus both on the weight-bearing forces involved and on functional outcome. Bone reconstruction depends on defect size and can range from bone allografts to free vascularized bone transfer such as fibula flap or iliac crest flap^[104] [Figure 2]. Reconstruction of Achilles tendon have to be performed in order to restore function^[105].

DEVASCULARIZED LIMBS

When dealing with severe mutilating upper and lower extremity injuries with devascularized limbs, the progress made by reconstructive microsurgery, together with progresses in trauma management, microvascular techniques, and skeletal fixation have helped developing stronger reconstructive alternatives to amputation. Even when amputation is necessary, the new approach with targeted muscle reinnervation have shown encouraging results in treating neuroma and phantom limb pain. Moreover, technologic developments in robotics and signal processing, as well as advancements in neuroplasticity research keep

expanding targeted muscle reinnervation applications in prosthesis control^[106]. Older studies reported complex Gustilo type IIIC injuries result in very high amputation rates, together with high and unjustified costs for the healthcare system and the patients^[107-109]. Recent studies, though, evaluated the impact of salvaged limbs both on patients' quality of life and costs for the healthcare system, suggesting it to be beneficial in both instances^[110,111]. Moreover, in these complicated cases, the introduction of devices such as the topical negative pressure therapy, has allowed surgeons to improve the local general conditions in terms of reduction of bacterial load and creation of a wound bed more suitable for a reconstructive attempt. Despite this, the management of these complex injuries is still debated. It has been demonstrated by several studies that vascular injury increases the severity of trauma^[23]. Stranix *et al.*^[20], compared Gustilo IIIB injuries with increasing arterial injury, finding that limbs with a single vessel uninjured had higher flap failure risk^[20]. A recent work by Ricci *et al.*^[112] though, compared the reconstructive outcomes of patients with Gustilo type IIIC injuries after emergent revascularization in order to determine whether there was an optimal treatment algorithm. According to their results, the rates of complications in these patients were comparable with the routinely reconstructed type IIIB injuries, therefore worth considering for limb salvage.

Both in upper and lower extremity, if the vascular defect is located within the soft-tissue defect, a flow-through flap can be considered as a reconstructive option. It may allow reconstruction of both vascular continuity and coverage with a single procedure^[113]. Different studies have shown that free flow-through flaps can be useful for emergency treatment of complex limb injuries with high success rate^[113,114]. Even though bringing a vascularized tissue to the injured leg or arm can already be beneficial for the overall blood supply of the region, a flap with flow-through anastomosis will certainly increase the perfusion of the distal limb. This also present other advantages such as increasing direct venous return and reducing edema formation, therefore improving the salvage rates^[114]. Fujiki *et al.*^[115] analyzed whether flow-through anastomosis affects the failure rate of free flaps, compared with traditional end-to-end and end-to-side anastomosis techniques. According to their clinical findings, in the leg, flow-through anastomosis for both the artery and vein had an excellent success rate. Moreover, flow-through venous anastomosis tended to reduce failure rates compared with conventional techniques.

Sometimes in devascularized limb salvage, local tissue is not available and direct free flap reconstruction can't be performed due to the lack of adequate recipient vessels^[116]. Since World War II, a valuable option in these cases have been represented by cross-leg flaps, giving the possibility of transferring contralateral healthy tissue to the injured lower limb^[117,118]. The use of this technique has continued over time, with different cross-leg flaps reported, and satisfying outcomes^[119-121]. Advances in microsurgical techniques have enhanced direct reconstruction but, some of the new concepts, such as free flaps and flow-through flaps, can be applied also to cross-leg flaps. Cross-leg free flaps can therefore be performed as a free flap firstly anastomosed to contralateral recipient vessels and then, secondarily, autonomized on the affected limb random blood supply. These reconstructive approach, in our experience, can be utilized in the distal third of leg, in case of large size defects with the absence of usable recipient vessels^[122]. When the extent of the injury requires further reach and a longer flap, a flow-through free flap can be used as a carrier for a second free flap. The free cross-leg bridge flap is anastomosed to contralateral recipient vessels granting a sufficient blood supply to the second free flap in order to reach and provide coverage for the entire defect. In our experience, the radial forearm free flap is best suited a vascular bridge flap. The skin paddle can be incised in a "bone" shape, with wider extremities to cover the anastomosis sites. The choice of the second free flap depends on defect size and characteristics. LD or vertical rectus abdominis myocutaneous flaps can be used for wide defects, moreover LD flap can be raised with portion of 1 or 2 ribs, for bony reconstruction. Initially the free flaps were raised in two stages, allowing assessment of the radial forearm flap survival before second flap harvest. In our latest experience, we feel confident that the procedure can be performed in a single stage. In the second surgery, an external fixator is used in order to avoid damages to the flap

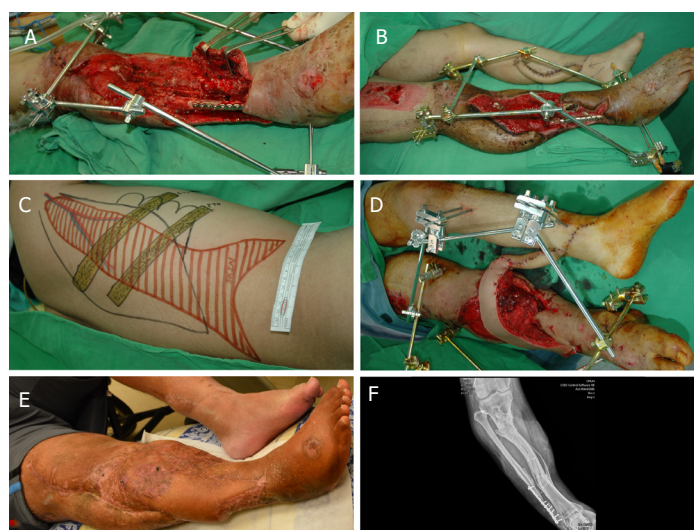


Figure 3. A: The 25-year-old patient had a severe crush injury to his right lower limb in a car accident. The leg survived after thrombectomy of the right femoral artery. There was a 12 cm defect of the right tibia after debridement, and the fractured fibula was plated as shown; B: there was no available recipient artery in the thigh and leg. In the first stage operation, a radial forearm flap was used as a vascular bridge flap, it was connected to the posterior tibial artery of the left leg in end-to-side fashion; C: in the second stage operation, a free flap was harvested from the back, including myocutaneous latissimus dorsi and the lower part of serratus muscle, carrying two ribs (6th and 8th); D: the flaps were connected to the free end of radial forearm flap. The two legs were temporarily bound together with an external skeletal fixator; E: four weeks later, the bridge was divided and part of the radial forearm flap was used for coverage of the residual defect of the right leg; F: bone union was achieved and, with proper physiotherapy, the right leg was gradually trained to resume weight-bearing. As shown, the ribs increased thickness, in a long term follow up

pedicle. In the meantime, the patients undergo physical therapy to preserve muscle status and function during immobility. After 3-4 weeks, the flaps undergo ischemic preconditioning by clamping the pedicle every day for 15 minutes. Indocyanine green angiography can be used to assess the flap neovascularization from the wound, by temporarily clamping the main pedicle. Only when flap perfusion has been assessed and found sufficient, the bridge is divided and skin closure achieved, also by using tissues from the vascular bridge flap to cover any residual areas. Manrique *et al.*^[122] in 2018 described our experience with cross-leg flaps by performing a retrospective review of a case series of 53 patients treated between 1985 and 2017 in China Medical University Hospital, Taichung, Taiwan and Mayo Clinic, Rochester, MN, USA. The average follow-up time was 7.5 years. Complications rates were low (with two flap loss) and the overall limb salvage rate was 96.2%. In our hands, cross-leg flaps, enhanced by the latest microsurgical developments, can still represent an option to avoid amputation in challenging lower extremity reconstructions, where no suitable vessels are found [Figure 3].

CONCLUSION

Up to date, many different options are available to reconstructive microsurgeons, therefore extremity reconstruction is reaching new levels of sophistication and the possibility of limb preservation is widening. It is important to remember, though, that this depends not only on the work of plastic surgeons, but also on their ability to interact with other practitioners and profit from new developments in other fields of study such as oncology, traumatology, radiology and medical engineering.

DECLARATIONS

Authors' contributions

Manuscript preparation and critical review: Bolletta A, Corrado R, Chen HC

Data collection: Bolletta A, Chen HC

Performance of surgery: Chen HC

Availability of data and materials

The authors confirm that the data supporting the findings of this study are available within the article.

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None.

Conflicts of interest

The authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

This study was performed with respect to the ethical standards of the Declaration of Helsinki, as revised in Tokyo 2004. Informed consent to participate was obtained from patients.

Consent for publication

Consent for publication was obtained from the patients.

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REFERENCES

1. Dibbs R, Grome L, Pederson WC. Free tissue transfer for upper extremity reconstruction. *Semin Plast Surg* 2019;33:17-23.
2. Engel H, Lin CH, Wei FC. Role of microsurgery in lower extremity reconstruction. *Plast Reconstr Surg* 2011;127 Suppl 1:228S-38.
3. Hollenbeck ST, Woo S, Komatsu I, Erdmann D, Zenn MR, et al. Longitudinal outcomes and application of the subunit principle to 165 foot and ankle free tissue transfers. *Plast Reconstr Surg* 2010;125:924-34.
4. Lee SH, Suh JT, Ahn TY, Hong SM, Lee HY. Differences between the upper extremity and the lower extremity in reconstruction using an anterolateral thigh perforator flap. *Clin Orthop Surg* 2017;9:348-54.
5. Abdelfattah U, Power HA, Song S, Min K, Suh HP, et al. Algorithm for free perforator flap selection in lower extremity reconstruction based on 563 cases. *Plast Reconstr Surg* August 2019; doi: 10.1097/PRS.00000000000006167.
6. Levin LS. The reconstructive ladder. An orthoplastic approach. *Orthop Clin North Am* 1993;24:393-409.
7. Gottlieb LJ, Krieger LM. From the reconstructive ladder to the reconstructive elevator. *Plast Reconstr Surg* 1994;93:1503-4.
8. Knobloch K, Vogt PM. The reconstructive clockwork of the twenty-first century: an extension of the concept of the reconstructive ladder and reconstructive elevator. *Plast Reconstr Surg* 2010;126:220e-2.
9. Schmidt K, Jakubietz MG, Gilbert F, Hausknecht F, Meffert RH, et al. Quality of life after flap reconstruction of the distal lower extremity: is there a difference between a pedicled suralis flap and a free anterior lateral thigh flap? *Plast Reconstr Surg Glob Open* 2019;7:e2114.
10. King EA, Ozer K. Free skin flap coverage of the upper extremity. *Hand Clin* 2014;30:201-9.
11. Chim H, Ng ZY, Carlsen BT, Mohan AT, Saint-Cyr M. Soft tissue coverage of the upper extremity: an overview. *Hand Clin* 2014;30:459-73.
12. Chim H, Bakri K, Moran SL. Complications related to radial artery occlusion, radial artery harvest, and arterial lines. *Hand Clin* 2015;31:93-100.
13. Heller F, Wei W, Wei FC. Chronic arterial insufficiency of the hand with fingertip necrosis 1 year after harvesting a radial forearm free flap. *Plast Reconstr Surg* 2004;114:728-31.
14. Terzis JK, Kostopoulos VK. Free muscle transfer in posttraumatic plexopathies: part III. The hand. *Plast Reconstr Surg* 2009;124:1225-36.
15. Kay S, Pinder R, Wiper J, Hart A, Jones F, et al. Microvascular free functioning gracilis transfer with nerve transfer to establish elbow flexion. *J Plast Reconstr Aesthetic Surg* 2010;63:1142-9.
16. Pu LLQ. A comprehensive approach to lower extremity free-tissue transfer. *Plast Reconstr Surg Glob Open* 2017;5:e1228.
17. Cho EH, Shammam RL, Carney MJ, Weissler JM, Bauder AR, et al. Muscle versus fasciocutaneous free flaps in lower extremity traumatic reconstruction: a multicenter outcomes analysis. *Plast Reconstr Surg* 2018;141:191-9.
18. Bajantri B, Bharathi RR, Sabapathy SR. Wound coverage considerations for defects of the lower third of the leg. *Indian J Plast Surg* 2012;45:283-90.
19. Ricci JA, Crawford K, Ho OA, Lee BT, Patel KM, et al. Practical guidelines for venous thromboembolism prophylaxis in free tissue transfer. *Plast Reconstr Surg* 2016;138:1120-31.
20. Stranix JT, Lee ZH, Jacoby A, Anzai L, Avraham T, et al. Not all gustilo type IIIB fractures are created equal: arterial injury impacts limb salvage outcomes. *Plast Reconstr Surg* 2017;140:1033-41.
21. Ricci JA, Koolen PG, Shah J, Tobias AM, Lee BT, et al. Comparing the outcomes of different agents to treat vasospasm at

- 14 microsurgical anastomosis during the Papaverine shortage. *Plast Reconstr Surg* 2016;138:401e-8.
22. Khouri RK, Shaw WW. Reconstruction of the lower extremity with microvascular free flaps: a 10-year experience with 304 consecutive cases. *J Trauma* 1989;29:1086-94.
23. Stranix JT, Lee ZH, Anzai L, Jacoby A, Avraham T, et al. Optimizing venous outflow in reconstruction of Gustilo IIIB lower extremity traumas with soft tissue free flap coverage: are two veins better than one? *Microsurgery* 2018;38:745-51.
24. Gustilo RB, Anderson JT. Prevention of infection in the treatment of one thousand and twenty-five open fractures of long bones: retrospective and prospective analyses. *J Bone Joint Surg Am* 1976;58:453-8.
25. Gustilo RB, Mendoza RM, Williams DN. Problems in the management of type III (severe) open fractures: a new classification of type III open fractures. *J Trauma* 1984;24:742-6.
26. Bulla A, Bolletta A, Fiorot L, Maffei M, Bandiera P, et al. Posterior tibial perforators relationship with superficial nerves and veins: A cadaver study. *Microsurgery* 2019;39:241-6.
27. Georgescu AV, Capota I, Matei I, Ardelean F, Avram A, et al. The place of local/regional perforator flaps in complex traumas of the forearm. *J Hand Microsurg* 2009;1:25-31.
28. Georgescu AV, Matei I, Ardelean F, Capota I. Microsurgical nonmicrovascular flaps in forearm and hand reconstruction. *Microsurgery* 2007;27:384-94.
29. Losco L, Lo Torto F, Maruccia M, Di Taranto G, Ribuffo D, et al. Modified single pedicle reverse adipofascial flap for fingertip reconstruction. *Microsurgery* 2019;39:221-7.
30. Innocenti M, Baldrighi C, Delcroix L, Adani R. Local perforator flaps in soft tissue reconstruction of the upper limb. *Handchir Mikrochir Plast Chir* 2009;41:315-21.
31. Pignatti M, Ogawa R, Hallock GG, Mateev M, Georgescu AV, et al. The “Tokyo” consensus on propeller flaps. *Plast Reconstr Surg* 2011;127:716-22.
32. Georgescu AV, Matei IR. Propeller perforator flaps in forearm and hand reconstruction. *Eur J Orthop Surg Traumatol* 2019;29:357-66.
33. Lecours C, Saint-Cyr M, Wong C, Bernier C, Mailhot E, et al. Freestyle pedicle perforator flaps: clinical results and vascular anatomy. *Plast Reconstr Surg* 2010;126:1589-603.
34. Matei I, Georgescu A, Chiroiu B, Capota I, Ardelean F. Harvesting of forearm perforator flaps based on intraoperative vascular exploration: clinical experiences and literature review. *Microsurgery* 2008;28:321-30.
35. Lee BT, Lin SJ, Bar-Meir ED, Borud LJ, Upton J. Pedicled perforator flaps: a new principle in reconstructive surgery. *Plast Reconstr Surg* 2010;125:201-8.
36. Georgescu AV. Propeller perforator flaps in distal lower leg: evolution and clinical applications. *Arch Plast Surg* 2012;39:94-105.
37. van Waes OJF, Halm JA, Vermeulen J, Ashford BG. “The Practical Perforator Flap”: the sural artery flap for lower extremity soft tissue reconstruction in wounds of war. *Eur J Orthop Surg Traumatol Orthop Traumatol* 2013;23 Suppl 2:S285-9.
38. Innocenti M, Menichini G, Baldrighi C, Delcroix L, Vignini L, et al. Are there risk factors for complications of perforator-based propeller flaps for lower-extremity reconstruction? *Clin Orthop* 2014;472:2276-86.
39. Gokrem S, Sarifakioğlu N, Toksoy K, Terzioğlu A, Aslan G. Effects of 360-degree pedicle torsion on island skin flaps: experimental study in rats. *J Reconstr Microsurg* 2005;21:313-6.
40. Selvaggi G, Anicic S, Formaggia L. Mathematical explanation of the buckling of the vessels after twisting of the microanastomosis. *Microsurgery* 2006;26:524-8.
41. Topalan M, Bilgin SS, Ip WY, Chow SP. Effect of torsion on microarterial anastomosis patency. *Microsurgery* 2003;23:56-9.
42. Koshima I, Moriguchi T, Etoh H, Tsuda K, Tanaka H. The radial artery perforator-based adipofascial flap for dorsal hand coverage. *Ann Plast Surg* 1995;35:474-9.
43. Hubmer MG, Fasching T, Haas F, Koch H, Schwarzl F, et al. The posterior interosseous artery in the distal part of the forearm. Is the term “recurrent branch of the anterior interosseous artery” justified? *Br J Plast Surg* 2004;57:638-44.
44. Bekara F, Herlin C, Somda S, de Runz A, Grolleau JL, et al. Free versus perforator-pedicled propeller flaps in lower extremity reconstruction: What is the safest coverage? A meta-analysis. *Microsurgery* 2018;38:109-19.
45. Dong KX, Xu YQ, Fan XY, Xu LJ, Su XX, et al. Perforator pedicled propeller flaps for soft tissue coverage of lower leg and foot defects. *Orthop Surg* 2014;6:42-6.
46. Gir P, Cheng A, Oni G, Mojallal A, Saint-Cyr M. Pedicled-perforator (propeller) flaps in lower extremity defects: a systematic review. *J Reconstr Microsurg* 2012;28:595-601.
47. Nelson JA, Fischer JP, Brazio PS, Kovach SJ, Rosson GD, et al. A review of propeller flaps for distal lower extremity soft tissue reconstruction: Is flap loss too high? *Microsurgery* 2013;33:578-86.
48. Herter F, Ninkovic M, Ninkovic M. Rational flap selection and timing for coverage of complex upper extremity trauma. *J Plast Reconstr Aesthetic Surg* 2007;60:760-8.
49. Heller L, Levin LS. Lower extremity microsurgical reconstruction. *Plast Reconstr Surg* 2001;108:1029-41; quiz 1042.
50. Philandrianos C, Moullot P, Gay AM, Bertrand B, Légré R, et al. Soft tissue coverage in distal lower extremity open fractures: comparison of free anterolateral thigh and free latissimus dorsi flaps. *J Reconstr Microsurg* 2018;34:121-9.
51. Wang HD, Alonso-Escalante JC, Cho BH, DeJesus RA. Versatility of free cutaneous flaps for upper extremity soft tissue reconstruction. *J Hand Microsurg* 2017;9:58-66.
52. Ninkovic M, Mooney EK, Ninkovic M, Kleistil T, Anderl H. A new classification for the standardization of nomenclature in free flap wound closure. *Plast Reconstr Surg* 1999;103:903-14; discussion 915-7.
53. Chan JK, Harry L, Williams G, Nanchahal J. Soft-tissue reconstruction of open fractures of the lower limb: muscle versus

- fasciocutaneous flaps. *Plast Reconstr Surg* 2012;130:284e-95.
54. Gosain A, Chang N, Mathes S, Hunt TK, Vasconez L. A study of the relationship between blood flow and bacterial inoculation in musculocutaneous and fasciocutaneous flaps. *Plast Reconstr Surg* 1990;86:1152-62; discussion 1163.
 55. Pederson WC. Upper extremity microsurgery. *Plast Reconstr Surg* 2001;107:1524-37; discussion 1538-9, 1540-3.
 56. Yazar S, Lin CH, Lin YT, Ulusal AE, Wei FC. Outcome comparison between free muscle and free fasciocutaneous flaps for reconstruction of distal third and ankle traumatic open tibial fractures. *Plast Reconstr Surg* 2006;117:2468-75; discussion 2476-7.
 57. Rodriguez ED, Bluebond-Langner R, Copeland C, Grim TN, Singh NK, et al. Functional outcomes of posttraumatic lower limb salvage: a pilot study of anterolateral thigh perforator flaps versus muscle flaps. *J Trauma* 2009;66:1311-4.
 58. Paro J, Chiou G, Sen SK. Comparing muscle and fasciocutaneous free flaps in lower extremity reconstruction--does it matter? *Ann Plast Surg* 2016;76 Suppl 3:S213-5.
 59. Gordon L, Buncke HJ, Alpert BS. Free latissimus dorsi muscle flap with split-thickness skin graft cover: a report of 16 cases. *Plast Reconstr Surg* 1982;70:173-8.
 60. Schaverien MV, Hart AM. Free muscle flaps for reconstruction of upper limb defects. *Hand Clin* 2014;30:165-83, v-vi.
 61. Whitney TM, Buncke HJ, Alpert BS, Buncke GM, Lineaweaver WC. The serratus anterior free-muscle flap: experience with 100 consecutive cases. *Plast Reconstr Surg* 1990;86:481-90; discussion 491.
 62. Logan SE, Alpert BS, Buncke HJ. Free serratus anterior muscle transplantation for hand reconstruction. *Br J Plast Surg* 1988;41:639-43.
 63. Dumont CE, Domenghini C, Kessler J. Donor site morbidity after serratus anterior free muscular flap: a prospective clinical study. *Ann Plast Surg* 2004;52:195-8.
 64. Taylor GI, Corlett RJ, Boyd JB. The versatile deep inferior epigastric (inferior rectus abdominis) flap. *Br J Plast Surg* 1984;37:330-50.
 65. Rao VK, Baertsch A. Microvascular reconstruction of the upper extremity with the rectus abdominis muscle. *Microsurgery* 1994;15:746-50.
 66. Horch RE, Stark GB. The rectus abdominis free flap as an emergency procedure in extensive upper extremity soft-tissue defects. *Plast Reconstr Surg* 1999;103:1421-7.
 67. Hallock GG. A paradigm shift in flap selection protocols for zones of the lower extremity using perforator flaps. *J Reconstr Microsurg* 2013;29:233-40.
 68. Koshima I, Yamamoto T, Narushima M, Mihara M, Iida T. Perforator flaps and supermicrosurgery. *Clin Plast Surg* 2010;37:683-9, vii-iii.
 69. Saint-Cyr M, Wong C, Buchel EW, Colohan S, Pederson WC. Free tissue transfers and replantation. *Plast Reconstr Surg* 2012;130:858e-78.
 70. Taylor GI. The angiosomes of the body and their supply to perforator flaps. *Clin Plast Surg* 2003;30:331-42, v.
 71. Demirtas Y, Kelahmetoglu O, Cifci M, Tayfur V, Demir A, et al. Comparison of free anterolateral thigh flaps and free muscle-musculocutaneous flaps in soft tissue reconstruction of lower extremity. *Microsurgery* 2010;30:24-31.
 72. Park JE, Rodriguez ED, Bluebond-Langer R, Bochicchio G, Christy MR, et al. The anterolateral thigh flap is highly effective for reconstruction of complex lower extremity trauma. *J Trauma* 2007;62:162-5.
 73. Hong JP. The use of supermicrosurgery in lower extremity reconstruction: the next step in evolution. *Plast Reconstr Surg* 2009;123:230-5.
 74. Nazerali RS, Pu LLQ. Free tissue transfer to the lower extremity: a paradigm shift in flap selection for soft tissue reconstruction. *Ann Plast Surg* 2013;70:419-22.
 75. Hong JPI, Goh TLH, Choi DH, Kim JJ, Suh HS. The efficacy of perforator flaps in the treatment of chronic osteomyelitis. *Plast Reconstr Surg* 2017;140:179-88.
 76. Pederson WC, Grome L. Microsurgical reconstruction of the lower extremity. *Semin Plast Surg* 2019;33:54-8.
 77. Hong JP, Koshima I. Using perforators as recipient vessels (supermicrosurgery) for free flap reconstruction of the knee region. *Ann Plast Surg* 2010;64:291-3.
 78. Hong JP, Yim JH, Malzone G, Lee KJ, Dashti T, et al. The thin gluteal artery perforator free flap to resurface the posterior aspect of the leg and foot. *Plast Reconstr Surg* 2014;133:1184-91.
 79. Momeni A, Krischak S, Bannasch H. The thoracodorsal artery perforator flap with a vascularized scapular segment for reconstruction of a composite lower extremity defect. *Microsurgery* 2006;26:515-8.
 80. Kim KN, Hong JP, Park CR, Yoon CS. Modification of the elevation plane and defatting technique to create a thin thoracodorsal artery perforator flap. *J Reconstr Microsurg* 2016;32:142-6.
 81. Yoon CS, Noh HJ, Malzone G, Suh HS, Choi DH, et al. Posterior interosseous artery perforator-free flap: treating intermediate-size hand and foot defects. *J Plast Reconstr Aesthetic Surg* 2014;67:808-14.
 82. Jeng SF, Wei FC. Classification and reconstructive options in foot plantar skin avulsion injuries. *Plast Reconstr Surg* 1997;99:1695-703; discussion 1704-5.
 83. Shanahan RE, Gingrass RP. Medial plantar sensory flap for coverage of heel defects. *Plast Reconstr Surg* 1979;64:295-8.
 84. Koshima I, Urushibara K, Inagawa K, Hamasaki T, Moriguchi T. Free medial plantar perforator flaps for the resurfacing of finger and foot defects. *Plast Reconstr Surg* 2001;107:1753-8.
 85. Zelken JA, Lin CH. An algorithm for forefoot reconstruction with the innervated free medial plantar flap. *Ann Plast Surg* 2016;76:221-6.
 86. Löfstrand JG, Lin CH. Reconstruction of defects in the weight-bearing plantar area using the innervated free medial plantar (Instep) flap. *Ann Plast Surg* 2018;80:245-51.
 87. Sinha AK, Wood MB, Irons GB. Free tissue transfer for reconstruction of the weight-bearing portion of the foot. *Clin Orthop* 1989;(242):269-71.

88. Sönmez A, Bayramiçli M, Sönmez B, Numanoğlu A. Reconstruction of the weight-bearing surface of the foot with nonneurosensory free flaps. *Plast Reconstr Surg* 2003;111:2230-6.
89. Chang KN, DeArmond SJ, Buncke HJ. Sensory reinnervation in microsurgical reconstruction of the heel. *Plast Reconstr Surg* 1986;78:652-64.
90. Fox CM, Beem HM, Wiper J, Rozen WM, Wagels M, et al. Muscle versus fasciocutaneous free flaps in heel reconstruction: systematic review and meta-analysis. *J Reconstr Microsurg* 2015;31:59-66.
91. Kremer T, Bickert B, Germann G, Heitmann C, Sauerbier M. Outcome assessment after reconstruction of complex defects of the forearm and hand with osteocutaneous free flaps. *Plast Reconstr Surg* 2006;118:443-54; discussion 455-6.
92. Soucacos PN, Korompilias AV, Vekris MD, Zoubos A, Beris AE. The free vascularized fibular graft for bridging large skeletal defects of the upper extremity. *Microsurgery* 2011;31:190-7.
93. Houdek MT, Wagner ER, Wyles CC, Nanos GP, Moran SL. New options for vascularized bone reconstruction in the upper extremity. *Semin Plast Surg* 2015;29:20-9.
94. Bodde EWH, de Visser E, Duysens JEJ, Hartman EHM. Donor-site morbidity after free vascularized autogenous fibular transfer: subjective and quantitative analyses. *Plast Reconstr Surg* 2003;111:2237-42.
95. Momoh AO, Yu P, Skoracki RJ, Liu S, Feng L, et al. A prospective cohort study of fibula free flap donor-site morbidity in 157 consecutive patients. *Plast Reconstr Surg* 2011;128:714-20.
96. Rendenbach C, Rashad A, Hansen L, Kohlmeier C, Dyck ML, et al. Functional donor site morbidity longer than one year after fibula free flap: a prospective biomechanical analysis. *Microsurgery* 2018;38:395-401.
97. Jones DB, Rhee PC, Bishop AT, Bishop AT, Shin AY. Free vascularized medial femoral condyle autograft for challenging upper extremity nonunions. *Hand Clin* 2012;28:493-501.
98. Kakar S, Duymaz A, Steinmann S, Shin AY, Moran SL. Vascularized medial femoral condyle corticoperiosteal flaps for the treatment of recalcitrant humeral nonunions. *Microsurgery* 2011;31:85-92.
99. Rao SS, Sexton CC, Higgins JP. Medial femoral condyle flap donor-site morbidity: a radiographic assessment. *Plast Reconstr Surg* 2013;131:357e-62.
100. Aktuglu K, Erol K, Vahabi A. Ilizarov bone transport and treatment of critical-sized tibial bone defects: a narrative review. *J Orthop Traumatol* 2019;20:22.
101. Henry SL, Frome BA, Pederson WC. Vascularized bone transfer for severe injury around the ankle. *Microsurgery* 2009;29:353-60.
102. Pederson WC, Person DW. Long bone reconstruction with vascularized bone grafts. *Orthop Clin North Am* 2007;38:23-35.
103. Pannunzio ME, Chhabra AB, Golish SR, Brown MR, Pederson WC. Free fibula transfer in the treatment of difficult distal tibia fractures. *J Reconstr Microsurg* 2007;23:11-8.
104. Innocenti M, Lucattelli E, Daolio PA, Bastoni S, Marini E, et al. Calcaneal reconstruction after total calcanectomy with iliac crest free flap. *Microsurgery* 2019; doi:10.1002/micr.30452.
105. Li J, Wang Z, Guo Z, Yang M, Chen G, et al. Composite biological reconstruction following total calcanectomy of primary calcaneal tumors. *J Surg Oncol* 2012;105:673-8.
106. Oh C, Carlsen BT. New innovations in targeted muscle reinnervation: a critical analysis review. *JBJS Rev* 2019;7:e3.
107. Flint LM, Richardson JD. Arterial injuries with lower extremity fracture. *Surgery* 1983;93:5-8.
108. Hansen ST. The type-IIIC tibial fracture. Salvage or amputation. *J Bone Joint Surg Am* 1987;69:799-800.
109. Goodman RS. The type-IIIC tibial fracture. Salvage or amputation. *J Bone Joint Surg Am* 1988;70:311.
110. Hertel R, Strebel N, Ganz R. Amputation versus reconstruction in traumatic defects of the leg: outcome and costs. *J Orthop Trauma* 1996;10:223-9.
111. MacKenzie EJ, Jones AS, Bosse MJ, Castillo RC, Pollak AN, et al. Health-care costs associated with amputation or reconstruction of a limb-threatening injury. *J Bone Joint Surg Am* 2007;89:1685-92.
112. Ricci JA, Abdou SA, Stranix JT, Lee ZH, Anzai L, et al. Reconstruction of Gustilo IIIC Injuries of the Lower Extremity. *Plast Reconstr Surg*. 2019; doi: 10.1097/PRS.0000000000006063.
113. Toia F, Zabbia G, Roggio T, Pirrello R, D'Arpa S, et al. Vascular grafts and flow-through flaps for microsurgical lower extremity reconstruction. *J Reconstr Microsurg* 2017;33:S14-9.
114. Zheng X, Zhan Y, Li H, Zhang Z, Xue X, et al. Emergency repair of severe limb injuries with free flow-through chimeric anterolateral thigh perforator flap. *Ann Plast Surg* 2019; doi: 10.1097/SAP.0000000000001913.
115. Fujiki M, Miyamoto S, Sakuraba M. Flow-through anastomosis for both the artery and vein in leg free flap transfer. *Microsurgery* 2015;35:536-40.
116. Ducic I, Rao SS, Attinger CE. Outcomes of microvascular reconstruction of single-vessel lower extremities: limb salvage versus amputation. *J Reconstr Microsurg*. 2009;25:475-8.
117. Stark RB. Pre-operatively applied, mated, plaster of paris casts as an aid in the migration of open-pedicle cross leg flaps. *Plast Reconstr Surg* (1946) 1947;2:433-8.
118. Stark RB. The cross-leg flap procedure. *Plast Reconstr Surg* (1946) 1952;9:173-204.
119. Morris AM, Buchan AC. The place of the cross-leg flap in reconstructive surgery of the lower leg and foot: a review of 165 cases. *Br J Plast Surg* 1978;31:138-42.
120. Yu ZJ, Zeng BF, Huang YC, He HG, Sui SP, et al. Application of the cross-bridge microvascular anastomosis when no recipient vessels are available for anastomosis: 85 cases. *Plast Reconstr Surg* 2004;114:1099-107.
121. Yu L, Tan J, Cai L, Yu G, Tao S, et al. Repair of severe composite tissue defects in the lower leg using two different cross-leg free

composite tissue flaps. *Ann Plast Surg* 2012;68:83-7.

122. Manrique OJ, Bishop SN, Ciudad P, Adabi K, Martinez-Jorge J, et al. Lower extremity limb salvage with cross leg pedicle flap, cross leg free flap, and cross leg vascular cable bridge flap. *J Reconstr Microsurg* 2018;34:522-9.

Review

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Diagnostic workup of lymphedema

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Abstract

Lymphedema is a chronic and progressive pathological state of tissue swelling caused by congenital or acquired lymphatic abnormality. History, physical and laboratory examinations could help to diagnosis > 90% lymphedema patients. Early stage lymphedema could be challenging to diagnose. The aim of this review is to provide an objective appraisal of current diagnostic methods, such as lymphoscintigraphy, lympho-fluoroscopies, lymphangiography and *etc.* focusing on their respective advantages and weaknesses, and hopefully shed some lights on developing a practical diagnosis modality beneficial to early detection and clinical decision making of lymphedema.

Keywords: Lymphedema, diagnosis, lymphoscintigraphy, magnetic resonance lymphangiography, indocyanine green, tissue dielectric constant, bioelectrical impedance spectroscopy

INTRODUCTION

Lymphedema is a pathological state of tissue swelling due to excess protein-rich fluid accumulation in the interstitial space. The equilibrium between load of lymph fluid and transport capacity of the lymphatics is almost invariably disturbed by either congenital dysplasia of the lymphatic system (primary lymphedema) or acquired impairment of the lymphatic drainage (secondary lymphedema). Contrary to all expectations, lymphedema has been reported to affect approximately 300 million people worldwide. The incidence of primary lymphedema is 1 in 100,000 individuals with that of secondary one being 1 in 1000 individuals^[1]. Its global impact may even be severely underestimated resulting from various diagnosis methods and common neglect of the disease. As a chronic and progressive condition, lymphedema, if left



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untreated, could give rise to disabling physical and psychosocial complications in the long run. Currently, the attention on lymphedema is far from enough resulting in delayed initial evaluation and treatment and poor prognosis. There is no existing cure for lymphedema and current therapies mainly focus on limiting progression and preventing severe complications. Early intervention is proved to be the root of improved prognosis thus highlighting the significance of early detection. Various new and effective diagnostic methods emerge over the years but there are still no standard guidelines for lymphedema diagnosis, let alone early detection. The aim of this review is to provide an objective appraisal of current diagnostic methods, focusing on their respective advantages and weaknesses, and hopefully shed some lights on developing a practical diagnosis modality beneficial to early detection and clinical decision making of lymphedema.

HISTORY AND MANIFESTATIONS

For suspected lymphedema patients, history and manifestations are invaluable and indispensable. The onset of swelling could be diagnostic for lymphedema. Extremity swelling present for less than 3 months or forms soon after lymphatic injury is not consistent with lymphedema. It's very common to see pediatrics-onset in primary lymphedema, boys' present in infancy and girls' during adolescence^[2]. For secondary lymphedema, travels to parasite-endemic area (filariasis), obesity (BMI > 50)^[2], radical cancer treatment for breast, gynaecological, head and neck cancer (nodes dissection, chemotherapy and radiotherapy), nodes biopsy can be crucial risk factors, while family history is more frequently seen in primary lymphedema. Docetaxel-based chemotherapy has been shown to increase the incidence of breast cancer treatment related lymphedema^[3].

Complaints of extremity heaviness and fatigue could be the main manifestation of early stage lymphedema. As it progresses, visible limb swelling and enlargement of circumference take place. Different tools are utilized to assess extremity volume/circumference. Tape measurement is applying a flexible and non-stretch tape to assess the girth of edematous limb at certain points following different protocols. Absolute values are usually converted into volumes using respective mathematical formulae visualizing the limb as a series of truncated cones, cylinders and trapezoidal solids^[4]. Absolute excess volume (affected limb-unaffected limb), excess volume in percent [(affected limb-unaffected limb)/unaffected limb × 100], relative value in percent (affected limb/unaffected limb × 100) and affected leg volume divided by BMI are useful indices in unilateral lymphedema diagnosis. Girth assessment is the most fundamental and commonly used method for its feasibility and economical advantages but is limited by its high inter- and intra-observer variability and poor reproducibility. In water plethysmography, the amount of water displaced after immersing the limb of interest into a water tank equals the extremity volume. It's considered as the criterion standard for lymphedema diagnosis but also deemed impractical in clinical setting for its cumbersome set-up, patient-unfriendly measurement protocol and extra contraindications concerning water. Extremity volume difference > 10%, volume change > 200 mL or circumference change > 2 cm at one certain point are deemed diagnostic, though there are still no standardized cut-off points among health practioners^[5].

A square frame emitting infrared lights is used in perometry. As the frame moves along the limb, information of the interrupted lights is converted into coordinates to reconstruct a 3D model and automatically calculate the volume^[6]. Similarly, three-dimensional imaging systems such as the VECTRA XT surface photo imaging system (Canfield Imaging Systems, Fairfield, NJ) are developed to capture 360° digital image data of the edematous extremity. Absolute values or image color change by photographs contrast presents volume changes before and after treatment, thus making VECTRA valuable in both diagnosis and monitoring^[7]. VECTRA, as a relatively new technique provides high resolution images and might be applied to the whole body, facial and pubic region included^[7,8]. However, both three-dimensional photography and perometry are costly and not obtainable in every clinic.

As edema persists, difficulty of fitting clothing, joint dysfunction and musculoskeletal agony may appear. Characteristic skin changes including *peau d'orange* (pitted or dimpled skin texture), Kaposi-Stemmer sign (the inability to pinch the fold of skin at the base of the second toe) and squared off appearance of toes assists to identify lymphedema. Hyperkeratosis and fibrosis with verruca and nodules usually indicate advanced stages. Lymphedematous extremity is prone to recurrent infection, cellulitis lymphangitis, lymphorrhea and skin ulceration. Angiosarcoma that initially presents itself as red-purple nodules with/without satellite lesions is a rare but lethal complication.

Laboratory examinations such as routine blood test, thyroid function or urinalysis are in need to rule out other causes of edema, including renal, heart or hepatic failure *etc.* Though thorough history, physical and laboratory examinations could help to diagnosis > 90% lymphedema patients, lymphedema in early stages could be surprisingly challenging to diagnose, making assistant methods necessary for early detection and confirmation.

STAGING

It's widely accepted that lymphedema progresses through 4 stages. Stage 0 is the subclinical stage where swelling is absent but with impaired lymph transport and possible complaints of discomfort or heaviness. Stage 1 is spontaneously reversible edema that subsides with limb elevation, while the swelling of stage 2 could not be relieved by elevation. Stage 3, also known as lymphostatic elephantiasis, describes nonpitting edema, fibrosis, hyperkeratosis and the aforementioned complications^[2,9].

DIAGNOSTIC TECHNIQUES

Lymphoscintigraphy

Lymphoscintigraphy has been regarded as the gold standard for the diagnosis of lymphedema since its first introduction. It involves the intradermal or subcutaneous injection into the hand or feet of radiolabeled particles usually under the size of 100 nmol/L, such as ^{99m}Tc (Technetium) human serum albumin nanocolloid, ^{99m}Tc sulfur colloid and ^{99m}Tc albumin colloid. Gamma camera systems are applied to capture the radiopharmaceutical emission as it is taken up and transported by the lymphatic vasculature. Lymphoscintigraphy demonstrates the lymphatic vessels efferent from the injected sites and lymph nodes along the pathway. Typical abnormalities include formation of collateral lymphatic channels, asymmetric visualization of lymphatic channels, delayed or asymmetric node uptake, absent or delayed visualization of lymph nodes, unusual visualization of the popliteal or antecubital lymph nodes (compensatory mechanism involving deeper lymph pathways)^[10,11].

Dermal backflow, accumulation of tracer outside the main lymph routes and in cutaneous lymphatics, and lymphangiectasia are considered major diagnostic findings for lymphedema. Other than morphologic-qualitative information, lymphoscintigraphy provides us with quantitative information of the lymphatics. Commonly used parameters consist of TAT (tracer appearance time, the time from injection to the appearance of the tracer in the inguinal or axillary lymph nodes, normally < 10 min) and TI (Transport Index, normally ranges from 1 to 10).

Hassanein *et al.*^[12] in their study including 227 patients (454 limbs) suggested the sensitivity and the specificity of lymphoscintigraphy for lymphedema is 96% and 100% respectively. Early primary lymphedema may result in false-negative lymphoscintigrams so repeat lymphoscintigraphy is recommended^[12]. The recently developed Taiwan Lymphoscintigraphy Staging might provide a new angle of assessing the severity of lymphedema^[13]. Lymphoscintigraphy is also valuable in early detection and treatment selection, especially surgical planning as it allows to seek out possible functional lymphatic vessels for vessels to use for lymphatic-venous anastomosis (LVA). Compared to lymphangiography, the

tracer used in lymphoscintigraphy rarely causes the allergy and pulmonary embolism, so it's safe and relatively minimally invasive.

Despite its distinct advantages, the protocol of lymphoscintigraphy is poorly standardized, such as the amount of the labeled particles and the injection volume, which substantially affect the quantitative parameters and hinders comparisons between studies. Injection site is also one of the major debates. Tartaglione *et al.*^[11] suggested intermetatarsal or intermetacarpal spaces injection, as compared with traditional interdigital area, results in rapid uptake of tracers, improved imaging quality and reduced examination time (average time 4 h reduced to < 1 h)^[11]. Though combined with computed tomography (CT) or SPECT, spatial resolution of lymphoscintigraphy images improves, it is still far from enough and limited for detection of the small lymphatic vessel leaks^[14]. Owing to discontinuous image acquisition, diagnostic events could happen between acquisition points and be missed. Irradiation is the frequent concern raised in many studies. Though, no cutaneous radio-necrosis has been reported, extra precautions still needs to be taken concerning pregnant and breastfeeding women.

Lympho-fluoroscopies

Lympho-fluoroscopies applies fluorescent molecules such as indocyanine green (ICG), methylene blue *etc.* as the imaging agent. ICG lymphography encompasses the subcutaneous injection of ICG, the usual amount being 0.2 mL. Common injection sites include webspaces of the hand or foot, the medial and/or lateral border of the Achilles tendon, the ulnar side of the palmaris longus tendon at the wrist level^[15,16]. Different near-infrared camera devices are used 12-24 h after injection to record the light emitted by ICG thus visualizing the collecting lymphatic vessels. Linear pattern represents normal or mildly impeded lymphatic collector function, while dermal backflow pattern including splash, stardust of diffuse pattern indicates lymphedema. ICG lymphography is deemed to be the most valuable tool for superficial lymphatics imaging. Compared to lymphoscintigraphy, ICG lymphography is not irradiating with similar sensitivity and specificity (97% and 92%^[17]) but superior resolution and at lower cost. Yamamoto *et al.*^[18] suggested in their study when utilizing ICG lymphography to select optimal sites for LVA, the overall lymphatic vessel detection rate, confirmed by intraoperative findings, is 96.1%^[18]. ICG lymphography can be used for early recognition of lymphedema, as some patients without symptoms can still show abnormal images^[19]. However, ICG lymphography is time consuming and operator dependent. It's unable to observe lymphatics where the tissue is thicker than 2 cm, limiting its possible application in the trunk area and obese patients. Quantification might be more difficult compared to lymphoscintigraphy due to the injection of free ICG (the amount, the concentration *etc.*). Potential toxicity in the lymphatic vessels and its persistence after subcutaneous injection raise some concern because of the lack of studies about its side effects.

The fluorescein used in fluorescence microlymphography (FML) is fluorescein isothiocyanate (FITC)-labeled dextran. 0.1 mL of 25% FITC-labeled dextran solution dissolved by 0.9% sodium or potassium chloride solution is injected into the intradermal layer of the forearm, toes or even the face with a tuberculin syringe and a 25-gauge needle^[20]. Under A fluorescent light microscope, a network of lymphatic becomes visible as the dye spreads through the lymphatics. 10 min after injection, the distance between the border of the injection site and the furthest visible lymphatics is measured in four directions. The maximum extension distance in healthy limbs should not exceed 14 mm. Sensitivity and specificity for the 14 mm cut off level is 91.4% and 85.7%^[20]. Sensitivity was higher in the secondary vs. primary lymphedema^[21]. FML could be used near venous ulcers or indurated skin and rarely cause allergy or other major side effects. However, deeper lymphatic vessels cannot be visualized by FML.

Lymphangiography

Lymphangiography applies various contrast medium and imaging systems to depict lymphatic structures. In direct contrast x-ray lymphangiography, liposoluble contrast medium, such as iodine is directly

injected into the lymphatic vessel dyed by methylene blue. It has been abandoned due to its traumatic nature, technical complexity, poor repeatability and unacceptable contrast complications. Based on the uptake of water-soluble non-ionic contrast agents by lymphatics, indirect lymphangiography avoids direct administration of peripheral lymphatic vessels and has less complications, which is considered to be the best way to differentiate between lipedema and lymphedema.

Magnetic resonance lymphangiography (MRL) involves the subcutaneous/intradermal injection of gadolinium-based MR contrast agents, such as gadobenate dimeglumine, gadoterate meglumine *etc.* into the 4 interdigital web spaces of the hand or foot, with 1% lidocaine as anesthetic. Recommended contrast volume is 1 ml for each site. A 3D heavily T2-weighted sequence or a 3D steady-state free precession balanced sequence^[22] is performed to assess the distribution and extent of edema before injection. Then a fat-suppressed T1-weighted 3D spoiled gradient-echo (SPGR) is used for the lymphatic visualization before and after injection. The number of phase acquisitions and interval varies^[22-24]. A 3D workstation with multiplanar reformations, maximum intensity projection reconstructions and the 3D cursor facilitates image analysis. MRL depicts lymphatic channels, lymph nodes and drainage pattern with supplemental information including fat deposition, muscle compartments and limb volume. Bae *et al.*^[24] and Neligan *et al.*^[25] suggested excellent correlation of MRL with lymphoscintigraphy and ICG lymphography respectively. MRL allows for early recognition, full assessment of lymphedema status and surgical planning especially LVA. Compared to lymphoscintigraphy and ICG lymphography, it is free of radiation and depicts deeper lymphatic channels with higher resolution. Though an extra MR venogram or intravenous administration of Ferumoxytol can help differentiate lymphatic vessels from veins, venous contamination could be a major obstacle in image interpretation. Furthermore, MRL is costly and potentially patient-unfriendly, because it requires patients to stay in the prone or supine position for up to 2 h (the examination duration).

Tissue dielectric constant measurements

Tissue dielectric constant (TDC) is proven to be proportional to local skin-to-fat water content. The Moisture Meter D or its compact version transmits an 300 MHz electromagnetic wave into the tissue and displays absolute TDC values or a percentage of local tissue water, after automatically processing reflected signal. It takes no more than 10 s for each measurement point. TDC ratio (TDC affected/TDC unaffected) > 1.26 is considered suggestive of lymphedema by some^[26]. It can be applied in virtually any areas, midline body regions included, for post-treatment monitoring and early detection. However, TDC is influenced by skin thickness, gender, age, body mass index or race^[27], thus comparison between groups should be dealt with caution and diagnostic threshold is still debatable. In a study by Bakar *et al.*^[28] specificity was 94% with only 65% sensitivity^[28].

Bioelectrical impedance spectroscopy

Bioelectrical impedance spectroscopy (BIS) utilizes a low frequency current to measure electrical resistance (R_0) of local tissue, which inversely proportional to the volume of extracellular fluid volume. For unilateral lymphoedema, the index $R_{0\text{unaffected}}/R_{0\text{affected}}$ is commonly used, the larger the ratio the greater the differences in excess extracellular fluid between limbs. Diagnostic cut-off values varies for non/dominant limbs due to natural asymmetry. The R_i/R_0 ratio is the widely accepted BIS index for bilateral lymphoedema, which R_i means the resistance of the unaffected body region with similar tissue composition as the region of interest. BIS examination only takes a few seconds and rarely causes adverse effects. It is uninfluenced by BMI and reliable in predicting onset up to 10 months prior to clinical manifestation^[29,30]. Sensitivity and specificity for BIS were 64% and 100%, respectively^[31]. However BIS's less sensitive in diagnosing fibrotic lymphedema and breast or trunk measurement is limited. Extra caution should be taken when it comes to patients with pregnancy, cardiac pacemaker or other implanted medical devices.

Table 1. Comparison of different diagnostic techniques

	Sensitivity	Specificity	Advantages	Limitations	Current clinical use
Tape measurement	/	/	Easy to conduct	High inter-/intra-observer variability Poor reproducibility	Therapeutic monitoring Full assessment Experiment
Water plethysmography	/	/	The most accurate measurement of limb volume	Cumbersome set-up Complex measurement protocol	
3D photography	/	/	3D reconstruction image of limb Automatic analysis	High cost	Therapeutic monitoring Diagnosis
Lymphoscintigraphy	96%	100%	Morphologic-qualitative and quantitative assessment of lymphatics	Irradiation Poorly standardized protocol	Diagnosis Surgical planning
ICG lymphography	97%	92%	Valuable superficial lymphatics imaging Low cost	Time consuming (12-24 h) Operator dependent Limited to superficial lymphatics	Surgical planning Early diagnosis
FML	91.4%	85.7%	Time saving (10 min) Applicable to any body regions	Limited to superficial lymphatics	Diagnosis
MRL	/	/	Full assessment of lymphatics and soft tissue High resolution No Irradiation	High cost Time consuming (2 h)	Diagnosis Surgical planning
TDC Measurements	65%	94%	Time saving (10s/measurement point) Applicable to any body regions	Lack of diagnostic threshold due to population variation	Early diagnosis
BIS	64%	100%	Time saving (a few seconds) Uninfluenced by BMI	Reduced sensitivity in late stage lymphedema	Early diagnosis
Ultrasonography	/	/	Central lymphatic channel assessment Ruling out venous cause	Limited measurement range	Supplementary assessment
PET lymphangiography	/	/	Rapid visualization of lymphatics	/	/
Genetic screening	/	/	Early detection	/	/

FML: fluorescence microlymphography; TDC: tissue dielectric constant; MRL: magnetic resonance lymphangiography; BIS: bioelectrical impedance spectroscopy; ICG: indocyanine green; PET: positron emission tomography

Others

CT and magnetic resonance imaging can detect the characteristic honeycomb pattern and the thickening of the subcutis in lymphedema. Ultrasonography rules out edema caused by venous thrombosis or reflux disease. Furthermore, high resolution ultrasonography helps assess central lymphatic channel, such as thoracic duct, the diameter of which is proven to significantly decrease in lymphedema^[32]. We retrospectively analyzed the data of all patients with lymphedema treated in our Medical College Hospital, Department of Lymphedema Treatment Center from September 2015 to January 2017. Patients who had received ultrasound of the thoracic duct were included. A total of 14 patients with lower extremity lymphedema were included. All 14 patients who underwent thoracic duct ultrasonography without lower limb arterial or venous thrombosis met the conditions. There were 5 men and 9 women, aged 15-70 years. All 14 patients had lymphedema in the lower extremities: 5 with left lower extremity lymphedema, 6 with right lower extremity lymphedema, and 3 with both lower extremity lymphedema. Of the 14 patients with lymphedema examined with ultrasound, 6 had a normal thoracic duct diameter and 8 had an abnormal thoracic duct diameter. Ultrasound analysis of the thoracic duct showed that the average inner diameter of the thoracic duct was 2.21 ± 0.15 mm in the six patients with a normal TD and 1.99 ± 0.33 mm in the patients with an abnormal thoracic duct.

Positron emission tomography (PET) lymphangiography with ⁶⁸Ga-labeled NOTA (1,4,7-triazacyclononane-N,N',N''-triacetic acid) with truncated Evans blue (NEB) (⁶⁸Ga-NEB PET) allows for rapid visualization of lymphatic vessels. Long *et al.*^[33] suggested ⁶⁸Ga-NEB PET combined with MRL shows significant advantages over ^{99m}Tc-SC lymphoscintigraphy with MRL in microsurgery preoperative evaluation^[33].

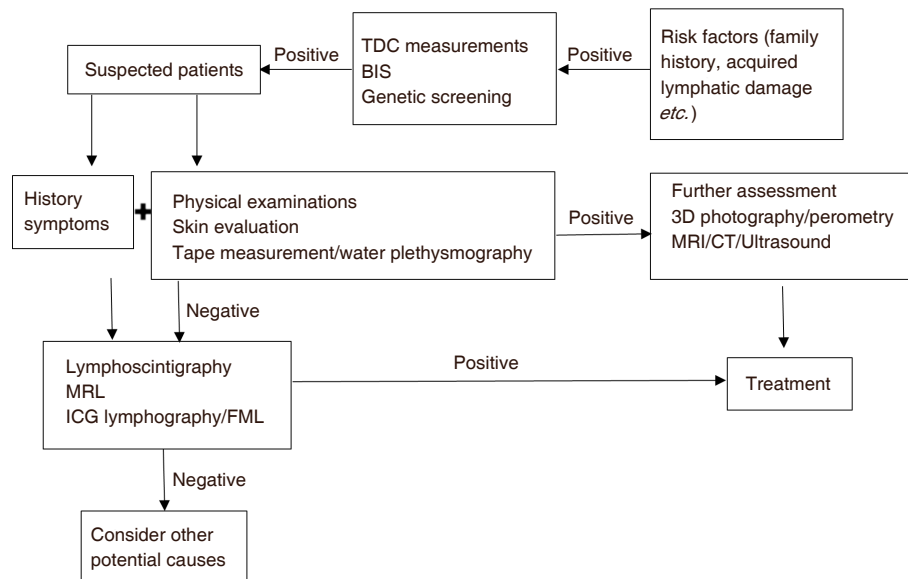


Figure 1. Diagnostic algorithm for lymphedema. FML: fluorescence microlymphography; TDC: tissue dielectric constant; MRL: magnetic resonance lymphangiography; ICG: indocyanine green; CT: computed tomography; BIS: bioelectrical impedance spectroscopy; MRI: magnetic resonance imaging

FOXC2, *GJC2*, *CCNE1*, *SOX18* and *FLT4* gene mutations have been known to be related to primary lymphedema^[9], while *GJA4*^[34], *GJC2*^[34] and *HGF/MET*^[35] mutations correlate with secondary lymphedema. As genomic medicine develops, genetic screening for patients at risk might assist in early detection of lymphedema for the foreseeable future.

CONCLUSION

Since each diagnostic technique has its own pros and cons [Table 1], there's no consensus on how to properly diagnose lymphedema. Adjusting to patients' conditions and clinic facilities, practitioners should choose and combine these diagnostic tools flexibly. Figure 1 demonstrates a potential diagnostic algorithm for lymphedema recommended by the authors.

DECLARATIONS

Authors' contributions

Conceived the structure of the review: Liang ZY

Wrote and revised the paper: Liang ZY, Long X, Yu NZ, Huang JZ

Read and approved the manuscript: Liang ZY, Long X, Yu NZ, Huang JZ

Availability of data and materials

Not applicable.

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Conflicts of interest

Long X is a first-author in one of the referenced papers; Long X, Yu NZ and Huang JZ are co-authors in one of the referenced papers.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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REFERENCES

- Grada AA, Phillips TJ. Lymphedema: pathophysiology and clinical manifestations. *J Am Acad Dermatol* 2017;77:1009-20.
- Greene AK, Goss JA. Diagnosis and staging of lymphedema. *Semin Plast Surg* 2018;32:12-6.
- Keeley V. Advances in understanding and management of lymphoedema (cancer, primary). *Curr Opin Support Palliat Care* 2017;11:355-60.
- Hidding JT, Viehoff PB, Beurskens CH, van Laarhoven HW, Nijhuis-van der Sanden MW, et al. Measurement Properties of Instruments for Measuring of Lymphedema: Systematic Review. *Phys Ther* 2016;96:1965-81.
- Bernas M, Thiadens SRJ, Smoot B, Armer JM, Stewart P, et al. Lymphedema following cancer therapy: overview and options. *Clin Exp Metastasis* 2018;35:547-51.
- Tierney S, Aslam M, Rennie K, Grace P. Infrared optoelectronic volumetry, the ideal way to measure limb volume. *Eur J Vasc Endovasc Surg* 1996;12:412-7.
- Tokumoto H, Akita S, Kuriyama M, Mitsukawa N. Utilization of three-dimensional photography (VECTRA) for the evaluation of lower limb lymphedema in patients following lymphovenous anastomosis. *Lymphat Res Biol* 2018; doi: 10.1089/lrb.2017.0058.
- Landau MJ, Kim JS, Gould DJ, Patel KM. Vectra 3D imaging for quantitative volumetric analysis of the upper limb: a feasibility study for tracking outcomes of lymphedema treatment. *Plast Reconstr Surg* 2018;141:80e-4.
- Grada AA, Phillips TJ. Lymphedema: diagnostic workup and management. *J Am Acad Dermatol* 2017;77:995-1006.
- Keo HH, Gretener SB, Staub D. Clinical and diagnostic aspects of lymphedema. *Vasa* 2017;46:255-61.
- Tartaglione G, Visconti G, Bartoletti R, Gentileschi S, Salgarello M, et al. Stress lymphoscintigraphy for early detection and management of secondary limb lymphedema. *Clin Nucl Med* 2018;43:155-61.
- Hassanein AH, Maclellan RA, Grant FD, Greene AK. Diagnostic accuracy of lymphoscintigraphy for lymphedema and analysis of false-negative tests. *Plast Reconstr Surg Glob Open* 2017;5:e1396.
- Cheng MH, Pappalardo M, Lin C, Kuo CF, Lin CY, et al. Validity of the novel taiwan lymphoscintigraphy staging and correlation of cheng lymphedema grading for unilateral extremity lymphedema. *Ann Surg* 2018;268:513-25.
- Yoshida RY, Kariya S, Ha-Kawa S, Tanigawa N. Lymphoscintigraphy for Imaging of the lymphatic flow disorders. *Tech Vasc Interv Radiol* 2016;19:273-6.
- Narushima M, Yamamoto T, Ogata F, Yoshimatsu H, Mihara M, et al. Indocyanine green lymphography findings in limb lymphedema. *J Reconstr Microsurg* 2016;32:72-9.
- Garza RM, Ooi ASH, Falk J, Chang DW. The relationship between clinical and indocyanine green staging in lymphedema. *Lymphat Res Biol* 2019;17:329-33.
- Akita S, Mitsukawa N, Kazama T, Kuriyama M, Kubota Y, et al. Comparison of lymphoscintigraphy and indocyanine green lymphography for the diagnosis of extremity lymphoedema. *J Plast Reconstr Aesthet Surg* 2013;66:792-8.
- Yamamoto T, Yamamoto N, Fuse Y, Narushima M, Koshima I. Optimal sites for supermicrosurgical lymphaticovenular anastomosis: an analysis of lymphatic vessel detection rates on 840 surgical fields in lower extremity lymphedema patients. *Plast Reconstr Surg* 2018;142:924e-30.
- Yamamoto T, Yamamoto N, Ishiura R. Indocyanine green lymphography for lymphedema screening following breast cancer treatment. *Plast Reconstr Surg* 2017;139:1365e-6.
- Keo HH, Husmann M, Groechenig E, Willenberg T, Gretener SB. Diagnostic accuracy of fluorescence microlymphography for detecting limb lymphedema. *Eur J Vasc Endovasc Surg* 2015;49:474-9.
- Keo HH, Schilling M, Buchel R, Grochenig E, Engelberger RP, et al. Sensitivity and specificity of fluorescence microlymphography for detecting lymphedema of the lower extremity. *Vasc Med* 2013;18:117-21.
- Mazzei FG, Gentili F, Guerrini S, Cioffi Squitieri N, Guerrieri D, et al. MR Lymphangiography: a practical guide to perform it and a brief review of the literature from a technical point of view. *Biomed Res Int* 2017;2017:2598358.
- Mitsumori LM, McDonald ES, Neligan PC, Maki JH. Peripheral magnetic resonance lymphangiography: techniques and applications. *Tech Vasc Interv Radiol* 2016;19:262-72.
- Bae JS, Yoo RE, Choi SH, Park SO, Chang H, et al. Evaluation of lymphedema in upper extremities by MR lymphangiography: Comparison with lymphoscintigraphy. *Magn Reson Imaging* 2018;49:63-70.
- Neligan PC, Kung TA, Maki JH. MR lymphangiography in the treatment of lymphedema. *J Surg Oncol* 2017;115:18-22.
- Koehler LA, Mayrovitz HN. Spatial and temporal variability of upper extremity edema measures after breast cancer surgery. *Lymphat Res Biol* 2019;17:308-15.
- Birkballe S, Jensen MR, Noerregaard S, Gottrup F, Karlsmark T. Can tissue dielectric constant measurement aid in differentiating lymphoedema from lipoedema in women with swollen legs? *Br J Dermatol* 2014;170:96-102.
- Bakar Y, Tugral A, Uyeturk U. Measurement of local tissue water in patients with breast cancer-related lymphedema. *Lymphat Res Biol* 2018;16:160-4.
- Kayiran O, De La Cruz C, Tane K, Soran A. Lymphedema: from diagnosis to treatment. *Turk J Surg* 2017;33:51-7.
- Cornish BH, Chapman M, Hirst C, Mirolo B, Bunce IH, et al. Early diagnosis of lymphedema using multiple frequency bioimpedance. *Lymphology* 2001;34:2-11.

31. Qin ES, Bowen MJ, Chen WF. Diagnostic accuracy of bioimpedance spectroscopy in patients with lymphedema: a retrospective cohort analysis. *J Plast Reconstr Aesthet Surg* 2018;71:1041-50.
32. Gao C, Yang M, Su N, Li XW, Yang EL, et al. Sonographic assessment of the terminal thoracic duct in patients with lymphedema. *Chin Med J (Engl)* 2017;130:613-6.
33. Long X, Zhang J, Zhang D, Gao C, Chi C, et al. Microsurgery guided by sequential preoperative lymphography using (68)Ga-NEB PET and MRI in patients with lower-limb lymphedema. *Eur J Nucl Med Mol Imaging* 2017;44:1501-10.
34. Hadizadeh M, Mohaddes Ardebili SM, Salehi M, Young C, Mokarian F, et al. GJA4/Connexin 37 mutations correlate with secondary lymphedema following surgery in breast cancer patients. *Biomedicines* 2018;6:E23.
35. Finegold DN, Schacht V, Kimak MA, Lawrence EC, Foeldi E, et al. HGF and MET mutations in primary and secondary lymphedema. *Lymphat Res Biol* 2008;6:65-8.

Review

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Advances in functional limb reconstruction in the irradiated setting

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Abstract

The management of extremity soft tissue sarcoma is constantly evolving, and, in recent decades, limb salvage has been the main goal. More commonly, this is being achieved with a combination of neo-adjuvant radiotherapy, followed by wide excision and soft tissue reconstruction in the form of vascularised soft tissue transfer. Although limb salvage is now readily achievable, the resultant functional disabilities following excision of major musculotendinous and neurovascular structures can be life changing. In recent years, there has been a move towards functional limb reconstruction in the form of free functioning muscle transfer. This paper reviews the advances in functional limb reconstruction in the setting of preoperative radiation and reports our experience in this challenging reconstructive field.

Keywords: Sarcoma, radiation, functional limb reconstruction, free functioning muscle transfer, nerve transfer

INTRODUCTION

Soft tissue sarcomas (STS) are a rare group of mesenchymal tumours commonly affecting the extremities. Historically, extremity STS patients were commonly treated by amputation, with rates of around 40%-50%^[1]. However, in the 1980s, "limb-preserving surgery" became the mainstay of treatment after Rosenberg *et al.*^[2] demonstrated equivalent five-year survival rates with a combination of wide excision and radiotherapy compared to amputation. Limb preserving surgery in combination with radiotherapy for high-risk extremity STS has been shown to yield superior local control over excision alone^[3-5]. There remains a debate



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over the optimum timing of radiotherapy in the management of extremity STS. Preoperative radiotherapy is associated with better overall survival but higher wound complications compared to postoperative radiation^[6]. The most important factor in obtaining local control is wide surgical excision margins^[7], which often involves the loss of major musculotendinous and neurovascular units in the extremities. These complex defects are further complicated by the issues of radiation related wound complications, which has led to the popularisation of free and pedicled flaps to reconstruct extremity STS defects. The main benefits of importing vascularised tissue in the form of free/pedicled flaps is to fill dead space, attain wound closure, protect important neurovascular structures, and improve wound healing^[8,9]. Despite these advances in reconstruction, a large proportion of patients will rely on splints and orthotics to aid activities of daily living, and the overall function remains poor.

More recently, there has been a paradigm shift in the goals of STS reconstruction, to a more innovative, functional approach, whereby the aim is to replace missing elements (e.g., skin, bone, tendon, muscle and neurovascular structures), restore functional muscle units and critical sensory pathways and provide soft tissue coverage in one procedure^[10-13]. The aim of this paper is to review current innovative techniques of functional limb reconstruction in the irradiated setting, and present our experience in this challenging field.

PERIPHERAL NERVE RECONSTRUCTION

Wide excision of composite tissue in sarcoma surgery may lead to segmental loss of critical sensory and motor nerves, with devastating functional loss. There are several techniques described for reconstructing nerve gaps, whereby direct epineural repair is not an option, including autologous nerve grafts, allografts and nerve conduits. The difficulty in the post radiation setting is the poor vascularity of the wound beds, leading to generally poor results with conventional techniques.

Although the results of functional recovery after nerve repair and nerve grafts had historically been attributed to irreversible muscle atrophy and the replacement of muscle with fat over time, research has demonstrated that this is not the sole factor responsible and progressive Schwann cells denervation, nerve ischaemia, intraneural fibrosis and chronic axotomy also play significant roles^[14]. The vascularised nerve graft (VNG), described by Taylor and Ham^[15], involves the transfer of a donor nerve along with its vascular pedicle. Transfer of a vascularised nerve graft avoids the initial period of nerve ischaemia and reduces central necrosis and intraneural fibrosis seen particularly in medium- to large-sized non-vascularised grafts^[16]. It is generally believed that VNGs perform better for longer gaps, larger diameter nerves and in the setting of poorly vascularised or scarred beds, however high-quality evidence is lacking. Improved nerve regeneration has been demonstrated with VNGs over standard nerve grafts in animal models in the setting of poorly vascularised beds^[17,18]. One of the suggested indications for the use of vascularised nerve grafts is the poorly vascularised and scarred bed, such as in the setting of prior radiotherapy, whereby success with standard nerve grafts is generally poor; however, there is not yet firm clinical evidence for this^[19,20].

As a general rule, there is a 50% loss of axons at each nerve coaptation site. Therefore, with primary nerve repair, approximately 50% of the original axons will successfully regenerate across the repair. With nerve grafts, because of two coaptation sites, only around 25% of axons will regenerate successfully across the distant coaptation, and there may be additional axonal loss depending on the distance to the distal target, due to the effects of chronic axotomy and muscle fibrosis^[16,21]. For this reason, nerve transfers, requiring a single coaptation, are favoured over nerve grafts when possible, and nerves with higher axonal input are favoured, to maximise axonal regeneration distally. Nerve transfer involves the coaptation of an expendable healthy donor nerve to a denervated or cut nerve, with the aim of maximising functional recovery with

Table 1. Summary of the differences between nerve grafts and nerve transfers

Nerve graft	Nerve transfer
2 Coaptations	1 Coaptation
~25% of available axons to target	~50% of available axons to target
Longer distance to target	Shorter distance to target
Longer time to reinnervation	Shorter time to reinnervation
Higher chance of motor end plate degeneration	Allows for delayed reconstruction
Less specific	Highly specific
Donor site morbidity	Micro-neurolisis can preserve donor function

faster reinnervation to distal targets^[22]. Most commonly, this nerve transfer is used to restore motor function, but it can be used to restore critical sensory function. The advantages of nerve transfer over nerve grafts are well documented in the literature and are summarised in Table 1.

The combination of peripheral nerve reconstruction, such as nerve graft or transfer, along with importing healthy vascularised tissue coverage in the form of free or pedicled tissue transfer is a useful technique to optimise the local environment for nerve regeneration. Nerve grafts and transfers play a significant role in extremity reconstruction and, depending on the defect characteristics (e.g., resection of major nerves and muscular units), can be employed in combination with newer microsurgical techniques that have developed in recent decades.

FUNCTIONING MUSCLE TRANSFER

Functioning muscle transfer (FMT) involves the transfer of a healthy donor muscle and its neurovascular pedicle to a new location to assume a new function. Free functioning muscle transfer (FFMT) involves restoring the circulation of the transferred muscle with microsurgical anastomosis to vessels at the recipient site along with coaptation of the motor nerve. Pedicled innervated flaps maintain their vascular supply but involve reorientation of the muscle and reinnervation from nerve transfer at the recipient site with a view to altering the function of that muscle. Within several months, the transferred muscle becomes reinnervated by the donor nerve, eventually begins to contract and ultimately gains independent function^[23]. FMT has traditionally been limited to muscles with a single nerve for transfer (e.g., gracilis), because of the view that segmental nerve supply would be an obstacle to reinnervation. However, we have previously published a series of 11 functional quadriceps reconstructions using innervated rectus abdominis flaps, whereby 2-3 segmental nerves have been coaptated to cut femoral nerve branches at the recipient site. The overall functional results were excellent with over 50% achieving M5 power [as per the Medical Research Council (MRC) grading system] with a mean follow-up of 12 months and with minimal donor site complications^[24]. The rectus abdominis has the added versatility of being used as a pedicled innervated flap for quadriceps reconstruction, and its segmental innervation does not preclude its use as a functional muscle transfer^[25].

The most reported FFMTs in the literature for STS extremity reconstruction are the gracilis^[11,12,26], latissimus dorsi (LD)^[11,25,26] and rectus abdominis muscle [vertical (VRAM) or transverse (TRAM)]^[24], with the other less commonly transferred muscles being the innervated medial gastrocnemius muscle^[27] and rectus femoris [Figures 1-4]. FFMT can be performed in combination with nerve grafts and/or nerve transfer, especially when the resection involves loss of major nerves and muscle units. Nerve grafts, either standard or vascularised, are generally used with the aim of restoring critical sensory function, whereas nerve transfer is primarily used to restore motor function.

LONG DONOR NERVE HARVEST WITH FFMT

In general, following sarcoma resection, there are usually native nerves available for coaptation to the transferred muscle flap, which is advantageous as the length of nerve available with most flaps is short.



Figure 1. Clinical images of functional upper limb reconstruction with a combination of free functioning muscle transfer and nerve transfer in an 83-year-old patient. A: right arm defect following sarcoma excision including 100% of biceps and over 50% of brachialis, which was denervated. This was reconstructed with a free innervated gracilis myocutaneous flap with the nerve coaptated to the cut end of the musculocutaneous nerve, along with a flexor carpi ulnaris branch to brachialis branch nerve transfer; B: results after 12 months, demonstrating very good cosmesis and contour; C, D: active elbow flexion from 110° to 40° with M4 power (see [Video 1](#))



Figure 2. Example of lower limb functional reconstruction with functional muscle transfer, nerve grafts and nerve transfers in a 30-year-old female. A: large defect to left groin following excision of sarcoma, which included femoral nerve and iliopsoas and sartorius muscle resection, also demonstrating exposed femoral artery and vein; B: nerve grafts performed using cutaneous femoral nerve branches, from proximal stump to quadriceps branches; C: pedicled, innervated rectus femoris myocutaneous flap raised prior to inset to reconstruct hip flexors; D: adductor longus nerve transfer to vastus medialis oblique branch; E: final result after inset and closure; F: patient had full return of hip flexors and quadriceps function, and was able to run, climb and descend stairs at 18 months (see [Videos 2 and 3](#))



Figure 3. Clinical images of an example of upper limb functional reconstruction with an innervated medial gastrocnemius myocutaneous flap, following left deltoid excision for recurrent sarcoma (previous partial deltoid resection and ALT flap). A: planned excision of previous ALT flap and remaining deltoid; B: defect following total deltoid resection, with exposed humerus; C: right medial gastrocnemius myocutaneous flap planning; D: flap islanded with its neurovascular bundle dissected prior to division; E: result at one year showing excellent flap contour; F: M5 power of shoulder abduction and flexion, equal to the contralateral side (see [Video 4](#)). ALT: antero-lateral thigh

However, there may be circumstances following more extensive resections where longer length is required to perform reinnervation. The senior author has successfully performed FFMT with long nerve harvest in both rectus abdominis and gracilis transfer. Free or pedicled rectus abdominis myocutaneous flaps can be raised with long dissection of over 10 cm of intercostal nerves [[Figure 5](#)].

We have had excellent results with pedicled, innervated rectus abdominis flaps in quadriceps reconstruction, with evidence of motor function in the donor muscle within three months and MRC 5/5 return of power at seven months^[24]. The most commonly used free functioning flap for both oncologic and trauma reconstruction is the gracilis flap. One of the limitations to its use is the relatively short neurovascular pedicle, usually allowing around 6-8 cm of length to be harvested. When longer lengths of donor nerve are required, long nerve gracilis flaps can be harvested through the obturator foramen, via a combined intra-abdominal approach, allowing up to 30 cm of donor nerve to be harvested with the muscle. Time to reinnervation is increased due to the longer distances for regeneration, but full function can be achieved successfully with these techniques.

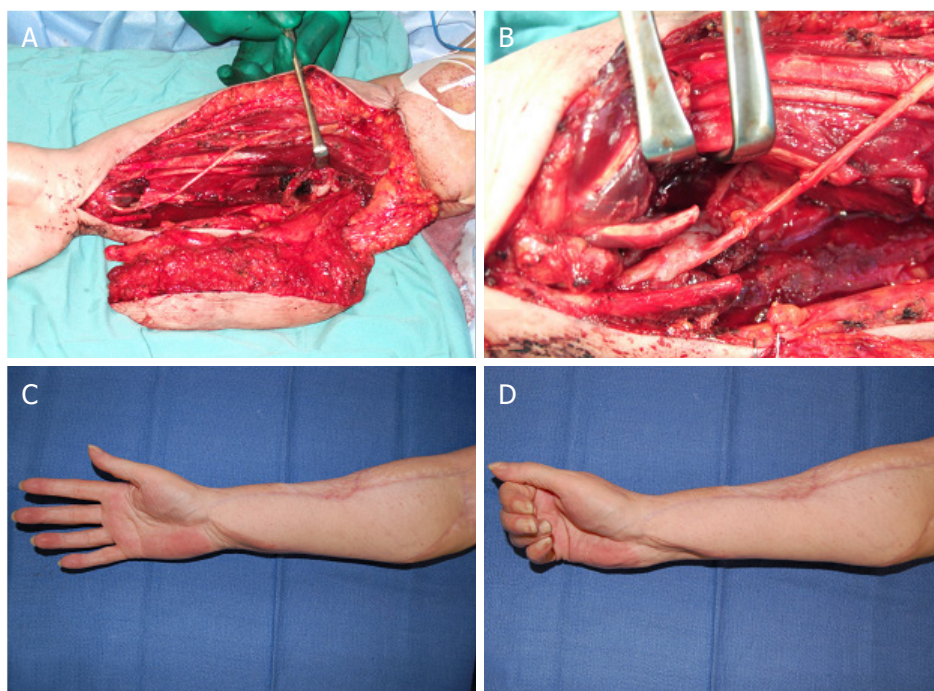


Figure 4. Functional upper limb reconstruction with a combination of free functioning muscle transfer and nerve transfer for a right forearm defect in a 68-year-old female, which involved resection of 15 cm of ulnar nerve and common flexor mass. A: free functioning gracilis myocutaneous flap in position with the proximal muscle inset into proximal flexor digitorum profundus stump; B: close up image demonstrating the anterior interosseous nerve to ulnar motor and lateral cutaneous nerve of the forearm to ulnar sensory nerve transfers; C: result at one year showing excellent flap contour, no claw-hand deformity; D: good flexion of digits demonstrating reinnervation of the gracilis muscle



Figure 5. Innervated rectus abdominis myocutaneous flap harvest with good length of intercostal nerve available through a standard approach

OUR EXPERIENCE

The senior author has been part of the local sarcoma multi-disciplinary team (MDT) for over 10 years, has been instrumental in advocating functional reconstruction for extremity STS in recent years and has pioneered numerous reconstructive techniques in this field.

Preoperative radiotherapy is the preferred method in our institution for the management of all extremity STS, because the sarcoma service feels the oncological outcomes are at least equivalent, and, functionally, these patients do better overall^[25]. Preoperative radiotherapy is associated with better overall survival but higher wound complications compared to postoperative radiation, which we feel is overcome by the combination of wide resection and flap coverage with healthy vascularised tissue^[6]. Preoperative radiotherapy allows the ability to give lower radiation doses due to improved limb perfusion and oxygenation^[4,28], smaller radiotherapy targets^[29] and therefore decreased late toxicity^[6] compared to postoperative methods. Single stage orthoplastic surgery is performed six weeks following completion of radiotherapy, with the oncologic surgeons performing wide excision and immediate reconstruction performed by the plastic surgeons. Our unit's protocol and experience with preoperative radiotherapy have previously been reported in the literature^[30] and the results are in keeping with the current literature, which demonstrates a significant increase in complications if flaps were performed beyond this six-week period^[31].

Over the past 10 years, the senior author has developed a systematic and regimented approach to STS extremity functional reconstruction with the aim of minimising errors and maximising ergonomics and improving functional outcomes. The general approach is as follows: after tumour excision by the resecting team, haemostasis is thoroughly performed and local anatomy is examined for recipient vessels and nerves. The defect is templated, taking into account the innervated muscle requirement, alongside the need for skin and dead space filling. The flap is not detached until the recipient vessels and nerves are ready for microsurgical anastomosis in order to minimise ischaemia time. The dichotomy of neurovascular pedicle length versus vessel calibre is addressed, prior to pedicle detachment. The flap is transferred to the defect and stretched to its original length in order to allow for the final inset and the lengths of the vessels and nerves matched to the recipients. The flap is then secured proximally to prevent avulsion. The nearest motor nerve, which has been tagged during the resection, is utilised for the neuroorrhaphy. The recipient nerves are stimulated intraoperatively before division with a handheld nerve stimulator in order to confirm the presence of motor axons. Anastomosis is then performed on the veins, artery and finally the nerve. The limb is then positioned appropriately depending on the compartment being reconstructed, e.g., knee extended or flexed for quadriceps and hamstring, respectively, or hip extended for gluteal reconstruction, before, finally, the distal end of the flap is tensioned and secured distally taking care to avoid tension on the anastomosis. The flap is inset in layers over suction drains and covered with a waterproof dressing. Postoperatively, the involved limb is immobilised in a fixed articulated splint for six weeks. For lower limb reconstructions, the patient is confined to bed rest for six days and nursed appropriately depending of position of the flap, before being mobilised on crutches. The uninvolved joints are allowed to move freely postoperatively, encouraging locomotion to prevent stiffness, DVT and other postoperative complications. After this six-week period, patients are allowed to start active and passive range of motion under guidance from specialist physiotherapists. Strengthening exercises are commenced after 3-6 months for a minimum period of 12 months.

Between 2009 and 2019, the senior author has performed 68 functional reconstructions, for extremity STS resections following neoadjuvant radiotherapy, including 53 free (of which two were vascularised sural nerve grafts) and 11 pedicled flaps [Table 2]. There were two patients who underwent non-vascularised nerve grafts and two who had nerve transfers alone. There were seven patients who underwent non-vascularised nerve grafts in combination with the flap coverage and four who had nerve transfers as well as flap coverage. Nerve grafts and transfers are generally used in combination with flap coverage when major

Table 2. Summary of the various functional reconstructions performed for extremity STS

Flap	Defects	Number
LD	Gluteal, hamstrings, quadriceps, gastroc/soleus	21
Gracilis	Hamstring, quadriceps, adductors, tibialis ant, biceps/brachialis, triceps	14
VRAM-Free	Quadriceps, adductors	10
-Pedicled		10
TRAM	Quadriceps, gluteals	4
Medial gastrocnemius	Deltoid, biceps/brachialis	2
Vascularised sural nerve	Common peroneal nerve, posterior cord	2
Rectus femoris (pedicled)	Groin (including femoral nerve and hip flexors)	1

STS: soft tissue sarcomas; LD: latissimus dorsi; VRAM: vertical rectus abdominis muscle; TRAM: transverse rectus abdominis muscle

nerves are sacrificed as part of the oncologic resection (as shown in [Figures 1, 2 and 4](#)). In this series, the most commonly resected nerves were the sciatic and femoral nerve, with one case of common peroneal nerve, one ulnar nerve and one posterior cord resection for malignant peripheral nerve sheath tumour.

The mean age of patient was 63 (in the range of 35-87 years). Ninety percent of the reconstructions were of the lower limb, most commonly the quadriceps, followed by the hamstring and gluteal compartments, and 10% were of the upper limb. There were three complete flap losses (4.4%) and one partial flap loss (1.5%) in the series. Reinnervation was seen in the transferred muscle as early as three months postoperatively, with a mean time of 12 months (follow up by the senior surgeon occurred at six weeks, and then 3, 6, 12 and 24 months, thus exact time points of reinnervation are estimates within these timeframes). The mean MRC grade achieved was 4/5, with over 50% ($n = 32$) achieving MRC 5/5 at latest follow up. Seven of the cases are too early in their follow-up to ascertain the level of functional recovery at the time of writing. With regards to nerve reconstruction, there are two patients with adequate follow-up who have recovered some protective sensation distally (one vascularised sural nerve graft and flexor carpi ulnaris (FCU) nerve branch transfer to triceps for a right posterior cord sarcoma and one sural to tibial nerve transfer following tibial nerve resection). The first patient has had an excellent result with M5/5 power of deltoid and triceps, and wrist and finger extension at 18 months (see [Videos 5 and 6](#)). A third patient who underwent vascularised sural nerve graft for common peroneal nerve (CPN) resection showed signs of sensory recovery five months postoperatively, and we await longer-term follow-up to assess final outcome.

The senior author's philosophy on functional limb reconstruction is: age is not a barrier to reconstruction (see [Figure 1](#)); the status of the joints proximal and distal to the defect are vital; aim to perform a single nerve coaptation either via nerve transfer or as part of an innervated free flap; and high axonal input is key to proximal nerve reconstruction.

DISCUSSION

Microsurgical reconstruction after soft tissue sarcoma excision has expanded the indications for limb salvage by allowing wider excision margins with the ability to adequately reconstruct the defect. However, limb salvage surgery with oncological resection of extremity STS often leads to a significant detrimental effect on mobility and the ability to perform activities of daily living, which has been shown to reduce patient's quality of life^[32]. Functional reconstruction of extremities following STS excision with FFMT can provide the dual functions of active muscle contraction and soft tissue coverage in one operation.

The concept of limb salvage surgery has evolved from just anatomical preservation of the limb to preservation with restoration of function and aesthetics. Despite this paradigm shift in recent years, functional reconstruction following extremity sarcoma resection is still relatively uncommon. A recently published review reported just 134 cases of functional sarcoma reconstruction of the limbs in the literature,

of which only 55 were FFMT and 17 were nerve reconstructions, with the remainder comprising tendon transfers^[23]. Nelson *et al.*^[33] investigated the difference between functional reconstruction of the extremities following STS resection and soft tissue coverage alone. The study demonstrated that, although there was an increased cost and slightly extended surgical time associated with functional reconstruction, the postoperative functional outcome was better, and they concluded that this justified its use.

Although the effect of neo-adjuvant therapy on functional reconstruction has not been investigated, numerous studies have demonstrated that preoperative radiotherapy does not increase complications when flaps are used for reconstruction^[34-36]. In addition, there appears to be no difference in outcomes and complication rates with muscle flaps compared to fasciocutaneous flaps when used in the post radiotherapy setting^[31].

One area which continues to be a topic for debate is the reconstruction of major nerve defects, particularly of the sciatic nerve. The senior author has utilised different techniques for reconstructing major nerve gaps, including cable nerve grafts and vascularised sural nerve grafts. Our results are in keeping with those in the literature, which show mixed sensory outcomes. Tokumoto *et al.*^[37] reported three cases of vascularised sural nerve grafts for sciatic nerve reconstruction, whereby they aimed to selectively reconstructed sensation to the plantar surface of the foot. They demonstrated some sensory recovery to the sole in two patients; however, limited protective sensation was achieved. They stated poor results in the setting of postoperative radiation therapy, although this was only the case in one patient^[37]. Melendez *et al.*^[38] reported five sciatic nerve reconstructions with cable sural nerve grafts. They demonstrated the return of partial distal sensory recovery in three patients and some protective sensation in the other two, with a mean follow up of one year^[38]. From our experience and that of the limited reports in the literature, although the chances of marked sensory recovery are slight, the amount of reinnervation is such that attempts at nerve reconstruction are justified.

In the opinion of the senior author, the difference between raising an innervated free flap as opposed to a non-innervated free flap is small, especially in the case of the latissimus dorsi and gracilis flap, where the nerves lie in close proximity to the vascular pedicle. Although dissecting out recipient nerves and appropriately securing and tensioning the musculotendinous components are critical in achieving a good outcome, this is not hugely time-consuming and can be learned quickly.

As Martin *et al.*^[23] concluded in their review paper, there is a significant lack of high-level evidence regarding the use of functional reconstruction in extremity sarcoma. We describe here the senior author's experience in this challenging and innovative field, and demonstrate how excellent functional outcomes can be achieved with a systematic and logical approach. However, large well-designed studies are required to clarify the differences in functional and non-functional reconstruction in terms of cost, donor morbidity and functional outcomes to cement its role in sarcoma surgery.

CONCLUSIONS

Limb sparing surgery following neo-adjuvant radiation has become the preferred treatment for extremity STS. However, adequate tumour resection can compromise critical limb function. Functional reconstruction in extremity sarcoma is a relatively new concept, with limited experience published in the literature. The use of advanced microsurgical techniques such as nerve transfer and FFMT provides the reconstructive surgeon with a way of not only salvaging limbs, but restoring function following loss of critical motor and sensory structures in upper and lower extremity sarcoma resection. We feel that the functional benefits outweigh the slightly increased cost and operative time of soft tissue only reconstruction and should be considered in patients undergoing extremity sarcoma resection following radiotherapy.

DECLARATIONS

Authors' contributions

Made substantial contributions to conception and design of the study, performed case note review and contributed to the final manuscript: Marsden N, Grinsell D

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All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Written, informed consent was obtained for all images and videos taken, for use in medical records, teaching and publications.

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REFERENCES

- 1 Abbas JS, Holyoke ED, Moore R, Karakousis CP. The surgical treatment and outcome of soft-tissue sarcoma. *Arch Surg* 1981;116:765-9.
- 2 Rosenberg SA, Tepper J, Glatstein E, Costa J, Baker A, et al. The treatment of soft-tissue sarcomas of the extremities: prospective randomized evaluations of (1) limb-sparing surgery plus radiation therapy compared with amputation and (2) the role of adjuvant chemotherapy. *Ann Surg* 1982;196:305-15.
- 3 Lindberg RD, Martin RG, Romsdahl MM, Barkley HT Jr. Conservative surgery and postoperative radiotherapy in 300 adults with soft-tissue sarcomas. *Cancer* 1981;47:2391-7.
- 4 Suit HD, Mankin HJ, Wood WC, Proppe KH. Preoperative, intraoperative and postoperative radiation in the treatment of primary soft tissue sarcomas. *Cancer* 1985;55:2659-67.
- 5 Yang JC, Chang AE, Baker AR, Sindelar WF, Danforth DN, et al. Randomized prospective study of the benefit of adjuvant radiation therapy in the treatment of soft tissue sarcomas of the extremity. *J Clin Oncol* 1998;16:197-203.
- 6 O'Sullivan B, Davies AM, Turcotte R, Bell R, Catton C, et al. Preoperative versus postoperative radiotherapy in soft-tissue sarcoma of the limbs: a randomized trial. *Lancet* 2002;359:2235-41.
- 7 Bell RS, O'Sullivan B, Liu FF. The surgical margin in soft-tissue sarcoma. *J Bone Joint Surg Am* 1989;71:370-5.
- 8 Popov P, Tukiainen E, Asko-Seljaavaara S, Huuhtanen R, Virolainen M, et al. Soft tissue sarcomas of the lower extremity: surgical treatment and outcome. *Eur J Surg Oncol* 2000;26:679-85.
- 9 Carlson GW. The evolution of extremity reconstruction for soft tissue sarcoma. *Ann Surg Oncol* 2006;13:610-1.
- 10 Doi K, Kuwata N, Kawakami F, Hattori Y, Otsuka K, et al. Limb-sparing surgery with reinnervated free-muscle transfer following radical excision of soft-tissue sarcoma in the extremity. *Plast Reconstr Surg* 1999;104:1679-87.
- 11 Muramatsu K, Ihara K, Doi K, Yoshida K, Iwanaga R, et al. Functional neuro-vascularised muscle transfer for oncological reconstruction of extremity sarcoma. *Surg Oncol* 2012;21:263-8.
- 12 Grinsell D, Di Bella C, Choong PF. Functional reconstruction of sarcoma defects utilizing innervated free flaps. *Sarcoma* 2012;2012:315190.
- 13 Stranix JT, Lee ZH, Lam G, Mirrer J, Rapp T, et al. Limb-sparing sarcoma reconstruction with functional composite thigh flaps. *Microsurgery* 2018;38:466-72.
- 14 Fu SY, Gordon T. Contributing factors to poor functional recovery after delayed nerve repair: prolonged denervation. *J Neurosci* 1995;15:3886-95.
- 15 Taylor GI, Ham FJ. The free vascularized nerve graft. A further experimental and clinical application of microvascular techniques. *Plast Reconstr Surg* 1976;57:413-25.

- 16 Grinsell D, Keating CP. Peripheral nerve reconstruction after injury: a review of clinical and experimental therapies. *Biomed Res Int* 2014;2014:698256.
- 17 Koshima I, Harii K. Experimental study of vascularized nerve grafts: multifactorial analyses of axonal regeneration of nerves transplanted into an acute burn wound. *J Hand Surg Am* 1985;10:64-72.
- 18 Kanaya F, Firrel J, Tsai TM, Breidenbach WC. Functional results of vascularized versus nonvascularized nerve grafting. *Plast Reconstr Surg* 1992;5:924-30.
- 19 D'Arpa S, Claes KEY, Stillaert F, Coleblunders B, Monstrey S, et al. Vascularized nerve "grafts": just a graft or a worthwhile procedure? *Plast Aesthet Res* 2015;2:183-94.
- 20 Terzis JK, Kostopoulos VK. Vascularized nerve graft and vascularized fascia for upper extremity nerve reconstruction. *Hand* 2010;5:19-30.
- 21 Millesi H. Progress in peripheral nerve reconstruction. *World J Surg* 1990;14:733-47.
- 22 Lee SK, Wolfe SW. Nerve transfers for the upper extremity: new horizons in nerve reconstruction. *J Am Acad Orthop Surg* 2012;20:506-17.
- 23 Martin E, Dullaart MJ, van de Sande MAJ, van Houdt WJ, Schellekens PPA, et al. Resuscitating extremities after soft tissue sarcoma resections: are functional reconstructions an overlooked option in limb salvage? A systematic review. *Eur J Surg Oncol* 2019;45:1762-9.
- 24 Grinsell D, Lonie S, Wilson KC, Choong PF. The innervated rectus abdominis flap for quadriceps reconstruction. *J Plast Reconstr Aesthet Surg* 2019;72:941-5.
- 25 Grinsell DG, Ahmad Z. The free innervated latissimus dorsi flap for functional reconstruction following soft tissue sarcoma resection of the posterior compartment of the thigh. *Eur J Plast Surg* 2019;42:371-8.
- 26 Doi K, Kuwata N, Kawakami F, Hattori Y, Otsuka K, et al. Limb-sparing surgery with reinnervated free-muscle transfer following radical excision of soft-tissue sarcoma in the extremity. *Plast Reconstr Surg* 1999;104:1679-87.
- 27 Grinsell D, Yue BTY. The functional free innervated medial gastrocnemius flap. *J Reconstr Microsurg* 2014;30:451-6.
- 28 Enneking WF, Spanier SS, Goodman MA. A system for the surgical staging of musculoskeletal sarcoma. *Clin Orthop Relat Res* 1980;106-20.
- 29 Nielson OS, Cummings B, O'Sullivan B, Catton C, Bell RS, et al. Preoperative and postoperative irradiation of soft-tissue sarcomas: effect on radiation field size. *Int J Radiat Oncol Biol Phys* 1991;21:1595-9.
- 30 Hui A, Ngan S, Wong K, Powell G, Choong P. Preoperative radiotherapy for soft tissue sarcoma: the Peter Macallum Cancer Centre experience. *Eur J Surg Oncol* 2006;32:1159-64.
- 31 Kadle R, Motosko CC, Zakhem GA, Stranix JT, Rapp T, et al. Flap reconstruction of sarcoma defects in the setting of neoadjuvant and adjuvant radiation. *J Reconstr Microsurg* 2019;35:287-93.
- 32 Gundel KR, Cizik AM, Jones RL, Davidson DJ. Quality of life measures in soft tissue sarcoma. *Expert Rev Anticancer Ther* 2015;15:95-100.
- 33 Nelson AA, Frassica FJ, Gordon TA, Deune EG. Cost analysis of functional restoration surgery for soft-tissue sarcoma. *Plast Reconstr Surg* 2006;117:277-83.
- 34 Chao AH, Chang DW, Shuaib SW, Hanasono MM. The effect of neoadjuvant versus adjuvant irradiation on microvascular free flap reconstruction in sarcoma patients. *Plast Reconstr Surg* 2012;129:675-82.
- 35 Barwick WJ, Goldberg JA, Scully SP, Harrelson JM. Vascularised tissue transfer for closure of irradiated wounds after soft tissue sarcoma resection. *Ann Surg* 1992;216:591-5.
- 36 Townley WA, Mah E, O'Neil AC, Wunder JS, Ferguson PC, et al. Reconstruction of sarcoma defects following pre-operative radiation: free tissue transfer is safe and reliable. *J Plast Reconstr Aesthet Surg* 2013;66:1575-9.
- 37 Tokumoto H, Akita S, Kubota Y, Kuriyama M, Mitsukawa N. Use of vascularised sural nerve grafts for sciatic nerve reconstruction after malignant bone and soft tissue tumour resection in the lower legs. *Ann Plast Surg* 2018;80:379-83.
- 38 Melendez M, Brandt K, Evans GRD. Sciatic nerve reconstruction: limb preservation after sarcoma resection. *Ann Plast Surg* 2001;46:375-81.

Review

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Posterior component separation/transversus abdominis release

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Abstract

The Rives-Stoppa technique for ventral hernia repair is commonly utilized due to well-proven outcomes with low overall morbidity. However, this approach is limited by the amount of myofascial advancement and sublay space available for a wide mesh overlap. Thus, anterior component separation was developed to allow further myofascial advancement. Some limitations were noted, which led to the subsequent study, utilization, and refinement of the posterior component separation (PCS) technique. PCS continues to demonstrate low hernia recurrence, surgical site occurrences, and improvement in rectus muscle function. Continued adoption of this technique has expanded to minimally invasive approaches for hernia repair. This paper is a comprehensive review of the evolution of PCS, technique, and outcomes.

Keywords: Posterior component separation, transversus abdominis release, ventral hernia repair

INTRODUCTION

The major tenants of herniorrhaphy and abdominal wall reconstruction are reduction of the hernia, defect closure, and strengthening the repair with mesh reinforcement. While small ventral defects lend themselves to various techniques of herniorrhaphy, larger, recurrent, and more complex hernias require more nuanced approaches. Stoppa *et al.*^[1] published his original technique of preperitoneal repair of recurrent bilateral inguinal hernias with polyester mesh in 1973. This was shortly followed by a colleague, Rives *et al.*^[2], who described incisional hernia repair with mesh placed behind the rectus muscle to protect



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the visceral sac from mesh contact. With minor modifications, the Rives-Stoppa repair became widely utilized due to well-proven outcomes with low overall morbidity^[3,4]. However, despite the great success of this repair, the retrorectus repair does not easily facilitate myofascial advancement and the limited surface area in the retrorectus space prevents wide mesh overlap.

To overcome these limitations, Ramirez *et al.*^[5] performed anatomic studies describing separation of the components of the abdominal wall to allow for medial mobility (myofascial advancement) to close large ventral hernias with restoration of the linea alba. This technique involved developing the avascular plane between the external and internal oblique muscle layers through relaxing incisions lateral to the rectus sheath, and became known as the anterior component separation (ACS). The authors were able to demonstrate up to 10-cm myofascial advancement at the umbilicus with this technique. With early adoption of this technique, subsequent study revealed some notable drawbacks including technical challenges in patients with enterostomies, difficulty repairing hernias lateral to the rectus muscles or near bony prominences, and recurrence rates as high as 32%. Most notably, raising large subcutaneous flaps in order to perform ACS puts patients at risk for skin necrosis or wound complication, with rates as high as 40%^[6].

Considering the limitations associated with the Rives-Stoppa and ACS techniques, Novitsky *et al.*^[7] developed the posterior component separation (PCS). Two years later, Carbonell *et al.*^[8] described their technique of dividing the transversus abdominis aponeurosis lateral to the linea semilunaris and developing a plane between the TA and IO, which allowed medial advancement of the external oblique (EO) and IO with a large space for mesh placement in a sublay fashion. One major pitfall of this technique is the division of the neurovascular bundles supplying the rectus laterally, which can lead to muscle atrophy, abdominal wall bulges, recurrent hernia, and asymmetry^[6].

To further the novel idea of separating the posterior components, but avoid division of the neurovascular bundles, Novitsky *et al.*^[9] described the Transversus Abdominis Release (TAR) in 2012, whereby, after extending the Rives-Stoppa technique laterally, an incision is made in the posterior rectus sheath to expose the TA. The muscle of its associated aponeurosis is then divided along its medial edge, separating the TA from the underlying transversalis fascia and peritoneum.

This modification allows the surgeon to develop the retromuscular space laterally as far as the retroperitoneum and psoas muscle. Initial study of this technique demonstrated low hernia recurrence and SSI with improvement in rectus muscle function^[9-11].

PATIENT SELECTION

Patient selection for the appropriate herniorrhaphy is paramount as there is a vast array of techniques, abdominal wall planes, and patient characteristics. The authors generally reserve laparoscopic repairs for small to medium sized defects (2-7 cm) in patients without a history of multiple abdominal operations or previous underlay mesh. Patients with defects greater than 8 cm in diameter are approached with a robotic or open repair. In some cases, posterior sheath reapproximation at the midline is achievable with a Rives-Stoppa repair. However, TAR may be required if a classic Rives-Stoppa is unable to achieve midline closure, when there is insufficient mesh coverage behind the rectus muscle or in the following settings: large defects, multiply recurrent hernias, non-compliant abdominal walls necessitating myofascial release, and parastomal hernias. Although it is hard to definitively predict preoperatively which patients will require a TAR in addition to a Rives-Stoppa repair, Love *et al.*^[12] hypothesized that Rives-Stoppa repair will achieve midline closure if the sum of the rectus widths is twice the width of the defect width when measured on CT scan. The authors recommend that previous subcutaneous or wound related complications should be approached with TAR rather than open ACS. In patients with tenuous vascularity (diabetics, smokers, and

patients with vasculopathies), we avoid open ACS and recommend a TAR approach, although a minimally invasive component separation (compared to open ACS) may be an appropriate option as this approach has demonstrated superior outcomes to open ACS^[13].

There are few relative contraindications to performing a TAR. TAR can be exceptionally challenging in patients with previously placed pre-peritoneal or retromuscular mesh. In patients who have undergone resection of the posterior abdominal wall components (such as occurs during radical cystectomy or procedures to excise peritoneal cancer implants), the loss of tissue planes may make the creation or continuation of a retromuscular plane impossible. Similarly, TAR should be used with caution in patients who have undergone previous ACS as this could lead to lateral hernia formation, although favorable results have been reported by Pauli *et al.*^[14] in short-term follow up.

PREOPERATIVE PREPARATION

The authors strongly recommend preoperative CT imaging of the abdomen and pelvis as it well elucidates the abdominal wall musculature, hernia defect, contents, and dimensions. CT scans can also show signs of active infection, previous mesh, and any evidence of underlying visceral abnormalities. Routine use of contrast is unnecessary, although IV contrast is recommended with concerns for intra-abdominal infection and oral contrast should be used to evaluate gastrointestinal pathologies such as obstructions or fistulas. Imaging is also advantageous in obese patients where physical exam is limited to evaluate the hernia.

Of utmost importance is preoperative patient optimization. There are increased complications after hernia repair in patients who are actively smoking, poorly controlled diabetics, obese, or with poor nutrition. Cigarette smoking adversely affects wound healing^[15]. After 4 weeks of smoking cessation, the inflammatory aspect of wound healing normalizes^[16]. Thus, a minimum of one month of smoking cessation is recommended before elective repair. Similar to smoking, poor glucose control (HbA1c > 7%) increases the rate of surgical site infections (SSI)^[17]. Studies have shown a 30% increase in SSIs with every increase of 40 mg/dL of glucose over 110 mg/dL^[18]. We recommend HbA1c < 7% before offering elective component separation hernia repair.

Obesity greatly effects the formation of hernias, hernia recurrence, and hernia repair morbidity. There is also an association between nosocomial infection, readmissions, and requirement for transfusions among obese patients. Wound morbidity increases sharply with body mass index (BMI), where a BMI > 40 incurs a 1.66 odds of surgical site occurrence (SSO)^[19]. We routinely encourage overweight patients to pursue an active weight loss program with a goal of achieving a BMI < 40. Given the often-elective nature of hernia repair, we routinely follow patients for three months. Patients are supported by our institutional weight loss program; however, if reasonable weight loss is not achieved despite best efforts, we often refer patients to our bariatric surgery program.

Lastly, we ensure our patients are nutritionally optimized. A large, multi-center study of nearly 90,000 veterans demonstrated that the single most valuable predictor of surgical morbidity was a serum albumin < 3.0 g/dL, which emphasizes the need to evaluate and address the nutritional status of patients prior to operation^[20]. Validated nutritional risk assessment tools are readily available^[21]. There are many data in support of nutritional supplementation preoperatively. One common regimen is arginine/omega-3 supplementation (Impact Advanced Recovery; Nestle Healthcare Nutrition Inc., Florham Park, NJ) given 3 times a day for the 5 days prior to surgery^[22].

RELEVANT ANATOMY FOR TRANSVERSUS ABDOMINIS RELEASE

With the above-mentioned evolution from a Carbonell PCS technique to Novitsky's TAR, understanding of the TA anatomy is vital. The TA is the deepest of the lateral muscles, and fibers run in a horizontal

direction, 90 degrees to the fibers of the rectus abdominis muscle. Inferiorly, it originates from the anterior aspect of the iliac crest and lateral third of the inguinal ligament. Below the arcuate line, the TA inserts into the pubic crest and pectineal line to form the conjoint tendon with contributions from the IO. In the upper third of the abdominal cavity, the TA muscle inserts onto the costal cartilages of the 7th-12th ribs as well as the xiphoid process. In this area, it extends medially beyond the semilunar line and lateral edge of rectus abdominis (RA). Cephalad, the TA fibers interdigitate with the diaphragm muscle as well. As the TA muscle moves caudally, its medial border moves obliquely and laterally. At the level of the arcuate line, TA muscle fibers may no longer be visible; rather, only the aponeurosis is noticed.

The TA and internal oblique muscles are key contributors to intra-abdominal tone throughout the thoracolumbar space. Mobilization of the TA off the underlying fascia removes its contribution to the lateral abdominal wall leaving the IO's contribution intact. This allows for expansion of the abdominal cavity and thus myofascial advancement to the midline of both the lateral and medial components of the abdominal wall, up to 8-12 cm per side in studies performed by Novitsky *et al.*^[9]. Additionally, TAR allows for extensive lateral dissection for herniorrhaphy of large, recurrent, off-midline defects as well as those that approach bony landmarks.

OPERATIVE TECHNIQUE

Patient position

The patient should be placed supine on the operating table with arms extended. The field should be prepped from the nipple line superiorly to the mid-thigh inferiorly and to the table edge laterally. This wide prep allows for wide mesh fixation points, if needed. Some surgeons routinely place an iodine impregnated drape over the field to protect the mesh prosthesis from contact with any skin flora.

Entering the abdominal cavity

The surgeon should take note of previous scars; we routinely mark all prior surgical incisions prior to placing the iodine-impregnated dressing. Poorly healed midline scars or ulcerated skin may be excised with an elliptical midline incision for cosmetic effect. A generous midline incision is made from above to below the hernia defect. We base the location for initial abdominal entry based on physical examination (ideally in a location not previously violated) and on CT scan review (ideally in an area where there is clear omental or pre-peritoneal fat present separating the fascia from the viscera). For hernias where the sac closely approaches the skin, care should be taken when entering the hernia sac, as viscera may be shallow to the incision. Once inside the abdominal cavity, we focus next on completing the midline laparotomy before addressing adhesions that may be found laterally. However, generous lysis of adhesions should be completed to free the undersurface of the posterior abdominal wall layers to allow medial advancement and free any attachments that could lead to internal hernias. Once completed, a countable, radiopaque towel is placed over the viscera to protect them during subsequent dissection.

Entering the retrorectus space

The medial edge of the rectus muscle should be palpated as the hernia sac or a diastasis of the recti can cause lateralization of the muscle. Using a finger-pinch technique, the rectus can be palpated and a Kocher clamp placed on the fascia at the anterior medial edge of the muscle. The posterior rectus sheath is then incised 5-10 mm lateral to the medial edge. The muscle fibers must be visible to ensure that entry into the retrorectus space (rather than transection of the linea alba) [Figure 1]. With few exceptions (notably prior PCS), this plane should easily open and reveal loose alveolar tissue. Electrocautery is then used to extend the incision on the posterior sheath superiorly and inferiorly. It is important to keep this incision close to the medial edge of the muscle and not skive laterally, to preserve as much posterior sheath as possible for reapproximation. As the incision is extended, we place more clamps (Kocher or Lahey) on both the anterior sheath (linea alba) and the now liberated posterior sheath. The more clamps on the fascia, the more the

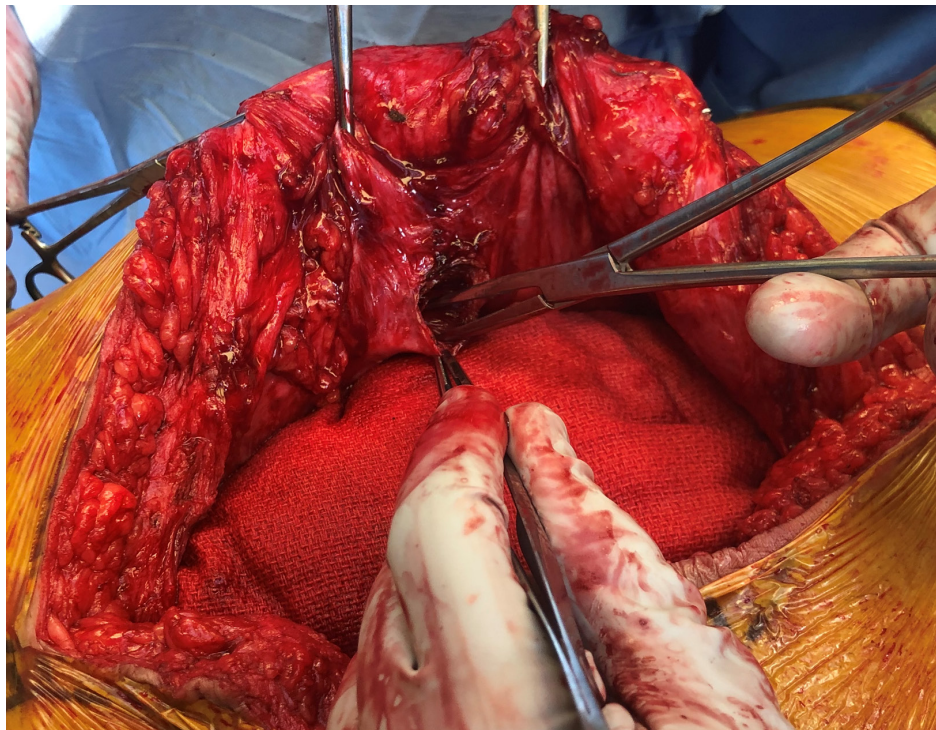


Figure 1. Entering the retrorectus space: After palpating the edge of the rectus muscle, the rectus sheath is incised 5-10 mm lateral to the medial edge revealing muscle fibers

retraction (tension) is evenly distributed and less likely to tear fascia. Blunt and electrocautery dissection is then used to extend the dissection to the lateral edge of the rectus muscle where the linea semilunaris is encountered. Working lateral, it is helpful to have the assistant use a Richardson retractor to lift the rectus up and away from the posterior sheath as the surgeon moves laterally. Kittner (peanut) dissectors are helpful tools to sweep the loose alveolar tissue off the posterior sheath as one works laterally.

The dissection is extended cephalad towards the costal margin. The extent depends on the size of the hernia, although it commonly extends to the epigastric or subxiphoid area. Inferiorly, the surgeon works towards the space of Retzius. Below the arcuate line, the posterior rectus sheath thins (being composed only of peritoneum and transversalis fascia). Crossing from the one retrorectus space to the other in the low midline requires division of the transversalis insertion points to the linea alba to create one confluent plane [Figure 2]. At this level, care must be taken to identify and preserve the deep inferior epigastric vessels as they run along the posterolateral surface of the rectus muscle in the pretransversalis plane. They are typically invested in fibro fatty tissue that can be swept off the posterior sheath/transversalis fascia towards the muscle in a dissection that mimics maneuvers performed during a laparoscopic inguinal hernia repair. Often, the caudal extent of dissection proceeds into the space of Retzius to expose the pubis symphysis and Cooper's ligaments. This completes the extent of a Rives-Stoppa exposure.

Division of the transversus abdominis

At this point, if the linea alba cannot be reconstructed in the midline without undue tension or there is insufficient sublay space for wide mesh overlap, a TAR should be completed. The TAR can be started cephalad first ("top-down" approach) or from the caudal aspect ("bottom-up" approach), often chosen by surgeon preference or dictated by patient anatomy. The "top-down" approach starts in the upper aspect of dissection where the TA muscle is more medial to the linea semilunaris and is generally thicker. Beginning the dissection at this level offers a level of safety, as the muscle belly is a good anatomic landmark and

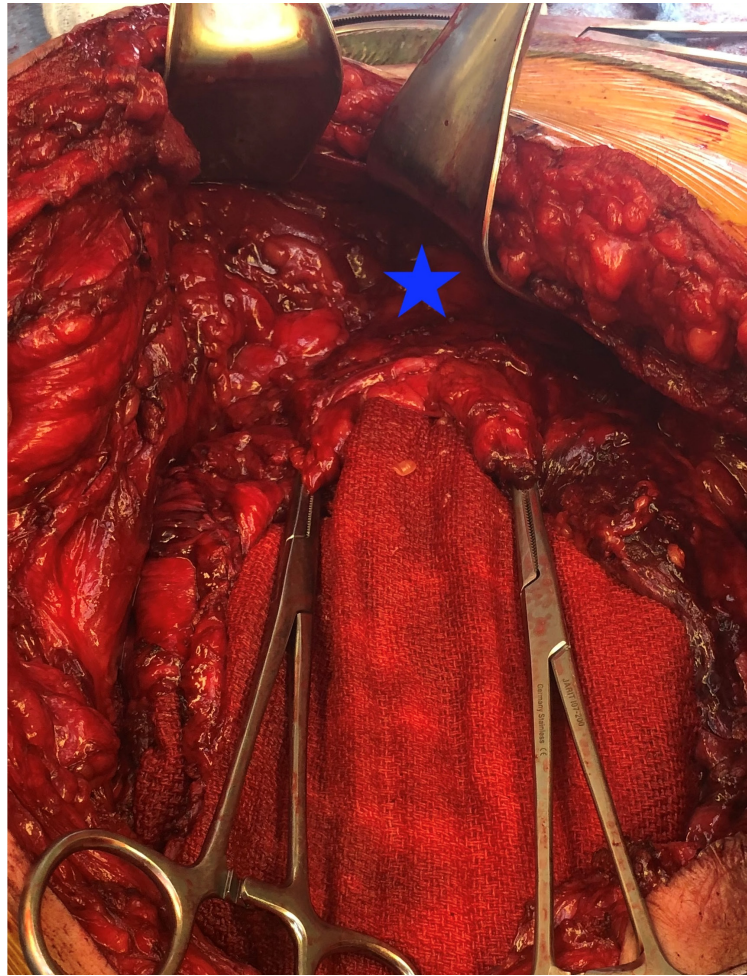


Figure 2. Connecting planes (inferior): crossing from the one retrorectus space to the other inferiorly to create one confluent plane. The blue star marks the pubic symphysis

is thick enough to prevent inadvertent holes from being created in the underlying transversalis fascia/peritoneum. It is important to remember that the lateral neurovascular supply to the rectus muscles penetrate the posterior lamina of the IO at the lateral rectus boarder; care must be taken to start the TAR medial to these bundles to prevent denervation of the rectus itself. To start the TAR, the posterior lamina of the IO aponeurosis is incised just medial to the perforating neurovascular bundles exposing the underlying TA muscle belly [Figure 3]. The TA fibers are separated from the underlying transversalis fascia/peritoneum [Figure 4]. The TA release should continue inferiorly. Once the edge of the TA is freed, it can be grasped with a clamp and carefully retracted anterior to further release it from the posterior elements.

There are 2 planes within which the dissection can proceed. Dissection between the TA and the transversalis fascia allows access to the pre-transversalis plane. Dissection in this layer is a bit more difficult as the fascia is generally quite stuck to the muscle belly. This can make the dissection more difficult, resulting in more bleeding/ooze. However, it also leaves both the transversalis fascia and the peritoneum as the posterior layers of the reconstruction, making it thicker and less prone to hole formation and tearing. Alternatively, dissection can proceed between the transversalis fascia and the peritoneum in the pre-peritoneal plane. Dissection in this layer is generally much easier as there is less connective tissue between the layers and no blood vessels. However, the peritoneum is exceptionally thin and is prone to tearing (and

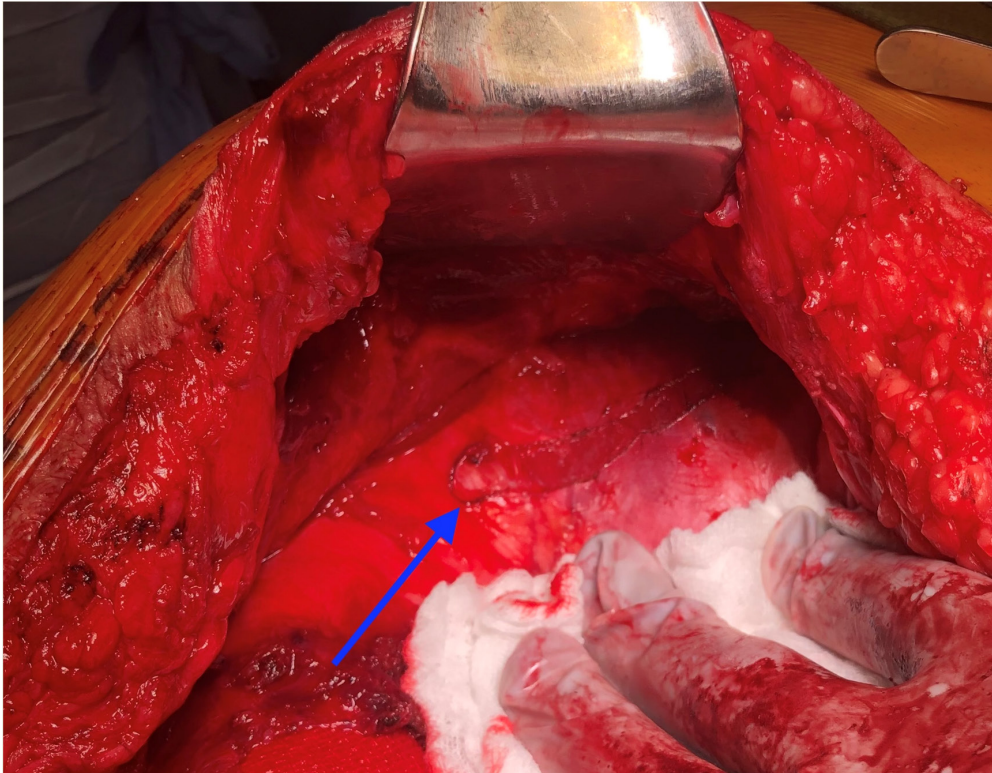


Figure 3. Accessing the transversus abdominis: the posterior lamella of the internal oblique is scored (blue arrow) to reveal the underlying transversus abdominis

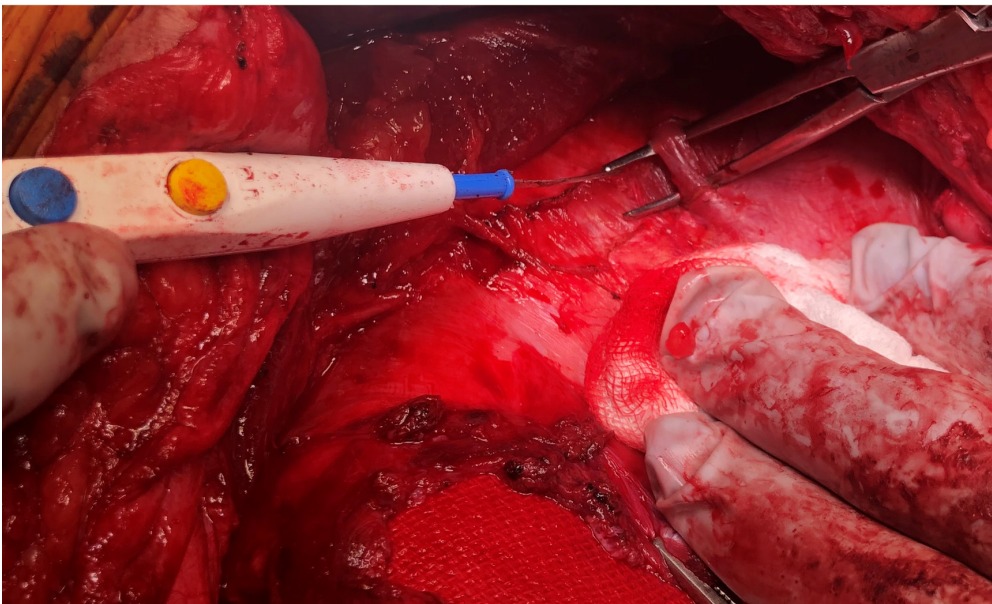


Figure 4. Releasing the transversus abdominis: a right angle clamp gently reveals the muscle fibers that are then divided with electrocautery

propagating tears once they start can be challenging to fix). Either plane can be used, and surgeons should become comfortable learning how to “plane-hop” between these two as needed on a patient-by-patient basis and based on the need to address focal areas of difficulty in any individual patient.

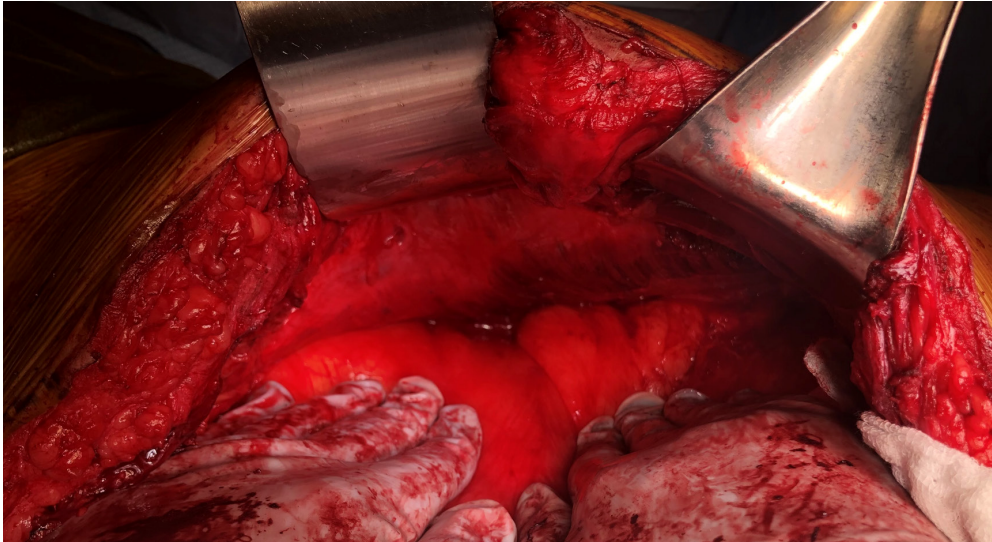


Figure 5. Lateral dissection: the lateral dissection can proceed as far back as the psoas muscle in the retroperitoneum

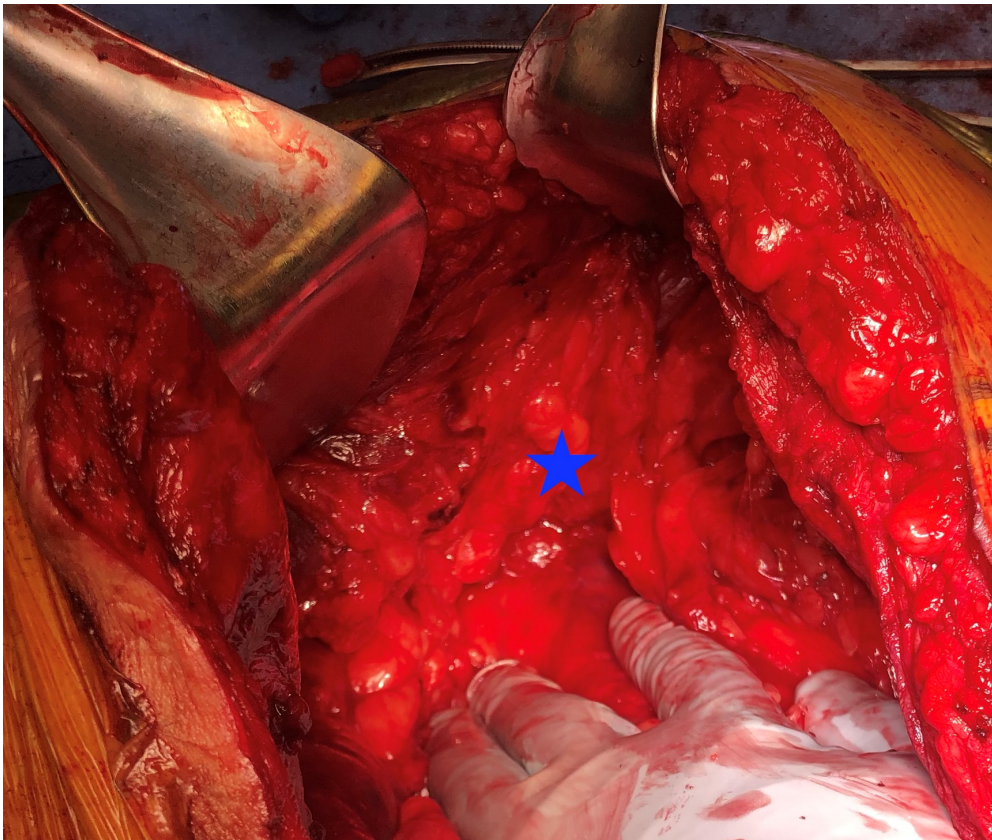


Figure 6. Inferior view: fat within the inferior pre-peritoneal plane should be cleared in this dissection to reveal the myopectineal orifice. The blue star marks the pubic symphysis

Dissection in the pre-peritoneal or pre-transversalis plane is continued moving laterally to extend the space towards the retroperitoneum and the psoas muscle [Figure 5]. Cranially, the dissection can proceed above the costal margin on the diaphragm. The plane stops at central tendon of the diaphragm in the midline. Care must be taken to perform limited finger dissection underneath the costal margin, dorsal

to the ribs, and not to inadvertently divide diaphragm fibers that interdigitate with the TA in the cranial-medial aspect. Doing so may create an iatrogenic diaphragm hernia. At the superior/medial extent of the dissection, the TA release will join a subxiphoid pre-peritoneal dissection plane (discussed in next section).

Working caudally, it is important to remember that the TA muscle fibers do not reach as far medial as they do in the upper abdomen. By the level of the umbilicus, there is only a bilayered aponeurotic insertion of the TA to divide as part of the TAR. The plane between the TA aponeurosis (tendon) and the underlying peritoneum can be dissected bluntly in a relatively straightforward fashion. Further caudally, there will be substantial fat within the pre-peritoneal plane that further facilitates this dissection [Figure 6]. The ease of separation of the layers is the basis for a “bottom-up” TAR. By bluntly dissecting from the retrorectus space towards the myopectineal orifice, a pre-peritoneal/pretransversalis plane can be created. Further blunt dissection cranially separates the TA aponeurosis from the underlying layers, and the aponeurosis can then be divided. Some surgeons prefer the “bottom-up” approach to TAR because of the ease of starting the plane at this level.

Midline crossover/transition

When the sublay plane is fully dissected to the superior and inferior extent, the right and left retromuscular planes need to be connected. This is sometimes referred to as “plane hopping” or “crossing over”. Inferiorly, the space of Retzius should be exposed down to the pubis. Connecting the right and left sides at this level requires no more than ensuring the dissection planes (either pre-peritoneal or pre-transversalis) meet in the midline. If one side is performed pre-peritoneal and one side pre-transversalis, they will not meet properly in the midline without additional division of transversalis fibers off of the linea alba in the midline. For low (European Hernia Society Classification: M4 or M5 zone) hernias, Cooper’s ligaments should be exposed and may be used as fixation points for mesh^[23]. Any hernias of the myopectineal orifice should be identified and reduced (including lipomas of the cord). The round ligament in women can routinely be divided, while the spermatic cord in men must be carefully dissected around. With this exposure, the sublay planes will connect at the caudal aspect.

For the cranial dissection, if the hernia defect approaches xiphoid process in the M1 zone, the insertion of the posterior rectus sheath into the linea alba is divided to the level of the xiphoid. First, a plane superficial to the falciform ligament and deep to linea alba must be developed. Next, retroxiphoid space should be accessed. This is a fatty subxiphoid plane that extends to the sternum. This can be finger-swept posteriorly off the xiphoid. Additionally, this preperitoneal space can be worked along the diaphragm to the central tendon. The process of connecting the right and left retrorectus spaces with the pre-peritoneal plane of the falciform ligament in the midline is referred to by some as the “pant leg maneuver” because of the appearance of the undivided planes [Figure 7]. The insertion should be cut 0.5 cm lateral to the linea alba on each side, which will drop the edge of the posterior sheath to allow reapproximation. Dividing the posterior sheath insertion into the lineal alba, moving cranially along the xiphoid process, connects these spaces [Figure 8].

Closure of the posterior sheath

Once the entirety of the retromuscular plane is developed, the posterior sheath is closed. Small defects in the posterior sheath should be closed with an absorbable suture, generally in a transverse direction (perpendicular to the midline) to prevent herniation of bowel into the retromuscular pocket. Larger defects or areas that are extremely thin may not be closable primarily. In such circumstances, a piece of autologous tissue (hernia sac and omentum) can be used to patch the graft. At times, difficulty with reconstruction of the posterior layer can be predicted before any myofascial release is performed. In such cases, we generally take the hernia sac off the subcutaneous tissues in the midline and leave it attached to the posterior rectus sheath to serve as a continuous layer for reconstruction later. Larger defects can also be closed

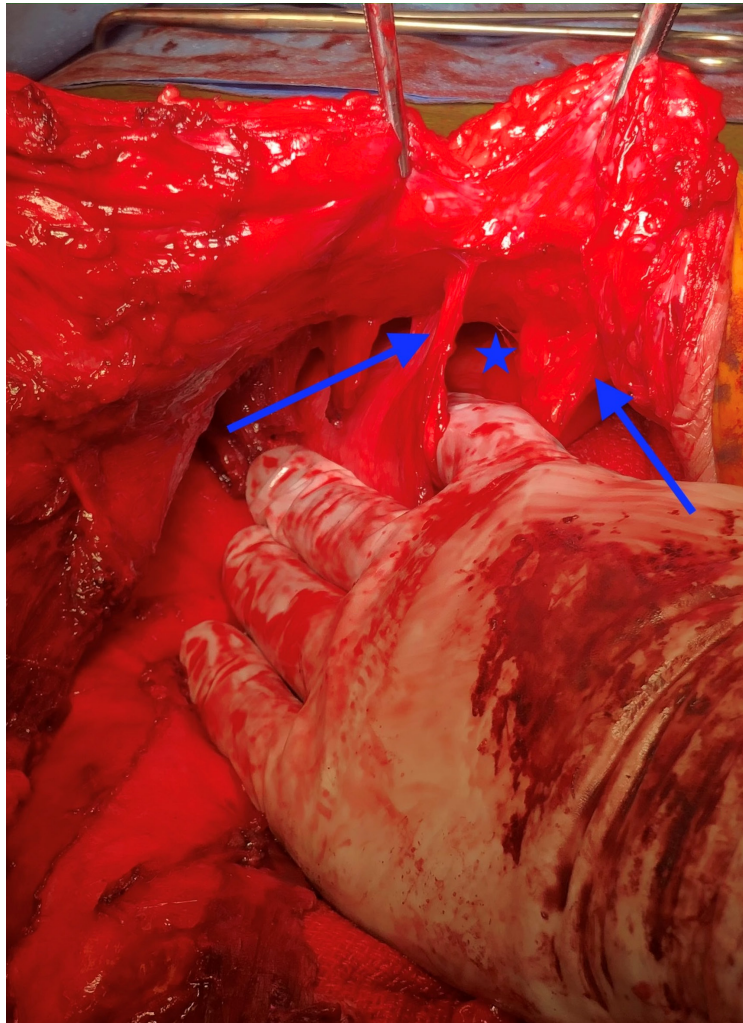


Figure 7. Pant leg maneuver: the subxiphoid plane is dissected. After the right and left retrorectus spaces are developed, the surgeon's fingers can straddle these planes demonstrating the two "pant legs". The blue arrows show the right and left "pant legs" (linea alba insertion) that straddle subxiphoid/preperitoneal space (blue star)

with polyglycolic acid, biologic or coated 4-hydroxybuterate mesh if autologous tissue is not available. Polyglycolic acid mesh is the most inexpensive of the three, and is proven to be safe for such reconstruction purposes^[24].

Bilateral TAR should provide enough myofascial advancement to allow the posterior sheaths to meet in the midline [Figure 9]. If there is undue tension on the midline closure, additional lateral dissection can be performed bluntly to gain additional midline advancement. The right- and left-hand sides of the posterior layer are closed in the midline with an absorbable running suture from the superior and inferior ends. If the midline can be approximated, but is closing with some tension, a locking bite can be performed every few travels. Prior to closing the mid portion, the countable towel must be removed from the peritoneal cavity.

Preparation of the sublay space

Any remaining hernia sac is dissected free from the subcutaneous fat. The sac and any unusable fascial bands are resected, revealing healthy EO fascia at the medial boarder of the RA. Some surgeons routinely irrigate the retromuscular space with antibiotic lavage solution. The purpose is to reduce the bioburden of

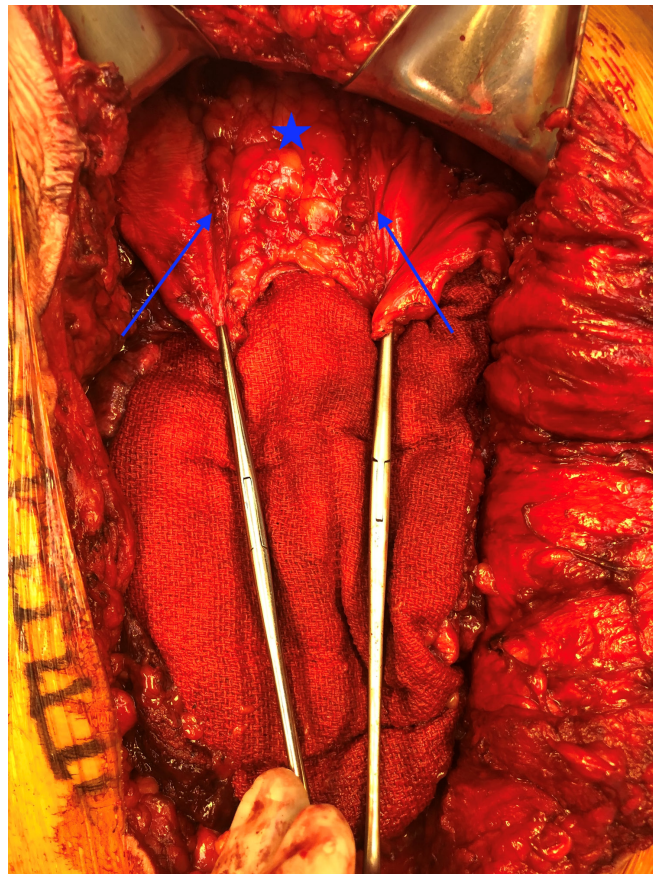


Figure 8. Connecting plans superiorly: cutting the “pant leg” insertion will drop the edge of the posterior sheath (blue arrows). This connects the bilateral retrorectus spaces with the subxiphoid/preperitoneal space (blue star)

the space prior to placement of mesh. Warren and colleagues showed that irrigation with a combination of gentamicin and clindamycin significantly lowers the rate of SSI/SSOs and reoperation for wound complications^[25]. Similarly, Majumder *et al.*^[26] showed that pressurized antibiotic pulse lavage was effective at reducing bioburden in the TAR plane in both clean and contaminated cases. While irrigation cannot eliminate SSI, we utilize lavage as part of our standard operative methods to reduce the risk of mesh contamination.

Next, we perform transversus abdominis plane blocks by injecting liposomal bupivacaine (266 mg/20 mL diluted in 180 mL of saline) into the intramuscular plane between the internal oblique and TA muscles with an 18-gauge needle under direct visualization. We have previously shown this method to provide superior analgesia (as proven by significantly less postoperative narcotic utilization) when compared to ultrasound-guided administration of the same agent in the same plane^[27].

Placement of mesh and fixation

The mesh should be large enough for large defect overlap (~8 cm), filling the entire retromuscular space. We generally favor a medium weight, large pore, polypropylene product to allow for robust tissue ingrowth and incorporation. Our typical mesh implant is 30 cm × 30 cm, which when oriented as a diamond has a 42 cm cranial-caudal dimension [Figure 10]. In this orientation, there is often insufficient overlap in the superior aspects (above the costal margin). In such cases, a second piece of 30 cm × 30 cm mesh is placed as a square, overlapping the top of the first mesh placed as a diamond. This configuration is commonly referred to as “home plate” mesh configuration due to the resemblance to home plate of a baseball field.

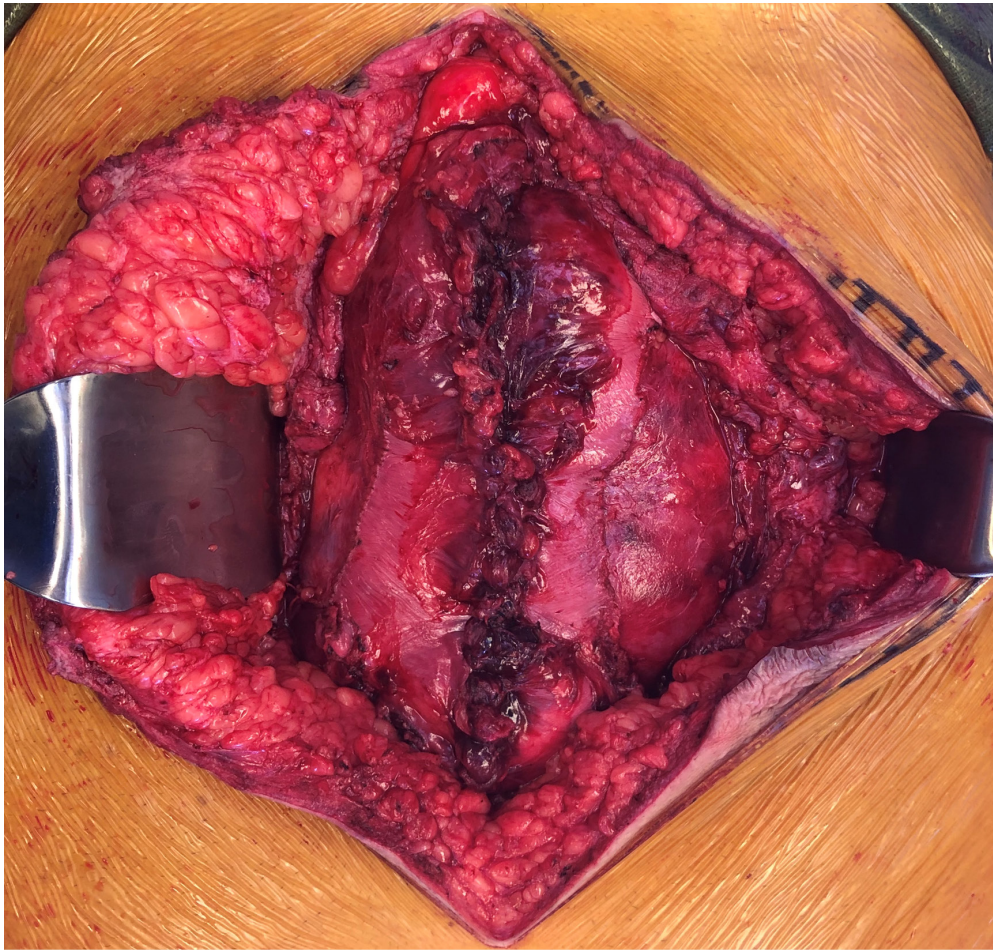


Figure 9. Reapproximation of posterior sheath: the visceral sac is reapproximated, and a large sublay space is created

The overlap of mesh in the midline appears to be inconsequential in our experience, although no study has evaluated this issue specifically.

Mesh fixation is an active topic of discussion among hernia surgeons. Most would agree that inferior fixation is important. For low hernia defects, the inferior aspect of the mesh can be sutured to Cooper's ligament bilaterally with 2 interrupted monofilament, slowly absorbable sutures. If the caudal extent is more than 5 cm above the pubis, transfascial fixation (described below) can be achieved without suturing to Cooper's ligament. Advocates of "minimal" or "no" fixation support the idea that wide placement mesh along with radial intra-abdominal pressure will keep the mesh in place. One "minimal fixation" technique is the use of fibrin sealant fixation to the underlying posterior sheath [Figure 11]. Others simply place the mesh in the retromuscular space with no fixation. When sutures are felt to be necessary, we place 6-8 #1 slowly absorbable, monofilament, slowly-absorbable sutures radially around the mesh utilizing a suture passer delivered through percutaneous stab incisions^[28]. This technique uses the transfascial sutures to "off load" the tension off the midline closure and onto the mesh and prevents buckling of the mesh during closure^[29].

Closure of anterior fascia and skin

For open TAR operations, we routinely place a single 19Fr drain into the retromuscular pocket to reduce the volume of seroma that can accumulate in the immediate postoperative period. The lineal alba is then



Figure 10. Mesh placement: after antibiotic irrigation of the sublay space, mesh is placed. In this case, a square piece of mesh oriented in diamond fashion with apices running vertically and horizontally

reapproximated with either a running (low tension closure) or interrupted [Figure 8](#) pattern (high tension closure) #1 slowly absorbable, monofilament suture [\[Figure 12\]](#). Any additional dermal scar, ischemic skin, and typically the umbilicus are resected back to healthy bleeding skin. The subcutaneous tissue is closed in layers. If large subcutaneous spaces remain, a 19Fr drain is placed on the patients left side (left = lipocutaneous). The peripheral stab incisions can be closed with skin adhesive. If there is significant radial tension on the skin closure, if there was GI tract contamination during the case, or there is an ostomy present, we choose to place a closed incisional vacuum dressing to further protect the wound. This practice may not be beneficial in routine TAR cases^{[\[30\]](#)}.

POSTOPERATIVE MANAGEMENT

One of the biggest immediate perioperative concerns is in patients with loss of domain defects that put them at risk for postoperative abdominal compartment syndrome and respiratory complication. If pulmonary plateau pressures increase more than 6 mmHg after closure, patients remain intubated in the intensive care unit overnight. In those with more than 11 mmHg increase in plateau pressures, consideration to 24 h of paralysis should be made^{[\[31\]](#)}. Generally, abdominal compliance improves within the first day. An abdominal binder is placed on all patients before exiting the operating room and the bladder catheter is kept in place.

Much attention is given to Enhanced Recovery After Surgery (ERAS) pathways and early outcomes in abdominal wall reconstruction are encouraging^{[\[32\]](#)}. Barring extensive lysis of adhesions or a bowel

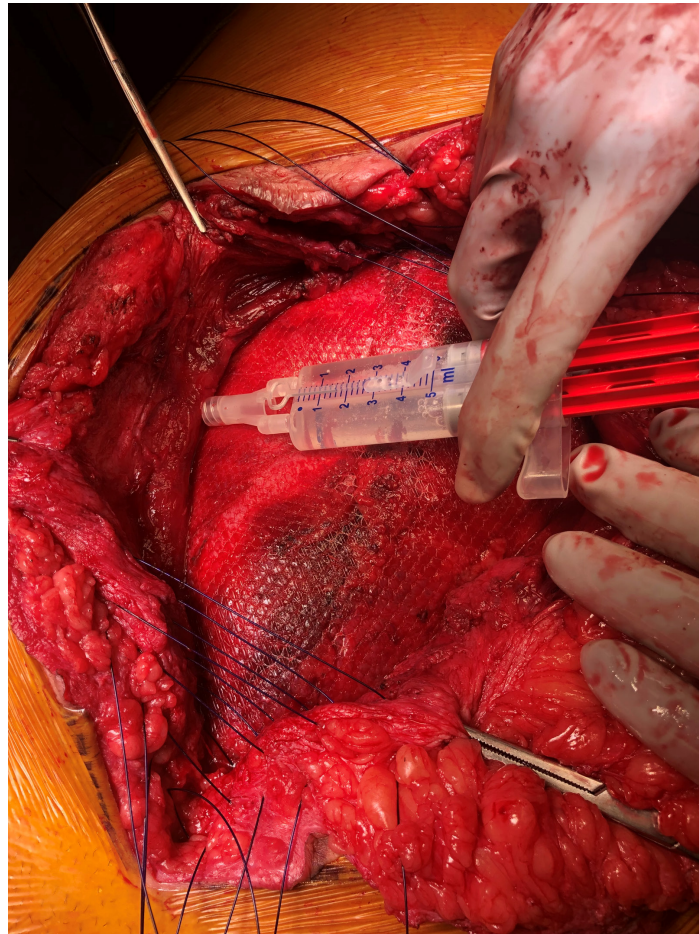


Figure 11. Fixation: fibrin glue is used to fixate the mesh in the sublay space

resection, a clear liquid diet is started on postoperative Day 1, and advanced as tolerated the following day. Alvimopan can be used to accelerate intestinal recovery, but first dose must be given in the preoperative holding area. Deep vein thrombosis prophylaxis is started the evening of surgery or the next morning and continues throughout their hospitalization. Intravenous fluids are weaned and held on postoperative Day 2 if the patient is self-hydrating. The bladder catheter is generally removed on postoperative Day 1.

Analgesia may be offered in many forms. For those who received intraoperative TAP blocks, minimal narcotics are used postoperatively. Otherwise, scheduled acetaminophen and gabapentin are used. If narcotics are required, we often use as needed oxycodone orally and a patient-controlled analgesia administration of intravenous hydromorphone. Patients are encouraged to ambulate as soon as they are able, and as frequently as possible. Pulmonary hygiene is equally emphasized. Drain output should be recorded daily. Our practice is to remove the retromuscular drain prior to discharge, unless the output is exceptionally high in the 24 h before discharge (> 150 - 200 mL). Subcutaneous drains (if utilized) are left until the output is < 30 mL per day for two consecutive days.

We typically have postoperative clinic follow up at 4-6 weeks and 1 year postoperatively. It is our practice to routinely perform CT imaging postoperatively to assess for occult issues (including fluid collections and recurrent hernias).

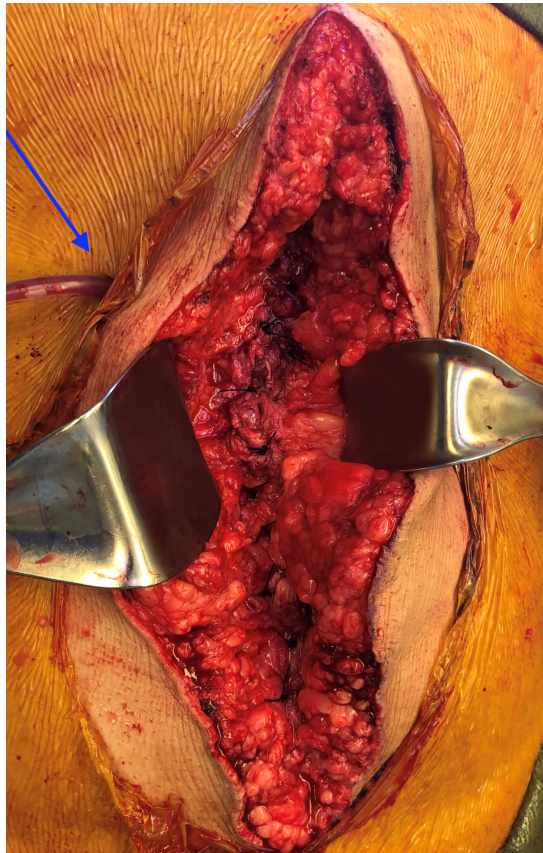


Figure 12. Anterior fascia reapproximation: the anterior fascia is closed. In this case, it was closed with interrupted suture to offload midline tension. A retromuscular drain is placed on the patient's right side (blue arrow)

SPECIAL SITUATIONS

The transversus abdominis release technique can be utilized in unique hernias as well. We have found TAR to be successful for the management of parastomal hernia (or for large midline hernias occurring in patient with an ostomy adjacent to the defect)^[33,34]. If the stoma does not warrant relocation, a TAR is carefully performed around the stoma as described above. Next, the posterior sheath defect for the stoma is intentionally extended laterally. The bowel proximal to the stoma is delivered into the retroperitoneal plane and posterior sheath defect is closed lateralizing the bowel within the retromuscular space. Mesh is positioned around the bowel in a Sugarbaker fashion, which permits wide overlap of hernia defects without the need to cut the mesh or relocate the stoma^[33].

Another special situation is a hernia recurrence after ACS, reported in 7%-32% of cases^[35]. As stated previously, the concern in performing a TAR after ACS centers on the potential for lateral hernia formation. Previous evaluation of TAR after EO release resulted in hernia recurrence in only 3% of patients after 11-month follow-up, suggesting the method may be utilized successfully in experienced hands^[12].

MINIMALLY INVASIVE APPROACHES TO TAR

In the era of new surgical technologies, much attention is paid to developing minimally invasive approaches to TAR. The following subsections briefly describe some of the novel techniques.

Mini or less-open sublay operation

The mini or less-open sublay operation (MILOS) technique was developed by Dr. Reinpold *et al.*^[36] out of a desire to minimize complications and pain related to open repair, but allow a large sublay mesh to be

placed through a small incision through the hernia. Briefly, this procedure starts with an incision centered over the hernia defect and exposure of the hernia sac. Transhernia laparoscopy is set up and adhesiolysis is performed to expose the hernia defect ring. The peritoneum is detached from the abdominal wall and the posterior sheath is entered. An assistant elevates the abdominal wall and the retrorectus space is developed laparoscopically or with direct visualization with a 10-mm light tube (Endo-torch, Wolf TM, Knittlingen, Germany). After 8 cm of extraperitoneal space is achieved circumferentially, the peritoneum is closed and the operation is converted to a laparoscopic extraperitoneal repair [extended total extraperitoneal repair (eTEP)]. The posterior sheath is closed under low gas insufflation and the mesh is rolled, inserted into the field, and then unfolded.

In 2019, this group reported their results after 615 MILOS repairs^[36]. There was a statistically significant reduction in postoperative complications, recurrences, and chronic pain compared to laparoscopic intraperitoneal onlay mesh (IPOM) technique.

Extended total extraperitoneal repair TAR

eTEP of ventral hernias was created as an extension of total extraperitoneal (TEP) repair of inguinal hernias. The major advantage of this approach is a lack of entry into the abdominal cavity, obviating bowel manipulation, peritoneal defect closure, and intra-abdominal adhesion formation. Classic TEP repairs are limited by their minimal dissection space, thus space for mesh overlap as well as restricted port placement. Daes^[37] popularized the “extended view” of TEP inguinal hernia repair to allow for easy creation of the extraperitoneal space in a large surgical field to facilitate mastery of the repair and utility in complex cases. Subsequently, Belyanky *et al.*^[38] and an international group of hernia specialists reported on expanding this technique to laparoscopic ventral hernia repairs (eTEP). Their technique is described briefly.

The patient is placed supine on the operating table in a flexed position to widen the space between the costal margin and anterior superior iliac spine. Port location depends on the location of the defect, but the guiding principles of eTEP rely on initiating the dissection in the retrorectus space of one side and “crossing over” to the contralateral retrorectus space in the fat pads of the falciform ligament of the space or Retzius. The dissection is carried out along the length of the RA muscles and the bilateral posterior sheaths are released to connect the contralateral spaces in the midline by mobilizing the hernia sac out of the defect, keeping it in continuity with the posterior rectus sheath. For larger defects, TAR can be added on either side (or both) to permit further posterior and anterior sheath mobilization. Posterior sheath defects are closed with absorbable suture, and the anterior fascial defect is closed with a running barbed suture under low-pressure pneumoperitoneum. Mesh is then placed to fill the retromuscular pocket and fixated as desired. Early results eTEP posterior component releases have shown promising results. Of the 79 patients reported by this group, there was a 3% wound complication rate, no 30-day readmissions, and only one hernia recurrence with 11 months of follow-up^[39].

ROBOTIC TAR

Further advancement in surgical technology leads to the development of robotics, which have the added benefit of finer instrument movements, greater range of freedom, and elimination of tremor. An essential first consideration is paid to trocar placement and robot docking. Patients are placed in the supine position. The arms are extended at 90 degrees to allow lateral robot arm placement for more working space and a full range of motion. An 8-mm robotic trocar is placed in the lower lateral abdomen as well as the upper abdomen on the ipsilateral side, while a 12-mm trocar is placed half way between the two as far lateral as possible. Future mesh placement can be through the camera's 12-mm port, or a fourth accessory port (12 mm) can be utilized and placed in a subxiphoid or suprapubic location. In general, a grasping instrument with bipolar energy and scissors with monopolar energy are used.

Initial steps in robotic TAR parallel those in open surgery. With the camera in a 30-degree-up configuration, extensive adhesiolysis is performed to free bowel from the abdominal wall. The contralateral edge of the rectus muscle is identified and grasped and the retrorectus space is entered with the scissors. This space is developed both inferiorly and superiorly staying parallel to the fibers of the rectus muscle. Once the retrorectus space is developed, the camera is changed to 30 degrees down to begin the TAR dissection, either in a top-down or bottom-up fashion (as discussed above). Below the arcuate line, the space of Bogros is developed. Staying medial to the linea semilunaris and the neurovascular bundles, the posterior lamina of the IO aponeurosis is incised exposing the TA muscle. The fibers are separated from the underlying transversalis fascia/peritoneum, extending laterally towards the psoas muscle. The dissection can be extended as laterally, inferiorly, and superiorly as previously described.

Once enough sublay space is developed for adequate mesh overlap and holes in the posterior sheath are closed, the posterior sheath is reapproximated with a running 2-0 absorbable barbed suture. Next, the hernia defect and linea alba are closed with a running #1 permanent barbed suture. Pneumoperitoneum can be lowered to reduce the tension on the closure. Mesh is introduced and unrolled to fill the sublay space. Fixation of the mesh is a debated topic, though many experts use fibrin sealant spray to achieve fixation and hemostasis. A surgical drain may then be introduced.

Outcome data of robotic repairs are promising. In a two-institution study, Martin-Del-Campo *et al.*^[39] reported reduced blood loss and systemic complications. The patients undergoing robotic repair also benefited from shorter length of stay and reduced readmissions compared to a matched group of open TAR patients. There is ongoing study of this new approach, and long-term data are approaching.

OUTCOMES

Hernia repair utilizing TAR is safe and effective in published series. Novitsky *et al.*^[11] described their experience in 428 consecutive cases in 2016. With a minimum of one-year follow-up, they demonstrated a 3% recurrence rate and a SSI rate of only 9%. No mesh prosthetics required explantation, although 3 patients required debridement. The most common reason for recurrence was central mesh failure followed by lateral, suprapubic, and subxiphoid recurrence.

Studies compared PCS with ACS to determine which release yields better outcomes. With regard to myofascial advancement, anatomic study in 13 human cadavers evaluated PCS, ACS, and the Rives-Stoppa repair^[40]. The authors found that ACS provided marginally more medialization of the anterior sheath compared to PCS. On the contrary, PCS advanced the posterior sheath more. A subsequent study of 10 cadavers revealed that each subsequent step of TAR (rectus sheath release, IO lamella release, TA muscle division, and lateral retromuscular dissection) permits increasing myofascial advancement up to approximately 10 cm per side^[41].

Clinical outcomes between these methods have similarly been evaluated. A retrospective comparison of 56 ACS cases to 55 PCS cases found significantly more wound complications in the ACS group (48.2% vs. 25.5%, $P = 0.01$) and a higher hernia recurrence rate (14.3% vs. 3.6%, $P = 0.09$)^[42]. To reduce wound healing complications associated with ACS, several minimally invasive techniques (MI-ACS) have been developed^[43]. However, even though a 2017 study comparing MIS-ACS to TAR found equivalent rates of SSI/SSO, there was a non-significant, albeit double, recurrence rate in the MIS-ACS group. A recent meta-analysis compared mesh location in the abdominal wall and reported reduced recurrence and SSIs with preperitoneal mesh (as performed in TAR) compared to intraperitoneal and onlay (in most ACS approaches)^[44].

Most comparative data are retrospective and heterogeneous. No randomized controlled, prospective trial comparing ACS to PCS has been completed at this time. However, data do support improvement in quality

of life scores and abdominal wall function after abdominal wall reconstruction with transversus abdominis release^[10,45,46].

CONCLUSION

The transversus abdominis release technique to repair large ventral defects is durable and reliable. It obviates the creation and morbidity of large lipocutaneous flap performed in ACSs. The TAR approach is beneficial in cases of previous anterior hernia repairs and provides the mesh with a well-vascularized space for tissue ingrowth and incorporation. This technique can be utilized in special scenarios and in novel techniques focusing on minimally invasive approaches.

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Made substantial contributions to the entirety of this review: Siegal SR, Pauli EM

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REFERENCES

1. Stoppa R, Petit J, Abourachid H, Henry X, Duclaye C, et al. Original procedure of groin hernia repair: interposition without fixation of Dacron tulle prosthesis by subperitoneal median approach. *Chirurgie* 1973;99:119-23.
2. Rives J, Lardennois B, Pire JC, Higon J. Large incisional hernias. The importance of flail abdomen and of subsequent respiratory disorders. *Chirurgie* 1973;99:547-63.
3. Iqbal CW, Pham TH, Joseph A, Mai J, Thompson GB, et al. Long-term outcome of 254 complex incisional hernia repairs using the modified Rives-Stoppa technique. *World J Surg* 2007;31:2398-404.
4. Mehrabi M, Jangjoo A, Tavoosi H, Kahrom M, Kahrom H. Long-term outcome of Rives-Stoppa technique in complex ventral incisional hernia repair. *World J Surg* 2010;34:1696-701.
5. Ramirez OM, Ruas E, Dellon AL. "Components separation" method for closure of abdominal-wall defects: an anatomic and clinical study. *Plast Reconstr Surg* 1990;86:519-26.
6. Kumar S, Edmunds RW, Dowdy C, Chang YW, King R, et al. Anterior versus posterior component separation: which is better? *Plast Reconstr Surg* 2018;142:47S-53.
7. Novitsky YW, Porter JR, Rucho ZC, Getz SB, Pratt BL, et al. Open preperitoneal retrofascial mesh repair for multiply recurrent ventral incisional hernias. *J Am Coll Surg* 2006;203:283-9.
8. Carbonell AM, Cobb WS, Chen SM. Posterior components separation during retromuscular hernia repair. *Hernia* 2008;12:359-62.
9. Novitsky YW, Elliott HL, Orenstein SB, Rosen MJ. Transversus abdominis muscle release: a novel approach to posterior component separation during complex abdominal wall reconstruction. *Am J Surg* 2012;204:709-16.
10. Criss CN, Petro CC, Krpata DM, Seafiler CM, Lai N, et al. Functional abdominal wall reconstruction improves core physiology and quality-of-life. *Surgery* 2014;156:176-82.

11. Novitsky YW, Fayeziadeh M, Majumder A, Neupane R, Elliott HL, et al. Outcomes of posterior component separation with transversus abdominis muscle release and synthetic mesh sublay reinforcement. *Ann Surg* 2016;264:226-32.
12. Love W, Ewing JA, Carbonell AM, Cobb WS, Warren JA. Computed tomography imaging in ventral hernia repair: can we predict the need for myofascial release? *Hernia*; 2019.
13. Ghali S, Turza KC, Baumann DP, Butler CE. Minimally invasive component separation results in fewer wound-healing complications than open component separation for large ventral hernia repairs. *J Am Coll Surg* 2012;214:981-9.
14. Pauli EM, Wang J, Petro CC, Juza RM, Novitsky YW, et al. Posterior component separation with transversus abdominis release successfully addresses recurrent ventral hernias following anterior component separation. *Hernia* 2015;19:285-91.
15. Sorensen LT. Wound healing and infection in surgery: the pathophysiological impact of smoking, smoking cessation, and nicotine replacement therapy: a systematic review. *Ann Surg* 2012;255:1069-79.
16. Kuri M, Nakagawa M, Tanaka H, Hasuo S, Kishi Y. Determination of the duration of preoperative smoking cessation to improve wound healing after head and neck surgery. *Anesthesiology* 2005;102:892-6.
17. Dronge AS, Perkal MF, Kancir S, Concato J, Aslan M, et al. Long-term glycemic control and postoperative infectious complications. *Arch Surg* 2006;141:375-80; discussion 80.
18. Ramos M, Khalpey Z, Lipsitz S, Steinberg J, Panizales MT, et al. Relationship of perioperative hyperglycemia and postoperative infections in patients who undergo general and vascular surgery. *Ann Surg* 2008;248:585-91.
19. Rosen MJ, Aydogdu K, Grafmiller K, Petro CC, Faiman GH, et al. A multidisciplinary approach to medical weight loss prior to complex abdominal wall reconstruction: is it feasible? *J Gastrointest Surg* 2015;19:1399-406.
20. Daley J, Khuri SF, Henderson W, Hur K, Gibbs JO, et al. Risk adjustment of the postoperative morbidity rate for the comparative assessment of the quality of surgical care: results of the National Veterans Affairs Surgical Risk Study. *J Am Coll Surg* 1997;185:328-40.
21. Kondrup J, Rasmussen HH, Hamberg O, Stanga Z, Ad Hoc EWG. Nutritional risk screening (NRS 2002): a new method based on an analysis of controlled clinical trials. *Clin Nutr* 2003;22:321-36.
22. Drover JW, Dhaliwal R, Weitzel L, Wischmeyer PE, Ochoa JB, et al. Perioperative use of arginine-supplemented diets: a systematic review of the evidence. *J Am Coll Surg* 2011;212:385-99, 999.e1.
23. Muysoms FE, Miserez M, Berrevoet F, Campanelli G, Champault GG, et al. Classification of primary and incisional abdominal wall hernias. *Hernia* 2009;13:407-14.
24. Winder JS, Majumder A, Fayeziadeh M, Novitsky YW, Pauli EM. Outcomes of utilizing absorbable mesh as an adjunct to posterior sheath closure during complex posterior component separation. *Hernia* 2018;22:303-9.
25. Fatula LK, Nelson A, Abbad H, Ewing JA, Hancock BS, et al. Antibiotic irrigation of the surgical site decreases incidence of surgical site infection after open ventral hernia repair. *Am Surg* 2018;84:1146-51.
26. Majumder A, Miller HJ, Patel P, Wu YV, Elliott HL, et al. Evaluation of antibiotic pressurized pulse lavage for contaminated retromuscular abdominal wall reconstruction. *Surg Endosc* 2017;31:2763-70.
27. Doble JA, Winder JS, Witte SR, Pauli EM. Direct visualization transversus abdominis plane blocks offer superior pain control compared to ultrasound guided blocks following open posterior component separation hernia repairs. *Hernia* 2018;22:627-35.
28. Gibreel W, Sarr MG, Rosen M, Novitsky Y. Technical considerations in performing posterior component separation with transverse abdominis muscle release. *Hernia* 2016;20:449-59.
29. Winder JS, Behar BJ, Juza RM, Potochny J, Pauli EM. Transversus abdominis release for abdominal wall reconstruction: early experience with a novel technique. *J Am Coll Surg* 2016;223:271-8.
30. Pauli EM, Krpata DM, Novitsky YW, Rosen MJ. Negative pressure therapy for high-risk abdominal wall reconstruction incisions. *Surg Infect (Larchmt)* 2013;14:270-4.
31. Blatnik JA, Krpata DM, Pesa NL, Will P, Harth KC, et al. Predicting severe postoperative respiratory complications following abdominal wall reconstruction. *Plast Reconstr Surg* 2012;130:836-41.
32. Fayeziadeh M, Petro CC, Rosen MJ, Novitsky YW. Enhanced recovery after surgery pathway for abdominal wall reconstruction: pilot study and preliminary outcomes. *Plast Reconstr Surg* 2014;134:151S-9.
33. Pauli EM, Juza RM, Winder JS. How I do it: novel parastomal herniorrhaphy utilizing transversus abdominis release. *Hernia* 2016;20:547-52.
34. Jones CM, Winder JS, Potochny JD, Pauli EM. Posterior component separation with transversus abdominis release: technique, utility, and outcomes in complex abdominal wall reconstruction. *Plast Reconstr Surg* 2016;137:636-46.
35. Hood K, Millikan K, Pittman T, Zelhart M, Secemsky B, et al. Abdominal wall reconstruction: a case series of ventral hernia repair using the component separation technique with biologic mesh. *Am J Surg* 2013;205:322-7; discussion 7-8.
36. Reinhold W, Schroder M, Berger C, Nehls J, Schroder A, et al. Mini- or less-open sublay operation (MILOS): a new minimally invasive technique for the extraperitoneal mesh repair of incisional hernias. *Ann Surg* 2019;269:748-55.
37. Daes J. The enhanced view-totally extraperitoneal technique for repair of inguinal hernia. *Surg Endosc* 2012;26:1187-9.
38. Belyansky I, Daes J, Radu VG, Balasubramanian R, Reza Zahiri H, et al. A novel approach using the enhanced-view totally extraperitoneal (eTEP) technique for laparoscopic retromuscular hernia repair. *Surg Endosc* 2018;32:1525-32.
39. Martin-Del-Campo LA, Weltz AS, Belyansky I, Novitsky YW. Comparative analysis of perioperative outcomes of robotic versus open transversus abdominis release. *Surg Endosc* 2018;32:840-5.
40. Sneider D, Yurtkap Y, Kroese LF, Jeekel J, Muysoms FE, et al. Anatomical study comparing medialization after Rives-Stoppa, anterior component separation, and posterior component separation. *Surgery* 2019;165:996-1002.
41. Majumder A, Miller HJ, Del Campo LM, Soltanian H, Novitsky YW. Assessment of myofascial medialization following posterior component separation via transversus abdominis muscle release in a cadaveric model. *Hernia* 2018;22:637-44.
42. Krpata DM, Blatnik JA, Novitsky YW, Rosen MJ. Posterior and open anterior components separations: a comparative analysis. *Am J Surg* 2012;203:318-22; discussion 22.
43. Parent B, Horn D, Jacobson L, Petersen RP, Hinojosa M, et al. Wound morbidity in minimally invasive anterior component separation

- compared to transversus abdominis release. *Plast Reconstr Surg* 2017;139:472-9.
44. Holihan JL, Nguyen DH, Nguyen MT, Mo J, Kao LS, et al. Mesh location in open ventral hernia repair: a systematic review and network meta-analysis. *World J Surg* 2016;40:89-99.
 45. Jensen KK, Munim K, Kjaer M, Jorgensen LN. Abdominal wall reconstruction for incisional hernia optimizes truncal function and quality of life: a prospective controlled study. *Ann Surg* 2017;265:1235-40.
 46. Jensen KK, Henriksen NA, Jorgensen LN. Endoscopic component separation for ventral hernia causes fewer wound complications compared to open components separation: a systematic review and meta-analysis. *Surg Endosc* 2014;28:3046-52.

Review

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Management of post-operative complications in open ventral hernia repair

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Abstract

Hernia repair is the most common general surgical procedure performed in the United States; however, historically, there has been a surprising lack of consensus regarding hernia complications and their management. The development of international, prospectively-collected databases such as the Americas Hernia Society Quality Collaborative has introduced a new era of evidence-based practice around the prevention and management of these complications. This review seeks to equip surgeons with evidence-based techniques for prevention and management of the most common complications of open ventral hernia repair.

Keywords: Hernia repair, complications, surgical site infection, seroma, flap necrosis, mesh exposure, interparietal hernia, recurrent hernia, enterocutaneous fistula

INTRODUCTION

Complications after hernia repair are divided into general surgical complications and hernia specific complications. The Clavien Dindo classification system can be used to classify general surgical complications based on severity and required interventions^[1]. The Ventral Hernia Working Group describes hernia specific complications as surgical site occurrence (SSO) to standardize the nomenclature when studying outcomes after hernia repair. SSO is a category of complications that includes surgical site infection (SSI), seroma, hematoma, wound dehiscence, and enterocutaneous fistula^[2]. Petro *et al.*^[3] found an association between SSO and the complexity of hernia repair using a hernia staging system that focuses



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on the defect size and presence of contamination. Stage 1 hernias are less than 10 cm and in clean fields and have been found to have a SSO and recurrence rate of 10%. Stage 2 hernias are larger, 10-20 cm or < 10 cm in contaminated fields, and have an SSO rate of about 20% and recurrence rate of 15%. Stage 3 hernias are > 20 cm wide or > 10 cm in contaminated fields and have the highest risk of SSO at 42% and recurrence of 26%. This system allows surgeons to have a frank discussion with their patients pre-operatively about their expected complication risk.

While such staging systems are helpful in risk stratification, SSO remains a broad category including 5 types of complications and fails to account for their clinical significance. Separate systems exist for each category of SSO to document a difference between small asymptomatic seromas and large, symptomatic seromas requiring intervention for example^[4].

EARLY COMPLICATIONS

Mesh infection

Much attention has been paid to prevention of SSI in hernia repair, especially with the increased use of prosthetic mesh. These are divided into superficial, deep, and organ space SSI and are directly correlated with the level of contamination during the case. Superficial SSI should be managed using general surgical principles of drainage and, possibly, short-course antibiotics. Management of deep and organ space SSI hinges greatly on the concern for infection of the prosthetic mesh^[5].

The true diagnosis of mesh infection requires a positive culture of fluid from around the mesh or a culture of the mesh itself. Periprosthetic fluid on imaging can often represent sterile seroma or hematoma, so fluid should be aspirated and sent for culture if there is concern for mesh infection. However, deep infections should be treated aggressively, and with a high index of suspicion, as seeding of the mesh can be subclinical and may lead to long-term complications. A retrospective review of 21 mesh infections found that 76% of mesh infections were due to *Staphylococcus aureus* and about half of these were methicillin-resistant. The minority of infections are due to *Staphylococcus epidermidis* or *Streptococcus pyogenes* or Gram-negative species of *Escherichia coli* or *Klebsiella* in the case of gastrointestinal contamination^[6,7].

Prevention of mesh infection begins with tailoring the type of mesh chosen for the clinical scenario. We recommend the use of medium-weight macroporous polypropylene (PP) in clean fields due to their resistance to biofilm formation, improved clearance of infection, and repair durability compared to PTFE-based meshes^[5]. In contaminated or clean-contaminated fields, the evidence on mesh selection is not as clear, and absorbable mesh is recommended due to the high risk of synthetic mesh infection. Itani *et al.*^[8] and Rosen *et al.*^[9] showed in a prospective trial that using biosynthetic absorbable mesh resulted in improved SSI rates (18% vs. 35%) as well as long-term recurrence rates (17% vs. 28%) when compared to previous trials of porcine mesh in these settings. More recently, however, macroporous synthetic mesh has been found to have equivalent infection rates in contaminated fields and is also an acceptable option^[10].

Once a mesh infection has been confirmed, early source control and antibiotics are required. An effort should be made to salvage the mesh, avoiding removal. Patients showing signs of sepsis may require early operative intervention characterized by pulse-lavage antibiotic solution irrigation, followed by wide closed suction drain placement adjacent to the mesh and fascial closure once again if the mesh had been placed retromuscular. In the setting of florid sepsis, source control, wound packing, and interval abdominal wall closure is often all the patient will tolerate. Some small series have shown the success of mesh removal with single stage primary closure with bilateral myofascial rectus abdominis release; however, the hernia recurrence rates range 35%-88%^[11,12]. This setting is an ideal application for absorbable biosynthetic mesh, where it can substantially reduce recurrence rates down to 17%^[9]. Absorbable mesh should be placed as a sublay in the retrorectus space and can be placed at the index operation or in a staged approach.

In patients without systemic signs of sepsis, an effort toward mesh salvage should be attempted. Patients should be immediately started on broad spectrum antibiotics and these can be narrowed based on culture data. Percutaneous drainage of any fluid surrounding the mesh should be performed and the drain should be left in place until source control is satisfactory. Any overlying necrotic tissue should be surgically debrided; exposed mesh can be irrigated with antibiotics; and negative pressure wound management systems can be placed to allow granulation formation over the mesh. Success rates of mesh salvage protocols have been promising; however, this is very dependent on the structure of the mesh, with macroporous mesh in the retrorectus position having the highest salvage rate^[13]. PTFE, multifilament polyester, and heavy weight, microporous PPE, however, almost universally require explantation once infected due to their poor tissue ingrowth and biofilm formation that prevent clearance of bacteria^[14]. Thus, upfront excision of these mesh types is recommended to expedite recovery and ultimate reconstruction^[12].

Seroma

Every patient who has an open hernia repair will develop some element of a seroma due to the potential spaces created in the abdominal wall. The vast majority of seromas are asymptomatic and most resolve without any intervention. Morales-Conde *et al.*^[4] created a seroma classification system, in which they defined seromas as a complication only if they are symptomatic, persist longer than 6 months, or become infected (Types III and IV). Clinically detected seromas that last less than 6 months (Types I and II) are classified as an incidental finding, reflecting that these are considered normal sequela of the operation. Type III seromas last longer than 6 months or become symptomatic, but do not require intervention, while Type IV seromas are symptomatic and require intervention. In this classification system, only Type III and IV seromas should be considered true complications as they affect the clinical progression of the patient.

Routine drain placement to prevent seromas has been debated over concerns that drains in direct contact with the mesh could increase the risk of infection. In 2017, Krpata *et al.*^[15] queried the Americas Hernia Society Quality Collaborative (AHSQC) and reviewed 200 cases where drains were placed in the retromuscular space and 100 cases where they were not. These cases were matched based upon hernia complexity and comorbidities. They found no difference in superficial, deep, or organ space SSI between the groups, but there was an overall increase in SSO in the no drain group (20% vs. 10%, $P = 0.02$) with seroma formation being the most significant increase (8% vs. 2%, $P = 0.01$). They did not, however, see a difference in surgical site occurrences requiring procedural intervention (SSOPI), suggesting that most of these seromas resolved without intervention. They concluded that routine drain placement does not increase the risk for infection and may reduce the risk of seroma formation, although the clinical significance of seroma formation continues to be debated.

Once a seroma has grown to cause pain, impede normal activities, or persist for longer than 6 months, intervention is recommended for the alleviation of symptoms. The primary treatment option is percutaneous drainage, which can be done with serial aspirations or by leaving a secured catheter in place and monitoring the output overtime. These can either be performed in the office blindly or under radiographic guidance with ultrasound or computed tomography, as long as a sterile technique is followed to prevent secondary infection of the seroma. For seromas refractory to simple drainage, chemical or mechanical sclerotherapy have both been described. Chemical sclerosing agents including talc, tetracycline, doxycycline, ethanol, erythromycin, fibrin glue, and povidone/iodine have all been used with high success rates and few complications; however, only small case series exist in the literature^[16,17]. Lehr and Schuricht^[18] described endoscopic ablation of the inner lining of the seroma using the argon beam in extreme cases. Three ports are inserted into the seroma and the fluid is drained, followed by insufflation to allow endoscopic guidance of the argon beam to ablate the entire lining of the seroma. These advanced techniques should be used only in extreme cases, after failure of watchful waiting and percutaneous drainage.

Flap necrosis

Any surgeon performing complex ventral hernia repair should have an intimate knowledge of the blood supply to the abdominal wall. The inferior epigastric artery supplies the majority of blood flow to the rectus abdominis muscle with collaterals to the superior epigastric from the internal mammary. These send perforating branches anteriorly through the anterior rectus sheath to supply the subcutaneous fat and overlying abdominal wall skin. The largest concentration of these perforators lies within 10 cm of the umbilicus in all directions and preservation of this pedicle is paramount in preventing tissue ischemia and subsequent SSO. This principle has driven innovation in abdominal wall reconstruction to preserve as much of the abdominal wall blood supply as possible^[19].

To minimize large subcutaneous flaps that contribute to skin necrosis, retrorectus placement of the mesh whenever possible in a “sublay” technique has been widely popularized in recent years^[20]. If a component separation is required for closure of the midline, the debate over wound complication rates between anterior component separation (ACS) and transversus abdominis release (TAR) still continues. The TAR repair has been described extensively with very low wound complication rate. In Novitsky’s 2012 paper, only one of the 42 original patients developed skin flap necrosis with the TAR technique, and this patient had subcutaneous flaps raised during the initial operation^[21]. Harth *et al.*^[22] presented similar findings when studying the flaps raised in panniculectomy during hernia repair. They found a 70% wound complication rate in the panniculectomy group with 40% requiring return to the operating room for debridement. This highlights the morbidity associated with large subcutaneous flaps on the abdominal wall when combined with hernia repair.

For large hernias in which mobility of the anterior elements prevents closure of the linea alba, an ACS may be required to gain mobility of greater than 15 cm. In this case, a periumbilical perforator sparing technique preserves blood supply to the skin flap and has been shown to reduce SSO and skin necrosis^[23,24]. This technique involves tunneling around the periumbilical pedicle of perforator vessels to gain access to the external oblique muscle release, and can be done either open or endoscopically^[19]. If concerns of ischemia remain, the flap can be evaluated with fluorescence angiography to thoroughly evaluate the viability of skin and subcutaneous tissue^[25]. The mesh should still be placed in the retrorectus space to prevent further undermining of the flap, and to provide another barrier between the skin and the mesh should skin necrosis or SSI occur^[20].

Interparietal hernia

Interparietal hernias occur in retromuscular repairs due to dehiscence of the posterior rectus fascia/peritoneal closure, allowing intrabdominal contents to herniate between the posterior fascia and the mesh. Bowel can become acutely incarcerated in this layer, or adhesions and fistulas can form due to direct exposure of the mesh to the bowel. This is a rare complication with only small case series in existence, the largest of which describes 9 (1.8%) cases out of 511 retromuscular hernia repairs. In this series, the majority of patients presented with acute obstruction within 30 days of the index operation. One patient presented over 10 months after surgery with resolving abdominal pain and 2 were found incidentally on imaging for other reasons. Because of its rarity, the diagnosis can be difficult and is often missed because of the atypical appearance on CT scan. On cross sectional imaging, the posterior sheath can appear as a shelf with fluid, omentum, or bowel lying between it and the overlying rectus muscles [Figure 1]^[26,27].

Lack of bowel function within a few days of surgery should be treated with a high index of suspicion and be evaluated with a CT scan to look for acute causes of bowel obstruction. In the case of interparietal hernia, management then depends on the timing of presentation. In the acute period, the mesh can be in direct contact with bowel increasing the risk of adhesions. The posterior defect should be bridged with a piece of absorbable synthetic or biologic mesh; this acts as a barrier between bowel and the mesh to allow

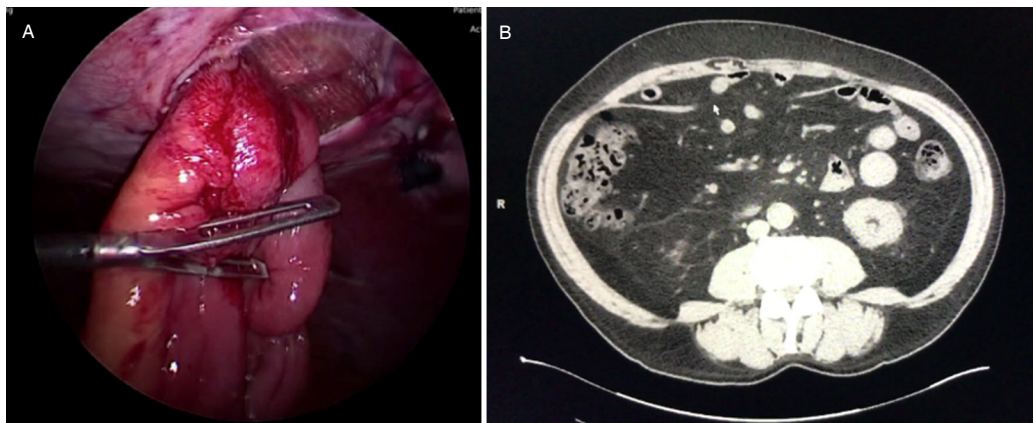


Figure 1. A: laparoscopic image of bowel herniated above the posterior rectus sheath and in contact with the exposed mesh. B: CT image showing the dehiscence posterior rectus sheath with bowel herniated above. Linea alba is intact with no full thickness herniation

time for reperitonealization. In the case of late presentations, 2-3 weeks post operatively, the mesh should be completely peritonealized, and the objective here is to obliterate the space above the posterior sheath to prevent bowel from herniating above. This can be done by simply lifting the edges of the posterior sheath with either transfascial sutures or an absorbable tacking device to attach it to the mesh and obliterate the potential space^[27].

LATE COMPLICATIONS

Mesh exposure

A long-term complication of SSI or flap necrosis can be exposure of the mesh. One of the arguments for retrorectus placement of mesh is that the rectus acts as another layer between the mesh and the skin, preventing exposure of the mesh if the skin and subcutaneous tissue are debrided. However, when mesh does become exposed, it can create a chronic wound that is difficult to epithelialize. A trial of mesh salvage is almost always appropriate when the patient is stable and not septic. Once necrotic tissue has been fully debrided, negative pressure wound therapy can be used to encourage granulation formation through the mesh pores, ultimately covering the mesh^[28]. In animal models, the degree and speed of tissue integration is greatest with macroporous (1.8 mm × 3.4 mm pore size) compared to microporous mesh (0.9 mm × 1 mm pore size)^[29]. This is thought to be one of the contributing factors in the improved salvage rate of macroporous mesh^[12]. Once a thick base of granulation tissue covers the entire mesh, the wound can be covered using a split-thickness skin graft.

Berrepoet *et al.*^[13] reviewed 54 cases of macroporous mesh placed in the retrorectus space that was exposed or infected. Mesh salvage was achieved in all patients studied, with a mean wound closure time of 44 days (range, 26-73 days) and 5 dressing changes. If chronic wounds or draining sinus tracts exist, small portions of the exposed mesh can be debrided to improve wound healing. Patients should be supported with enteral or parenteral nutrition to avoid protein calorie malnutrition, and immunosuppressants should be minimized to improve wound healing. PTFE, multifilament polyester, and heavy weight, microporous PPE are more difficult to salvage due to their poor tissue ingrowth and biofilm formation, which prevents complete clearance of bacteria. If explantation is required, meticulous removal of all mesh and synthetic material, including suture and tacks, should be performed. Primary closure with staged repeat repair should be performed if possible, or use of biosynthetic mesh if required for coverage of intrabdominal contents^[9].

Enterocutaneous fistula

Enterocutaneous fistula (ECF) is a feared long-term complication of hernia repair, occurring on average 2 years after the index operation. These often present as a chronic mesh infection that is followed by bilious

or feculent drainage and require multiple interventions and hospital admissions to resolve. The literature suggests that avoidance of enterotomies at the index operation is the best way to prevent fistula formation post operatively. In a large database review of elective ventral hernia repairs, enterotomy or unplanned bowel resection (EBR) increased the ECF formation rate from 0.7% to 7.1% ($P < 0.01$). The authors found that repair of recurrent hernias where mesh had been placed at the index operation had a significantly higher rate of EBR compared to primary hernia repair or recurrent repair after prior suture repair alone (20.4% vs. 5.7%, $P < 0.001$). This highlights the difficulty of reoperative hernia surgery and the importance of meticulous lysis of adhesions to prevent devastating complications in the future^[7,30].

For many years, it has been thought that PP mesh would have a higher risk of ECF formation due to the vigorous foreign body response and inflammation it incites when compared to polyester or PTFE. However, long-term data on retrorectus technique have shown no increased ECF formation with PP mesh when compared to PTFE^[31]. This was further supported by Brandi *et al.*^[32], who reported no ECF even with uncoated polypropylene mesh in the intraperitoneal position.

Management of ECF should start with conservative measures and control of contamination, because immediate mesh explanation is associated with a high risk of EBR, which could result in even further fistula formation^[7]. Macroporous polypropylene and polyester mesh are more likely to be salvaged than PTFE due to its poor tissue ingrowth and biofilm formation. Conservative management should include opening the tract to control sepsis, nutritional support with TPN, somatostatin, downstream decompression, and appropriate wound care, which can lead to spontaneous closure in many cases^[33]. If the fistula fails to close, it is recommended to wait for 6 months to allow for spontaneous closure and maturing of adhesions before mesh excision and bowel resection is undertaken^[34]. In a recent review of the AHSQC database, Kao *et al.*^[35] looked at outcomes from partial mesh excision (PME) vs. complete mesh excision in clean, clean-contaminated, contaminated, and dirty wounds as well as cases with ECF. Not surprisingly, they found a higher rate of SSI, SSO, SSOPI, and reoperation in the PME group in cases of ECF, contaminated or dirty wounds^[35]. In the case of mesh infection or fistula, all permanent pieces of mesh and suture should be removed as they will serve as a nidus for future infection or wound complications.

Hernia recurrence

It is well established at this point that placement of synthetic mesh during hernia repair reduces hernia recurrence rates compared to suture repair alone. The largest study on recurrence was on the Denmark national health system data bank, which followed 3242 patients for a median of 5 years and found a 12.3% recurrence rate with mesh compared to 17.1% without^[36]. The most common site of recurrence is in the midline directly through central fractures in the mesh, accounting for up to 39.6% of recurrences^[37]. Factors that increase the risk of mesh fracture can be both technical in nature and due to material weakness. There has been a shift in mesh material towards lightweight mesh due to its improved flexibility and decreased shrinkage over time as there is less inflammatory reaction to a decreased volume of material^[38]. However, this comes at the price of decreasing its overall strength, especially when combined with a macroporous configuration to allow for bacterial clearance. Petro *et al.*^[39] recently published their experience with macroporous lightweight polyester placed in the retrorectus position on 36 patients. Of the eight (22%) recurrences after 13 months, seven (19%) were found to have a central mesh fracture as the mechanism of recurrence. Warren *et al.*^[37] also found that the use of lightweight polypropylene mesh was an independent risk factor for central mesh fracture. Because of this, medium- or heavyweight mesh is recommended, especially when using a macroporous mesh.

While the material of the mesh itself may be partially to blame, there are also technical factors that place patients at risk for central mesh fracture. Failure to close the midline or midline dehiscence leaves the mesh unsupported by the abdominal wall, causing increased stress and eventual fracture of the mesh. There is

no substitute for good technique when closing the linea alba, utilizing small bites and adequate myofascial release to bring the midline together with minimal tension^[40]. Mesh fracture has also been associated with SSI, which weakens the fascial layers and in turn places mechanical stress on the mesh. Mesh fixation with sutures, staples, and tacks has not been associated with fracture, although this was previously thought to be a possible source. Failures around the mesh are most commonly found at the site of transfascial fixation sutures, which pull through and weaken the abdominal wall, or due to inadequate mesh-tissue overlap in all directions.

Maloney *et al.*^[24] reviewed a large hernia database to determine risk factors for recurrence after component separations. There was a higher risk of SSO with ACS leading to a higher overall recurrence rate; however, on univariate analysis, there was no difference between anterior and posterior component separations, and no association with smoking status, steroid use, diabetes, or peripheral vascular disease. There was, however, an association with BMI greater than 35, use of absorbable mesh, SSO, SSI, and failure to close the fascia. The exact effect of BMI on recurrence after hernia repair is difficult to ascertain due to heterogeneity in the literature, although an increase in hernia recurrence has consistently been found with BMI > 30-35^[41]. Interestingly, recurrence was not associated with the size of the defect as long as the fascia was closed, reinforcing the importance of adequate myofascial release and midline closure technique.

Unfortunately, recurrent hernia itself is a risk factor for recurrence of subsequent repairs, meaning that many patients enter a vicious cycle of multiple failed repairs. The risks of complete mesh excision can be significant, often requiring extensive lysis of adhesions with risk of bowel injury. In addition, if the mesh is well incorporated, there is a risk of destruction of the native abdominal wall components, making subsequent repairs more difficult. In the aforementioned review of the AHSQC database, Kao *et al.*^[35] also compared partial *vs.* complete mesh excision in clean cases such as excision for pain or recurrent hernia. In these cases, there was no difference in SSO, SSI, SSOPI, or reoperation in patients who only underwent partial excision of the mesh. This suggests that, in the case of small recurrence without any infection, it is reasonable to repair the hernia without complete excision of previous mesh. If the recurrent defect is through the mesh, primary repair should be performed with permanent suture bites through the previous mesh to reestablish its continuity. Defects above or lateral to the mesh can be repaired with underlay or sublay technique either laparoscopically or open. Mesh fractures larger than 2 cm should be treated with explantation and repeat repair with permanent mesh to prevent layering of mesh in the abdominal wall.

DECLARATIONS

Authors' contributions

Made substantial contributions to conception and design of the study and performed data analysis and interpretation: O'Connor SC, Carbonell AM

Availability of data and materials

Not applicable.

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None.

Conflicts of interest

Sean C. O'Connor, M.D. has no disclosures. Alfredo M. Carbonell, D.O. has received honoraria from W.L. Gore and Associates, Ethicon Inc. and Intuitive.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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REFERENCES

1. Dindo D, Demartines N, Clavien PA. Classification of surgical complications: a new proposal with evaluation in a cohort of 6336 patients and results of a survey. *Ann Surg* 2004;240:205-13.
2. Kanters AE, Krpata DM, Blatnik JA, Novitsky YM, Rosen MJ. Modified hernia grading scale to stratify surgical site occurrence after open ventral hernia repairs. *J Am Coll Surg* 2012;215:787-93.
3. Petro CC, O'Rourke CP, Posielski NM, Criss CN3, Raigani S, et al. Designing a ventral hernia staging system. *Hernia* 2016;20:111-7.
4. Morales-Conde S. A new classification for seroma after laparoscopic ventral hernia repair. *Hernia* 2012;16:261-7.
5. Cevasco M, Itani KMF. Ventral hernia repair with synthetic, composite, and biologic mesh: characteristics, indications, and infection profile. *Surg Infect (Larchmt)* 2012;13:209-15.
6. Cobb WS, Carbonell AM, Kalbaugh CL, Jones Y, Lokey JS. Infection risk of open placement of intraperitoneal composite mesh. *Am Surg* 2009;75:762-7.
7. Sanchez VM, Abi-Haidar YE, Itani KMF. Mesh infection in ventral incisional hernia repair: incidence, contributing factors, and treatment. *Surg Infect (Larchmt)* 2011;12:205-10.
8. Itani KMF, Rosen M, Vargo D, Awad SS, Denoto G, et al. Prospective study of single-stage repair of contaminated hernias using a biologic porcine tissue matrix: The RICH Study. *Surgery* 2012;152:498-505.
9. Rosen MJ, Bauer JJ, Harmaty M, Carbonell AM, Cobb WS, et al. Multicenter, prospective, longitudinal study of the recurrence, surgical site infection, and quality of life after contaminated ventral hernia repair using biosynthetic absorbable mesh: The COBRA Study. *Ann Surg* 2017;265:205-11.
10. Carbonell AM, Criss CN, Cobb WS, Novitsky YW, Rosen MJ. Outcomes of synthetic mesh in contaminated ventral hernia repairs. *J Am Coll Surg* 2013;217:991-8.
11. Szczerba SR, Dumanian GA. Definitive surgical treatment of infected or exposed ventral hernia mesh. *Ann Surg* 2003;237:437-41.
12. Kao AM, Arnold MR, Augenstein VA, Heniford BT. Prevention and treatment strategies for mesh infection in abdominal wall reconstruction. *Plast Reconstr Surg* 2018;142:149-55S.
13. Berrevoet F, Vanlander A, Sainz-Barriga M, Rogiers X, Troisi R. Infected large pore meshes may be salvaged by topical negative pressure therapy. *Hernia* 2013;17:67-73.
14. Hawn MT, Gray SH, Snyder CW, Graham LA, Finan KR, et al. Predictors of mesh explantation after incisional hernia repair. *Am J Surg* 2011;202:28-33.
15. Krpata DM, Prabhu AS, Carbonell AM, Haskins IN, Phillips S, et al. Drain placement does not increase infectious complications after retromuscular ventral hernia repair with synthetic mesh: an AHSQC analysis. *J Gastrointest Surg* 2017;21:2083-9.
16. Sood A, Kotamarti VS, Theratil PJ, Lee ES. Sclerotherapy for the management of seromas: a systematic review. *Eplasty* 2017;17:e25.
17. Al Daoud F, Thayer A, Sachwani Daswani G, Maraqa T, Perinjelil V, et al. Management of chronic abdominal wall seroma with Doxycycline sclerotherapy using a Negative Pressure Wound Therapy System KCI-V.A.C.Ultatm - A case report. *Int J Surg Case Rep* 2018;51:25-8.
18. Lehr SC, Schuricht AL. A minimally invasive approach for treating postoperative seromas after incisional hernia repair. *J Soc Laparoendosc Surg* 2001;5:267-71.
19. Rosen MJ. Atlas of abdominal wall reconstruction. Philadelphia: Elsevier; 2012. p. 74-95.
20. Holihan JL, Nguyen DH, Nguyen MT, Mo J, Kao LS, et al. Mesh location in open ventral hernia repair: a systematic review and network meta-analysis. *World J Surg* 2016;40:89-99.
21. Novitsky YW, Elliott HL, Orenstein SB, Rosen MJ. Transversus abdominis muscle release: a novel approach to posterior component separation during complex abdominal wall reconstruction. *Am J Surg* 2012;204:709-16.
22. Harth KC, Blatnik JA, Rosen MJ. Optimum repair for massive ventral hernias in the morbidly obese patient: panniculectomy helpful? *Am J Surg* 2011;201:396-400.
23. Saulis AS, Dumanian GA. Periumbilical rectus abdominis perforator preservation significantly reduces superficial wound complications in "separation of parts" hernia repairs. *Plast Reconstr Surg* 2002;109:2275-80.
24. Maloney SR, Schlosser KA, Prasad T, Kasten KR, Gersin KS, et al. Twelve years of component separation technique in abdominal wall reconstruction. *Surgery* 2019;166:435-44.
25. Colavita PD, Wormer BA, Belyansky I, Lincourt A, Getz SB, et al. Intraoperative indocyanine green fluorescence angiography to predict wound complications in complex ventral hernia repair. *Hernia* 2016;20:139-49.
26. Carbonell AM. Interparietal hernias after open retromuscular hernia repair. *Hernia* 2008;12:663-6.
27. Davis JR, Villarreal JE, Cobb WS, Carbonell AM, Warren JA. Interparietal hernia complicating retromuscular ventral hernia repair. *Am Surg* 2016;82:658-9.
28. Garcia-Ruano A, Deleyto E, Garcia-Fernandez S. VAC-instillation therapy in abdominal mesh exposure: a novel indication. *J Surg Res* 2016;206:292-7.
29. Weyhe D, Cobb W, Lecuivre J, Alves A, Ladet S, et al. Large pore size and controlled mesh elongation are relevant predictors for mesh integration quality and low shrinkage - systematic analysis of key parameters of meshes in a novel minipig hernia model. *Int J Surg*

- 2015;22:46-53.
30. Gray SH, Vick CC, Graham LA, Finan KR, Neumayer LA, et al. Risk of complications from enterotomy or unplanned bowel resection during elective hernia repair. *Arch Surg* 2008;143:582.
 31. Yaghoobi Notash A, Yaghoobi Notash A, Seied Farshi J, Ahmadi Amoli H, Salimi J, et al. Outcomes of the rives-stoppa technique in incisional hernia repair: ten years of experience. *Hernia* 2007;11:25-9.
 32. Brandi CD, Roche S, Bertone S, Fratantoni ME. No enterocutaneous fistula development in a cohort of 695 patients after incisional hernia repair using intraperitoneal uncoated polypropylene mesh. *Hernia* 2017;21:101-6.
 33. Quinn M, Falconer S, McKee RF. Management of enterocutaneous fistula: outcomes in 276 patients. *World J Surg* 2017;41:2502-11.
 34. Schechter WP. Management of enterocutaneous fistulas. *Surg Clin North Am* 2011;91:481-91.
 35. Kao AM, Arnold MR, Otero J, Huang LC, Prasad T, et al. Comparison of outcomes after partial versus complete mesh excision. *Ann Surg* 2019; Epub ahead of print doi: 10.1097/sla.0000000000003198
 36. Kokotovic D, Bisgaard T, Helgstrand F. Long-term recurrence and complications associated with elective incisional hernia repair. *J Am Med Assoc* 2016;316:1575-82.
 37. Warren JA, McGrath SP, Hale AL, Ewing JA, Carbonell AM, et al. Patterns of recurrence and mechanisms of failure after open ventral hernia repair with mesh. *Am Surg* 2017;83:1275-82.
 38. Cobb WS, Kercher KW, Heniford BT. The argument for lightweight polypropylene mesh in hernia repair. *Surg Innov* 2005;12:63-9.
 39. Petro CC, Nahabet EH, Criss CN, Orenstein SB, von Recum HA, et al. Central failures of lightweight monofilament polyester mesh causing hernia recurrence: a cautionary note. *Hernia* 2015;19:155-9.
 40. Deerenberg EB, Harlaar JJ, Steyerberg EW, Lont HE, van Doorn HC, et al. Small bites versus large bites for closure of abdominal midline incisions (STITCH): a double-blind, multicentre, randomised controlled trial. *Lancet* 2015;386:1254-60.
 41. Menzo E Lo, Hinojosa M, Carbonell A, Krpata D, Carter J, et al. American Society for Metabolic and Bariatric Surgery and American Hernia Society consensus guideline on bariatric surgery and hernia surgery. *Surg Obes Relat Dis* 2018;14:1221-32.

Review

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Perforator propeller flaps in lower limb reconstruction: a literature review and case reports

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Abstract

Perforator-pedicled propeller flaps, which base their blood supply on isolated perforators, have been gaining popularity among plastic surgeons over the past two decades. They have proven to be of great value in the reconstruction of soft tissue defects in different areas of the body but are, thanks to their maximal mobility, mostly used in the reconstruction of extremities. In this article, we focus on perforator-pedicled propeller flaps in lower limb reconstruction, where they can be implemented in the coverage of primary as well as secondary soft tissue defects. Firstly, a brief literature review on evolution of propeller flap use in lower extremity is provided. Moreover, we present our surgical technique including the use of indocyanine green real-time angiography for reliable flap transfer. In addition, we report 3 cases of patients in whom we used a local propeller flap for the closure of skin defects in different parts of the leg.

Keywords: Propeller flap, perforator flap, local flap, lower limb reconstruction, microsurgery

INTRODUCTION

Reconstruction of soft tissue defects in the lower limb is known to be difficult due to the lack of spare local tissue in the immediate vicinity of such defects^[1]. Traditionally, these defects used to be covered, depending on the location, size, and the underlying tissue, by split skin grafts, local transposition flaps, or free flaps^[2-4]. All of the above have their obvious drawbacks and limitations; thus, over the past two decades, perforator propeller flaps have been gaining popularity among reconstructive surgeons.



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The first authors to use the term “propeller flap” were Hyakusoku *et al.*^[5] in 1991. His group designed an adipocutaneous flap with a skin island of a length largely exceeding its width, based on a random pedicle in the center, on which the flap was then rotated through 90° similar to a propeller to release burn scar contractures in the cubital and axillary regions.

Thanks to the advances in microsurgical techniques and anatomical knowledge, perforator flaps have been developed, where a skin island flap is harvested without the underlying muscle. Koshima and Soeda^[6] were the first to use the name “perforator flaps” in 1989 and since then perforator flaps have broadened our armamentarium in reconstructive microsurgery.

The two terms were first combined by Hallock^[7] in 2006 when he described an adductor perforator flap of the posteromedial thigh designed in a propeller fashion for coverage of ischial or trochanteric pressure sores. This flap was comparable in shape to the one developed by Hyakusoku, but it was based on a skeletonized perforator and rotated through 180°.

Already in the 1990s, Teo^[8] greatly developed the surgical technique of perforator-based propeller flap in the reconstruction of the distal third of the lower limb (without having named it as such) and more recently also contributed to the definition.

What is a propeller flap? By the definition of the “Tokyo” Consensus on Propeller Flaps^[9] from 2011, a propeller flap is an island flap that reaches the recipient site through an axial rotation of more than 90°. It can be thought of as a propeller with 2 blades of unequal length with the perforator forming the pivot point. Pignatti *et al.*^[9] proposed a further classification based on the nourishing pedicle (subcutaneous, perforator and supercharged), degree of rotation of the skin island (90°-180°), and the artery of origin of the perforator vessel (as defined for perforator flaps by the “Gent” consensus^[10]).

Due to the conus-like shape of the lower leg, there is a shortage of local soft tissue for reconstruction of defects. Using a proximally based peninsular fasciocutaneous flap, it is difficult to get a sufficient amount of healthy tissue into the defect without exposing the anterior tibial crest or the Achilles tendon, both of which are difficult to graft. The propeller flap circumvents these challenges/problems by transferring healthy tissue from the proximal calf into the primary defect. Thus, the secondary defect is moved to the area over the proximal muscle bellies, which is easily graftable or even primarily closed, either through a direct mobilization and closure of the skin or even through another propeller flap, as already described by our department^[11]. Another advantage of the propeller flap, compared to the local flap, is that it avoids the awkward twisting at the base of the flap. This twist is unsightly, and it might even compress or stretch the pedicle, which may endanger the flap survival. Furthermore, the propeller flap design expands the reach of the flap and enables an easier inset.

SURGICAL TECHNIQUE

Preoperatively, the most appropriate perforator is identified using CT-angiography and a handheld Doppler device. With the perforator used as the pivot point, a provisional flap design is drawn. First, the proximal limit of the flap is determined by transposing the distance between the perforator and the distal border of the defect proximally over the axis of the source artery and adding 1 cm to that length. Thus, the flap is easily inset without tension and allowed to contract. Next, the width of the proximal flap is determined by measuring the width of the defect and adding 0.5 cm for the same reason. A thigh tourniquet is used but without exsanguination of the limb, which makes for an easier identification and dissection of the perforator. The raising of the flap begins with an initial exploratory incision under loupe magnification and, thereupon, usually several potentially applicable perforators are found. Based on the position and size, the best one is chosen, and it may not necessarily be the one identified on Doppler sonography. The design of



Figure 1. Wound dehiscence with plate exposure after plate osteosynthesis of a lateral malleolus

the flap can be adjusted accordingly. Perforators enclosed in scar or granulation tissue should be avoided. Once the appropriate perforator is chosen, it is carefully prepared and freed of all muscular side branches for at least 2 cm. Wherever feasible, the pedicle is cleaned all the way from the flap to its source vessel. After the flap is islanded, it is inset into the defect and the tourniquet is released. When rotating the flap 180°, the surgeon turns it in both directions to evaluate which rotational direction exerts less extrinsic compression on venae comitantes. Once the decision regarding the rotation is made, two skin sutures are placed on either side of the flap axis. At this point, the perfusion of the flap is controlled using the indocyanine green real-time angiography. Firstly, 2 mL of ICG (Indocyanine green by Verdy®) is administered intravenously, followed by 10 mL of normal saline. Using a near-infrared camera (Fluobeam® by Fluoptics Grenoble, France), the blood supply of the flap is recorded. Firstly, the arterial perfusion is evaluated. Parts of the flap, which present dark under the Fluobeam, are cut away. Twenty minutes after ICG administration, the flap is checked once again. It is of foremost importance to look for wash-out, and, if the flap is still fluorescent, it is a sign of venous congestion. If the isolated perforator is not providing a sufficient arterial inflow or a sufficient venous outflow, an extra pedicle can be added, as described by Pignatti *et al.*^[9] and Iida *et al.*^[12] In the case of an insufficient arterial inflow, an extra artery can be microsurgically anastomosed to a second arterial pedicle of the flap. When there is no wash-out on ICG, the pedicle is further dissected and cleaned of all the fibrous bands and, if this is insufficient, a superficial or perforating vein of the flap can be microsurgically anastomosed to a recipient vein to increase the blood flow. Thereafter, the wound closure is straightforward. However, it is important not to close the donor site too tightly as it might endanger the blood supply of the flap through the tourniquet effect.

CASE REPORTS

Case 1: peroneal artery perforator propeller 180° flap

A 41-year-old male patient underwent plate osteosynthesis of a lateral malleolus due to trauma and developed a wound dehiscence with plate exposure [Figure 1]. The plate was removed and, after debridement, a new one was implanted. A local perforator flap measuring 16 cm × 4 cm, based on a Y-shaped perforator of the peroneal artery perforator [Figure 2], was harvested and propelled 180° into the defect [Figure 3]. In this way, the soft tissue defect from the debridement and the plate were covered with an undamaged tissue. After the inset of the flap, an intraoperative ICG angiography was performed, confirming a good blood perfusion of the whole flap [Figure 4]. The patient's postoperative recovery was unremarkable. He was able to ambulate with no restriction and limitation at six-month follow-up [Figure 5].

Case 2: posterior tibial artery perforator propeller 180° flap

A 24-old-male patient sustained a penetrating injury of her right leg, dorsally to the medial ankle. After debridement and a period of wound care, a deep, circle-shaped soft tissue defect measuring 4 cm × 3.5 cm × 2.5 cm

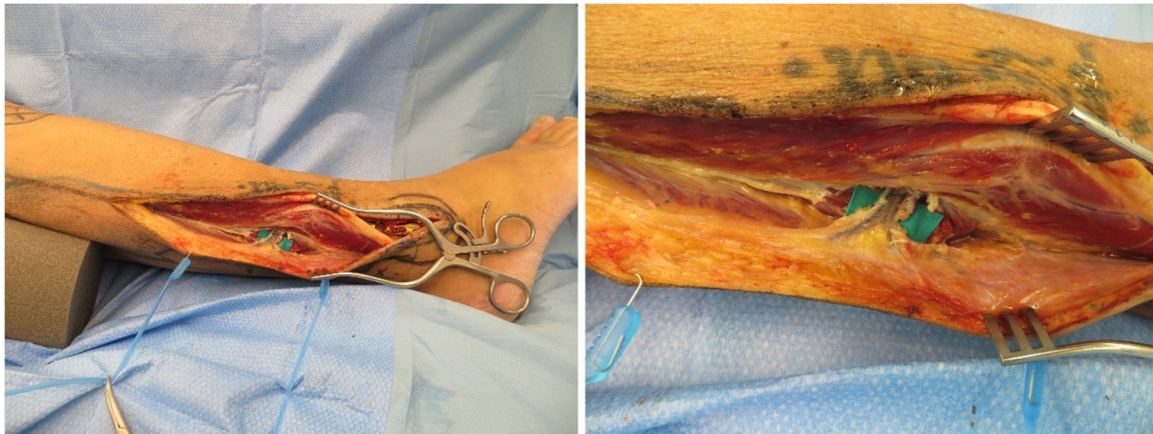


Figure 2. Perforator flap measuring 15 cm × 5 cm is raised, based on a Y-Shape perforator of peroneal artery

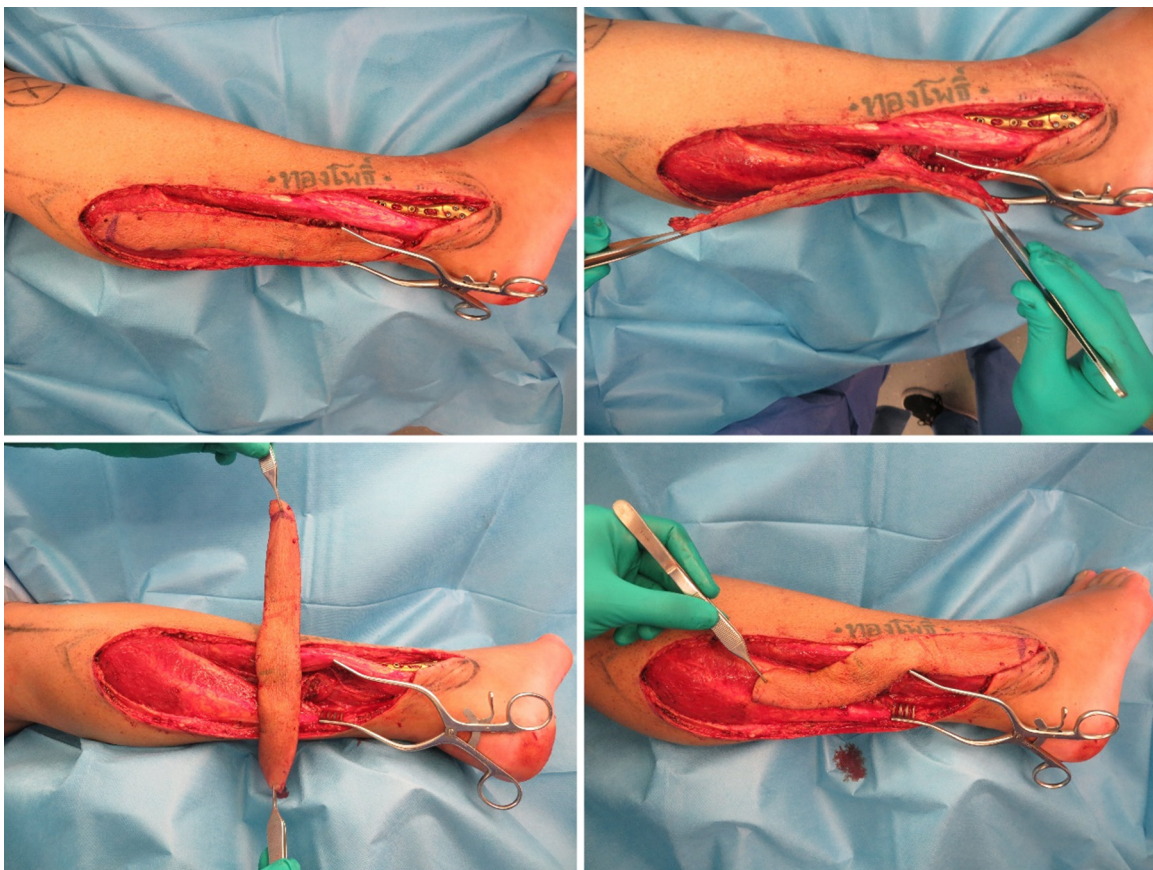


Figure 3. The peroneal artery perforator flap is effortlessly propelled into the defect by 180°

was noted, with Achilles tendon and calcaneus bone exposure [Figure 6, upper left]. A local perforator flap based on the posterior tibial artery measuring 12 cm × 4 cm was designed. Two appropriate perforators were found [Figure 6, upper right]. Based on the size and location farther from the defect, the proximal one was chosen. The proximal part of the flap was de-epithelized [Figure 6, lower left], the flap was propelled for 180°, and the de-epithelized part of the flap was used to fill the deep defect [Figure 6, lower right]. The donor site could be closed directly [Figure 7, left]. The wound healed uneventfully. Ambulation was permitted five days postoperatively with a VACOPed® leg cast for 4 weeks to prevent wound dehiscence through the



Figure 4. Left: immediate postoperative result, showing the donor site was closed directly. Right: indocyanin green angiography for blood perfusion at the tip of the flap after flap insetting

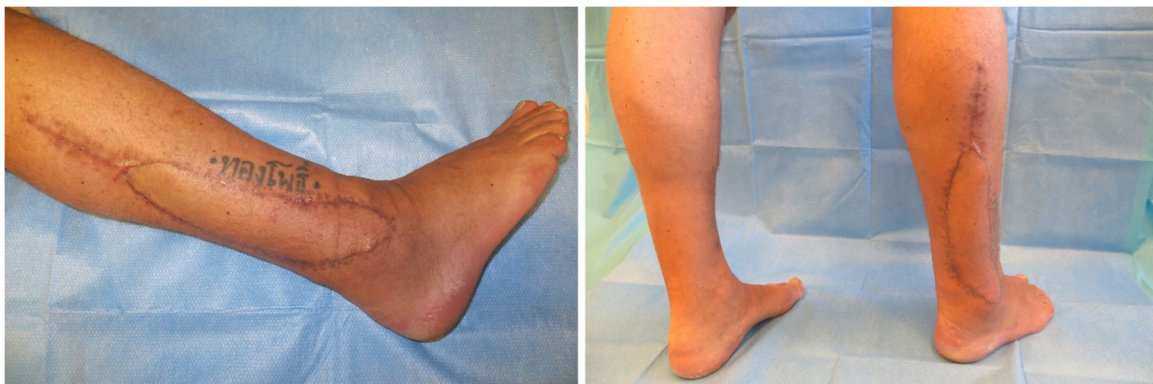


Figure 5. Follow-up at 6 months, showing no functional deficit and good cosmesis

shearing force of the Achilles tendon. The flap survived completely at four-month follow-up [Figure 7, right].

Case 3: anterolateral thigh propeller flap

A 66-old female patient was presented to us with a large synovial sarcoma of the right lateral thigh [Figure 8, upper left]. She had already undergone radiotherapy preoperatively. Tumor excision and defect reconstruction with a pedicle anterolateral thigh perforator propeller flap were planned in the same setting. The defect following tumor excision measured 12 cm × 7 cm [Figure 8, upper right]. A pedicle anterolateral thigh flap measuring 14 cm × 8 cm, based on a perforator of the descending branch of the lateral femoral circumflex artery, was raised [Figure 8, lower left]. The flap was rotated 130° in counter clockwise direction and inset into the defect, covering it without tension [Figure 8, lower right]. The donor site could be closed directly [Figure 9, left]. The wound healed well, the patient was cancer free, and no gait disturbance was observed five months after the operation [Figure 9, right].

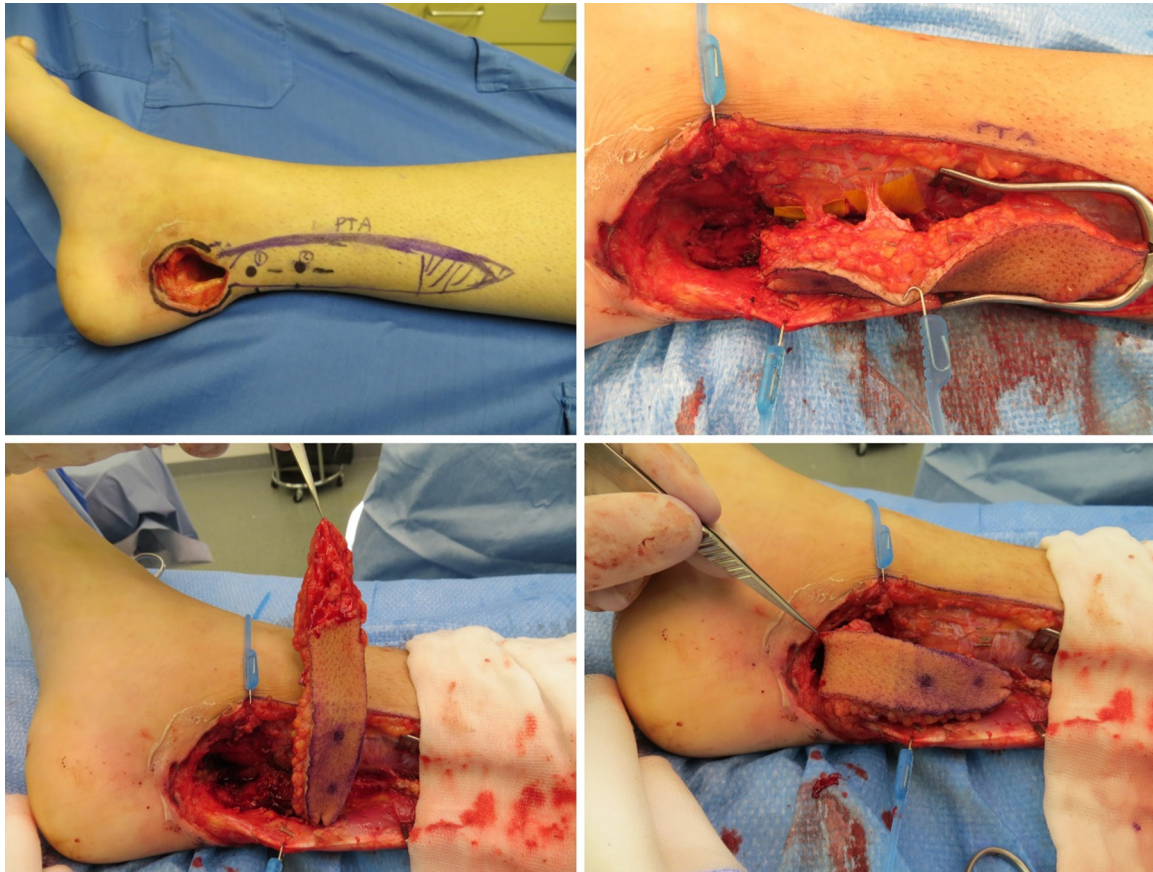


Figure 6. Upper left: penetrating injury of the distal lower limb dorsally to the medial ankle (after debridement), measuring 4 cm × 3.5 cm × 2.5 cm. Upper right: perforator flap measuring 12 cm × 4 cm was harvested, based on a perforator of the posterior tibial artery. Another more distally located perforator was found but was ligated due to the close proximity of the wound. Lower left: the proximal tip of the flap was de-epithelized to fill the dead space. Lower right: the flap was rotated 180° and filled the defect

DISCUSSION

The propeller flap is an extremely useful reconstructive tool and enables exceptional functional and cosmetic results in the lower extremity. Similar to a local flap, it provides the possibility of reconstructing “like with like”, covering the defect with tissue of similar color and thickness but without the awkward dog ears. Being a perforator flap, it offers the freedom of choice regarding the skin island shape and dimension as well as a safe perfusion. Compared with a free flap, it requires a simpler operation without the need of microsurgical anastomosis and, thus, significantly shorter operating times. In a review of 21 studies, spanning from 2004 to 2012 and describing 310 propeller flaps, Nelson *et al.*^[13] noted a total flap loss in 5.5% and a partial flap loss in 11.6%. Bekara *et al.*^[14] observed a 10.2% rate of partial necrosis and a 3.5% rate of complete necrosis in their meta-analysis of 40 publications on propeller flaps in lower limb reconstruction, representing 428 flaps and spanning from 2003 to 2014. These values are notably lower than those for free flaps in lower extremity, as observed by Wettstein *et al.*^[15]. Furthermore, the decline of the complication rate seen when comparing the reviews of Nelson *et al.*^[13] from 2013 and Bekara *et al.*^[14] from 2014 could imply a reduction of complications with the surgeons’ experience.

Propeller flaps can be used to reconstruct many different types of defects of the lower extremity, both traumatic and non-traumatic in origin. Most commonly^[14], they are performed for coverage of primary defects in the distal third of the leg, as described by Teo^[16]. More and more authors apply them in reconstructing the wounds of the foot, an example being the medial plantar artery perforator flap for



Figure 7. Left: the donor site was closed primarily without tension. Right: follow-up at 4 months, showing the functional and cosmetic result is satisfactory

reconstruction of the heel, middle foot sole, and plantar forefoot^[17]. A large part of the scientific papers currently being published on this topic describes the closure of the secondary defects after free flap transfer from the lower extremity for use in other parts of the body, mostly head and neck reconstruction. Propeller flaps have been described for reconstruction of donor sites of anterolateral thigh flaps^[12,18], anteromedial thigh flaps^[18], vertical posteromedial thigh flaps^[19], and fibula flaps^[20]. Furthermore, the propeller flap has even been used to cover the donor site of another propeller flap in the lower leg (sequential propeller flap)^[11].

The dissection of propeller flaps in the literature is mostly subfascial^[7,8,14,21], which is easier to learn, safer, and faster than the suprafascial dissection. The suprafascial dissection is slower but leaves a less important donor-site defect and facilitates flap dissection at the sites where the intermuscular septa join the muscular fascia^[22].

One of the biggest concerns when planning a propeller flap is the torsional twist of the pedicle. Teo^[8] showed that a single vascular pedicle is able to tolerate up to 180° rotational twist without suffering vascular distress. The key to that is the radical skeletonization of the pedicle that divides all the fine fascial strands surrounding the vessels, allowing the flap to rotate 180° without kinking of the vessels. Most authors systematically skeletonize the pedicle^[8,9] to allow for gentle spiral twist of the pedicle. It is logical to assume that the length of a vessel (l) is inversely proportional to the critical angle of twisting (Δt), namely $\Delta t = [l \times (1/\Delta t)]$, and this has been proven by experimental studies^[23,24]. Wong et al.^[25] performed nonlinear finite element simulations to elucidate the determinants of perforator patency in propeller flaps and proposed that the selected perforator should be approximately 1 mm in diameter and more than 30 mm in length. In our institution, the pedicle is always skeletonized for at least 3 cm and, if there are signs of venous congestion in ICG after inseting the flap, a further skeletonization of the pedicle is performed.

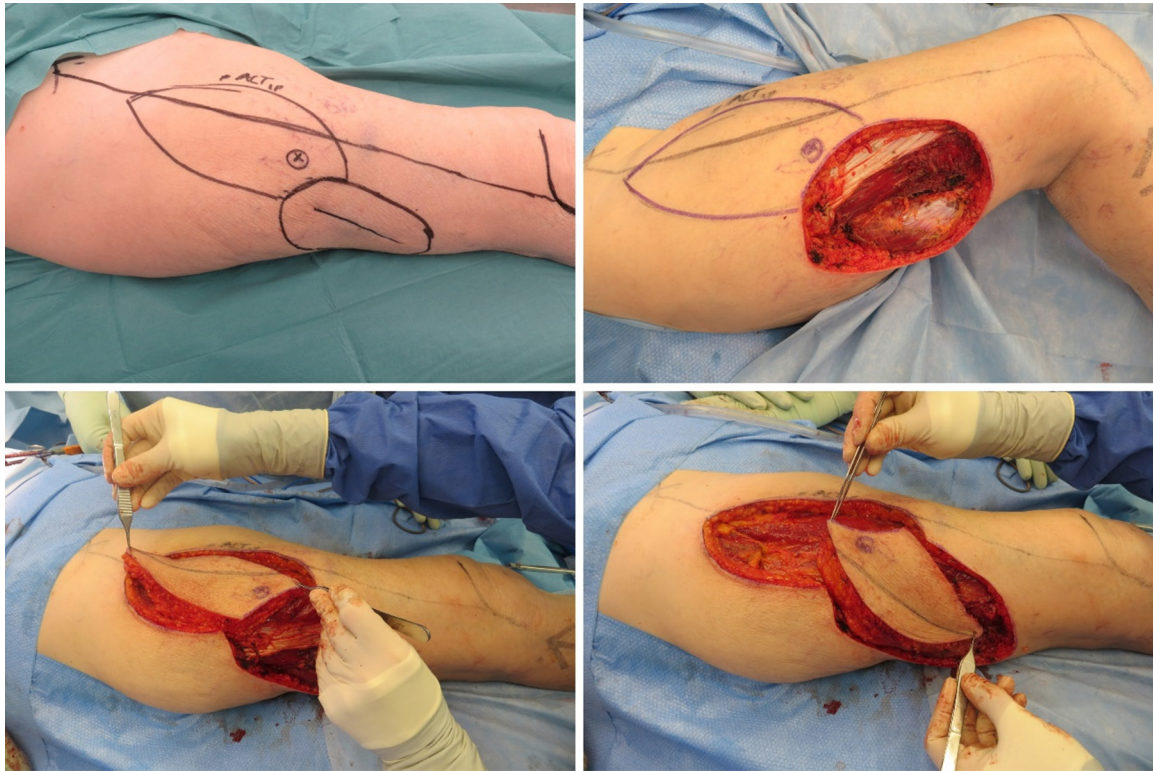


Figure 8. Upper left: preoperative markings of the sarcoma and the anterior lateral thigh flap design. The perforator was mapped using a handheld Doppler device. Upper right: large soft tissue defect on the lateral thigh with exposure of T. rectus iliotibialis, M. vastus lateralis, and M. biceps femoris. Lower left: The anterior lateral thigh flap, measuring 16 cm × 8 cm, was raised. Lower right: the flap was propelled into the defect 130° counter clockwise, comfortably covering the defect



Figure 9. Left: primary closure of the donor site was possible without tension. Right: uneventful wound healing and no gait disturbance at five-month follow-up

To date, there is no certain way of predicting preoperatively the exact size of the flap that will safely be perfused by one perforator. Nevertheless, there are possible technical refinements of the flap design and execution, which help improve the success rate by a large margin. Iida *et al.*^[12] proposed double-axes propeller flap, intraoperative ICG, and supercharging of the propeller flap to minimize the ratio of (partial) flap necrosis. When dissecting the flap, the perforators located farther than 3 cm from the main perforator are clamped and ligated. When perfusion seems insufficient in intraoperative ICG, supercharging can be performed using the ligated perforators.

Much research has been done into the correlation between the size of the perforator, its blood flow, and the volume of tissue it can sustain. Donski and Fodgestam^[26] proposed that the suprafascial interconnections between perforators lying along a septum effectively form an axial type flap, allowing for longer flaps to be designed. Taylor *et al.*^[27] demonstrated that a single vascular perforator can, in addition to its own angiosome, safely supply the angiosome of the adjacent perforator and, depending on the type of the anastomoses between the angiosomes (choke or true), even part of the territory of the perforator next to it. Saint-Cyr *et al.*^[28] described the perforasome theory based on the mechanism of opening “potential” vascular territories using linking vessels after ligation of adjacent perforators. Further studies should be conducted on defining the borders of perforasomes and the possibility of turning choke anastomoses into real anastomoses.

As for the significant risk factors for failure or complications for propeller flaps in lower limb reconstruction, Bekara *et al.*^[14] identified age older than 60 years, diabetes, and arteriopathy. Smoking did not significantly increase the complication rate. In a review of 119 studies from 1991 to 2015, comprising 1315 propeller flaps in different areas of the body, Sisti *et al.*^[29] found that the complication rate for propeller flaps was by far the highest in the lower limb (31.8%), compared to trunk (19.5%), head and neck (15.7%), and upper limb (15.9%).

CONCLUSION

The perforator-pedicled flap has been gaining popularity among plastic surgeons over the past 20 years. In our experience, it is an excellent option for lower limb soft tissue reconstruction in appropriately chosen patients, enabling a functional and aesthetically pleasing result.

DECLARATIONS

Authors' contributions

Senior author and corresponding, performed all surgeries and revised the manuscript: Scaglioni MF
Wrote the manuscript under Scaglioni supervision: Macek A

Availability of data and materials

Data from Scaglioni MF, Department of Plastic Surgery Lucerne.

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All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Followed Helsinki Guidelines, Case reports with review.

Consent for publication

Not applicable.

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REFERENCES

- Reddy V, Stevenson TR. MOC-PS (SM) CME article: lower extremity reconstruction. *Plast Reconstr Surg* 2008;121:1-7.
- Hallock GG. Lower extremity muscle perforator flaps for lower extremity reconstruction. *Plast Reconstr Surg* 2004;114:1123-30.
- Ponten B. The fasciocutaneous flap: its use in soft tissue defects of the lower leg. *Br J Plast Surg* 1981;34:215-20.
- Khouri RK, Shaw WW. Reconstruction of the lower extremity with microvascular free flaps: a 10-year experience with 304 consecutive cases. *J Trauma* 1989;29:1086-94.
- Hyakusoku H, Yamamoto T, Fumiiri M. The propeller flap method. *Br J Plast Surg* 1991;44:53-4.
- Koshima I, Soeda S. Inferior epigastric artery skin flaps without rectus abdominis muscle. *Br J Plast Surg* 1989;42:645-8.
- Hallock GG. The propeller flap version of the adductor muscle perforator flap for coverage of ischial or trochanteric pressure sores. *Ann Plast Surg* 2006;56:540-2.
- Teo TC. The propeller flap concept. *Clin Plast Surg* 2010;37:615-26.
- Pignatti M, Ogawa R, Hallock GG, Mateev M, Georgescu AV, et al. The “Tokyo” consensus on propeller flaps. *Plast Reconstr Surg* 2011;127:716-22.
- Blondeel PN, Van Landuyt K, Monstrey SJ, Hamdi M, Matton GE, et al. The “Gent” consensus on perforator flap terminology: preliminary definitions. *Plast Reconstr Surg* 2003;112:1378-83.
- Scaglioni MF, Franchi A, Fritsche E. Propeller flap donor site closure by means of another propeller flap: a case report and literature review. *Microsurgery* 2019; Epub ahead of print doi: 10.1002/micr.30497
- Iida T, Yoshimatsu H, Koshima I. Reconstruction of anterolateral thigh defects using perforator-based propeller flaps. *Ann Plast Surg* 2017;79:385-9.
- Nelson JA, Fischer JP, Brazio PS, Kovach SJ, Rosson GD, et al. A review of propeller flaps for distal lower extremity soft tissue reconstruction: is flap loss too high? *Microsurgery* 2013;33:578-86.
- Bekara F, Herlin C, Mojallal A, Sinna R, Ayestary B, et al. A systematic review and meta-analysis of perforator-pedicled propeller flaps in lower extremity defects: identification of risk factors for complications. *Plast Reconstr Surg* 2016;137:314-31.
- Wettstein R, Schürch R, Banic A, Erni D, Harder Y. Review of 197 consecutive free flap reconstructions in the lower extremity. *J Plast Reconstr Aesthet Surg* 2008;61:772-6.
- Teo TC. Perforator local flaps in lower limb reconstruction. *Cir Plast Ibero-Latinoamericana* 2006;32:15-6.
- Scaglioni MF, Rittirsch D, Giovanoli P. Reconstruction of the heel, middle foot sole, and plantar forefoot with the medial plantar artery perforator flap: clinical experience with 28 cases. *Plast Reconstr Surg* 2018;141:200-8.
- Hung KS, Chen SH, Chen WC, Tseng WL, Lee YC. Surgical algorithmic approach to facilitate primary closure of the anterolateral thigh flap donor site in head and neck reconstruction. *Ann Plast Surg* 2018; Epub ahead of print doi: 10.1097/SAP.0000000000001729
- Scaglioni MF, Barth AA, Chen YC. Perforator flap based on the third perforator of the profunda femoris artery (PFA)-assisted closure of the free vertical posteromedial thigh (vPMT) flap donor site. *Microsurgery* 2018;38:758-62.
- Sharma M, Balasubramanian D, Thankappan K, Sampathirao CL, Mathew J, et al. Propeller flaps in the closure of free fibula flap donor site skin defects. *Ann Plast Surg* 2013;71:76-9.
- Moscatiello F, Masià J, Carrera A, Clavero JA, Larrañaga JR, et al. The ‘propeller’ distal anteromedial thigh perforator flap: anatomic study and clinical applications. *J Plast Reconstr Aesthet Surg* 2007;60:1323-30.
- Chaput B, Herlin C, Bekara F, Bertheuil N. Thinning: the difference between free and propeller perforator flaps. *Arch Plast Surg* 2015;42:241-2.
- Bravo FG, Schwarze HP. Free-style local perforator flaps: concept and classification system. *J Plast Reconstr Aesthet Surg* 2009;62:602-8.
- Bilgin SS, Topalan M, Ip WY, Chow SP. Effect of torsion on microvenous anastomotic patency in a rat model and early thrombolytic phenomenon. *Microsurgery* 2003;23:381-6.
- Wong CH, Cui F, Tan BK, Liu Z, Lee HP, et al. Nonlinear finite element simulations to elucidate the determinants of perforator patency in propeller flaps. *Ann Plast Surg* 2007;59:672-8.
- Donski PK, Fogdestam I. Distally based fasciocutaneous flap from the sural region. A preliminary report. *Scand J Plast Reconstr Surg* 1983;17:191-6.
- Taylor GI, Corlett RJ, Ashton MW. The functional angiosome: clinical implications of the anatomical concept. *Plast Reconstr Surg* 2017;140:721-33.
- Saint-Cyr M, Schaverien M, Arbique G, Hatef D, Brown SA, et al. Three- and four-dimensional computed tomographic angiography and venography for the investigation of the vascular anatomy and perfusion of perforator flaps. *Plast Reconstr Surg* 2008;121:772-80.
- Sisti A, D’Aniello C, Fortezza L, Tassinari J, Cuomo R, et al. Propeller flaps: a literature review. *In Vivo* 2016;30:351-73.

Review

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Evolution of local perforator flaps in lower extremity reconstruction

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Abstract

Lower extremity reconstruction is challenging for a variety of reasons. New techniques for soft tissue coverage continue to evolve. While free flaps are always an option, free flaps require significant microsurgical expertise, a proficient staff, advanced equipment, and a patient with a somewhat healthy baseline. However, as microsurgery has evolved, so has the identification of new anatomy and new techniques - namely, perforator based pedicled flaps. These flaps have expanded options for lower extremity reconstruction, and continue to advance the field of microsurgery. The purpose of this article is to review the evolution of perforator based pedicled flaps in the lower extremity, review the anatomy, and offer examples of design and indications.

Keywords: Perforator flaps, lower extremity reconstruction, soft tissue coverage

INTRODUCTION

Lower extremity coverage has long proved challenging for reconstructive surgeons primarily due to the paucity of soft tissue and skin available locally. Very often, lower extremity soft tissue injuries are complicated by associated bone, arterial, or nerve damage. Additionally, the lower extremities have a functional and mechanical component that further complicates the reconstructive process.

In the pre-microsurgery era, soft tissue reconstructive options were limited to tubularized flaps, popularized by Gilles, as well as the cross leg flap, originally described in a case report by Hamilton in



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1854^[1]. It was not until 1971 that Ger^[2] published his techniques on rotation muscle flaps. In 1981, Pontén^[3] published his technique on fasciocutaneous flaps, showing that long narrow flaps, including the fascia, could be safely raised on the lower extremity. With a greater understanding of vascular anatomy, it was soon discovered that flaps could be safely based off of single septocutaneous or myocutaneous perforators.

Pedicled perforator flaps expand the possibility of coverage and salvage. They can be performed with basic surgical equipment and without need for microsurgery training. Additionally, they offer a quicker operative time, thus making them an option for nearly any patient, regardless of age and medical comorbidities. They also spare underlying musculature and vasculature, preserving in-line flow and therefore minimize morbidity.

The purpose of this article is to review the historical evolution and development of pedicled-perforator flaps for reconstruction in the lower extremity. Case examples are presented to illustrate the use of different flaps for coverage in the lower extremity.

VASCULAR TERRITORIES

Defining the vascular territories of the lower extremity has helped greatly in safe flap design. Fasciocutaneous flaps based on random pedicles for lower extremity reconstruction demonstrated high necrosis rates of up to 25%^[4]. With the careful anatomic study of cutaneous arteries and the emergence of the “angiosome” concept^[5], axial flaps were described all over the body. Some of this early work was performed by Salmon^[6], who in 1936 published his work on cadavers, mapping the entire cutaneous circulation. Taylor and Pan^[7] specifically evaluated the angiosomes of the leg. They determined that source vessels to the skin arise directly from arteries or their muscular branches, piercing the deep fascia in longitudinal rows at the intermuscular septum or alongside tendons. They also noted interconnections between vascular territories, and that, as vessels traveled down the leg, the perforators made a more direct course for the skin. Ultimately, they defined the territories of the popliteal, posterior tibial, peroneal, and anterior tibial arteries.

The introduction of perforasome theory further increased possibilities for flap design by introducing the concept of perforator flaps. This began with the deep inferior epigastric perforator flap described by Koshima and Soeda^[8], but many other flaps were subsequently described. There were many attempts to define perforator flaps^[9]. Finally, in 2002, the Gent Consensus^[10] was published, defining what a perforator flap was, standardizing terminology, and offering examples. Saint-Cyr *et al.*^[11] defined the territories of perforators through an anatomic cadaveric study studying flaps over different territories. Flaps were injected with methylene blue dye for the dissection. Once the perforator was identified, contrast was injected to perform CT scans. Direct and indirect linking vessels were noted between perforasomes. Based on their anatomic study, they recommended that flaps should be designed in direction of linking vessels, in an axial direction.

The design and reliability of the perforator flap depends on the location of the perforating vessels and number of vessels included in the flap. Perforator flap design begins with understanding the anatomy based on the territories described above.

Perforator territories in the lower extremity

Posterior tibial perforators

The posterior tibial artery is the continuation of the popliteal artery as it exits the popliteal fossa and is the largest terminal branch. It extends in an oblique and inferior direction into the lower leg, behind the tendinous arch of the soleus, spending the majority of its course behind the tibialis posterior after it gives

off the peroneal artery^[12]. Distally, it is located posterior to the medial malleolus and is divided into the medial and lateral plantar arteries. The posterior tibial artery supplies the posterior compartment of the leg.

The perforators from the posterior tibial artery are most commonly septocutaneous - between the flexor digitorum longus and the soleus muscle^[13]. These perforators, concentrated at the middle third of the lower leg, are some of the largest of the entire lower extremity^[12-15]. They are most readily identifiable 10-12 cm above the medial malleolus. However, flap design can occur anywhere up to 10 cm distal to the popliteal crease^[16-18].

Historically, flaps based off the posterior tibial system included sacrifice of the main artery. The use of a perforator flap with preservation of the main vessel was described by Koshima *et al.*^[19], and its popularity quickly increased.

Peroneal Artery perforators

The peroneal artery takes its course off of the posterior tibial artery. From there, it descends through the posterior compartment of the leg, next to the posterior intermuscular septum^[12]. Peroneal perforators, although not as numerous, remain another reliable vascular supply to a perforator flap. The perforators are located at the middle third of the fibula and are easily found with a Doppler. Schaverien *et al.*^[18] found that musculocutaneous perforators emerge proximally from within the soleus or the peroneus longus muscles and septocutaneous perforators between the flexor hallucis longus and peroneus brevis muscles. Most of these perforators were found to emerge 13-18 cm proximal to the lateral malleolus. Distally, they found that these perforators often emerge superficial to the Achilles tendon^[18].

Anterior tibial perforators

The last main vascular territory to the lower extremity is supplied by the anterior tibial artery. The anterior tibial artery begins at the inferior border of the popliteus muscle. It passes anteriorly through a gap in the interosseus membrane and descends on the anterior surface of the membrane between the tibialis anterior and extensor digitorum longus^[11]. It provides the blood supply to the anterior compartment of the leg. The major perforators from the anterior tibial artery are located proximally - documented 21-26 cm proximal to the intermalleolar line between the tibia and the tibialis anterior muscle^[14,16]. These also happen to be the largest perforators. There is also a series of smaller perforators that emerge 4-9 cm above the intermalleolar line between the tendons of the anterior compartment; these supply the skin over both malleoli^[20].

FLAP DESIGN

While identification of appropriate vasculature was an important step in the evolution of perforator flaps of the lower extremity, flap design has also played a large role in the evolution of these flaps (including the need for vascular territories to be studied).

V-Y perforator flaps

V-Y flaps have been designed and utilized for reconstruction over the face, trunk, and extremities. Although first described based on a random pattern blood supply, they can also be designed along a single perforator. This increases the reach of the flap as well as the mobility when the flap is isolated on a single perforator. The primary benefit of the flap is decreased morbidity at the donor site, which in most cases can be closed primarily.

The flap is designed so that the length is twice the diameter of the defect to accommodate for longitudinal advancement^[19,20-22]. A perforator can be selected via doppler location preoperatively. The skin, subcutaneous tissue, and muscle fascia are incised.



Figure 1. Left lower extremity traumatic wound on medial malleolus, after debridement and placement of external fixator



Figure 2. Immediately after V-Y advancement flap and closure. Tension free closure achieved over the wound

Figure 1 shows a healthy young male involved in a trauma. He sustained an open fracture with a wound located over his medial malleolus. Closure was performed with a V-Y flap based on the posterior tibial artery. This was identified via Doppler, and the flap was elevated only on the perforator, which allowed increased mobility for closure of the defect. The flap is shown immediately post-operatively in **Figure 2**. There was complete tension free closure. Finally, the wound is shown one-month post-operatively in **Figure 3**. The wound healed without any complications and with good coverage distally.

Propeller flaps

In 1991, Hyakusoku *et al.*^[23] published the concept of the propeller flap, which was described for scar release in the axilla and groin. Originally designed as a random pattern flap with a 90-degree arc of rotation, it had little utility in the lower extremity. However, as this idea emerged and was blended with the perforator flap concept, its application expanded to include coverage of wounds in the lower extremity.

Based on the Tokyo Consensus^[24], a propeller flap is now defined as an axial flap that reaches the recipient site through axial rotation. With a designated perforating vessel, a propeller flap indicates a flap that rotates anywhere 90-180 degrees along its axis with a “large blade” and a “small blade”. The division between the blades is marked by the perforator.



Figure 3. One-month post-operation: There is good healing over the wound without any distal necrosis



Figure 4. Traumatic wound of the medial lower third of the leg after debridement and operative fixation with intramedullary nail

Traditionally, the flap is designed along the axis of the limb, but the end can be modified to fit the skin defect. Although there are no absolute limitations of the length of the flap, it can be difficult to predict the perforasome perfused by the perforator. Investigators have attempted to define the safe skin territory perfused by a single perforator. One study found that the necrosis rate was six times higher in flaps designed more than 1/3 of the limb length^[25]. Unfortunately, there is no clear way to predict necrosis at the tip of the flap and careful intra-operative and post-operative observations should be made, and secondary reconstruction should be considered if there is necrosis over vital structures.

[Figure 4](#) shows a medial lower third wound after trauma. There is exposure of the tibia following intramedullary nail placement. To reconstruct this defect, a propeller flap was designed on the posterior tibial artery system. The entire flap was isolated on the perforator. The flap is shown elevated in [Figure 5](#). [Figure 6](#) shows isolation of the flap on the posterior tibial perforator. A skin graft was applied to the donor site. The flap is shown in [Figure 7](#) at a follow-up appointment post-operatively, with complete viability and no distal necrosis. There is good coverage of the wound and the skin graft has taken well proximally.

The same applications can be applied to other perforators when designing propeller flaps. [Figure 8](#) shows a lateral malleolar wound after a resection of a recurrent melanoma. There is exposure of the Achilles tendon



Figure 5. A propeller flap was designed on a posterior tibial perforator. The flap was isolated circumferentially on the perforator. The blue X marks the location of the perforator

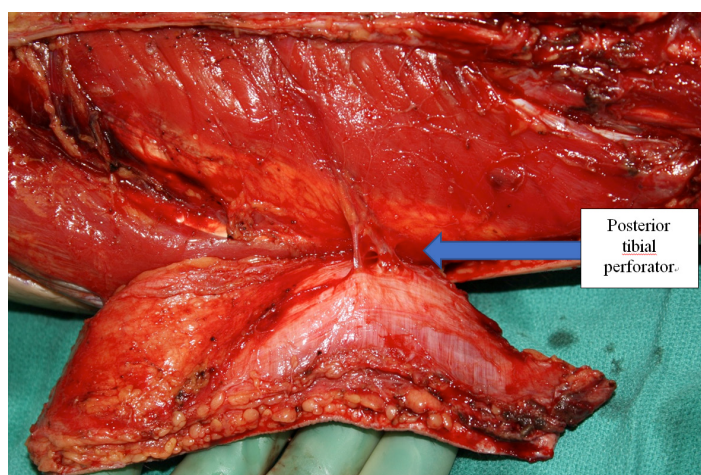


Figure 6. This shows the isolation of the flap in the subfascial plane on a large posterior tibial perforator



Figure 7. Post-operatively, good healing of the fracture site with no flap necrosis is shown. There is skin grafting to the donor site with good take



Figure 8. Lateral malleolar wound after resection of a recurrent melanoma



Figure 9. Large propeller flap was designed on the peroneal artery perforators. This was isolated on a single perforator and rotated into the wound. The blue "X" denotes the location of the peroneal artery perforator

and lateral joint capsule. A large propeller flap was designed on the peroneal arteries [Figure 9]. This was rotated 180 degrees to fill the distal defect [Figure 10]. Figure 11 shows the flap healed post-operatively. There is good coverage over the joint, which is soft and supple and has full range of motion.

Keystone flaps

Although originally described for trunk defects, there is a limited but important role in lower extremity reconstruction. The keystone flap is based on fasciocutaneous perforators. The flap is designed so that each limb of the flap is 90 degrees from the longitudinal axis of the flap. This has been described throughout the literature for lower extremity defects mostly in the setting of oncologic reconstruction^[26-28] with good outcomes. Limitations of the keystone flaps include limited advancement and no rotational movement.

Sequential perforator flaps: Kiss flap technique

A persisting problem in lower extremity perforator flaps is the donor site. They often cannot be closed primarily and may require skin grafting, which can have negative cosmetic outcomes, especially in African American or Asian populations. The Kiss flap, described by Zhang *et al.*^[29], is based on the goal of harvesting multiple skin paddles and rearranging them side by side for defect reconstruction. This then

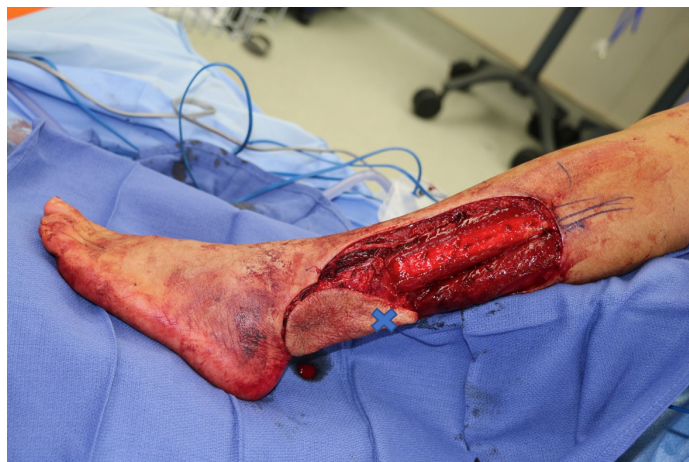


Figure 10. Peroneal artery perforator flap rotated 180 degrees into the wound. The blue "X" denotes the local of the peroneal artery perforator



Figure 11. Peroneal artery perforator flap shown post-operatively. There is good healing of the flap and coverage of wound. The skin graft was placed on donor site and has healed well

allows for donor sites to be closed primarily. This group described five main types of flaps based on the vascular source. Different types may have important implications in the lower extremity, depending on the perforator location and choice of flap.



Figure 12. Traumatic wound of the left lower extremity after a motor vehicle collision. There were three separate wounds connected by skin bridges

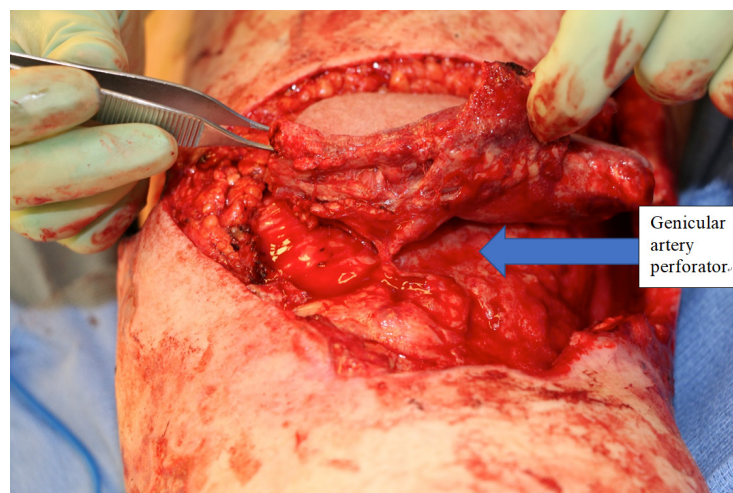


Figure 13. Freestyle propeller perforator flap designed off a superior lateral genicular artery perforator. The flap was isolated on the perforator and islandized

The benefits of the Kiss flap technique include improved donor sites with adequate soft tissue coverage. This often negates the need for grafting and therefore improves functional outcomes on the lower extremity, especially over joint surface. Shortcomings include complex design of flap and potential for tedious perforator dissections in order to receive adequate closure.

Figure 12 shows a 45-year-old female after a motor vehicle collision with multiple traumatic injuries including an open left knee joint. After adequate debridement, there were three separate wounds on the lateral portion of the knee with significant soft tissue loss. First, a freestyle propeller perforator flap was raised based off a perforator from the superior lateral genicular artery [Figures 13 and 14], which was rotated inferiorly. To repair the secondary donor site and the more proximal parts of the defect, an anterolateral thigh flap based on a single perforator was raised and advanced distally in V-Y fashion to repair the donor site [Figure 15]. The patient had complete closure of all defects as well as the donor site [Figure 16].

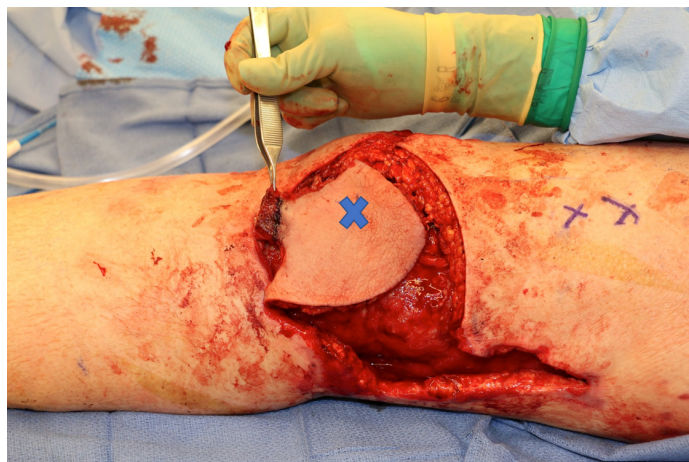


Figure 14. The flap was then rotated inferiorly into the first defect. The two other defects were connected. The blue "X" denotes the location of the genicular artery perforator



Figure 15. An anterolateral thigh flap was then elevated on a single perforator and advanced distally to close the two other connected defects as well as the donor site of the first perforator flap



Figure 16. The patient is shown here two weeks post-operatively, with closure of defects and the donor site. In addition, she had a separate superficial thigh wound that was managed with local wound care, with complete healing

GENERAL CONSIDERATIONS

For all perforator and propeller flaps of the lower extremity, the senior author offers several key points essential to maximize chances of success in reconstruction:

1. Preoperative imaging of the lower extremity to help identification of perforators. This can include CT angiography, utilizing thin cuts (≤ 1 mm), color duplex, and Doppler.
2. Intra-operative use of tourniquets to the lower extremity to aid in dissection.
3. Minimizing tension by completely dissecting a visualized perforator free from surrounding tissue.
4. Do not extend propeller perforator flaps in the distal third of the leg beyond the junction of the proximal 1/3 and distal 2/3 of leg to reduce chance of partial necrosis.
5. Observe flap 10 min after rotating to confirm no kinking of pedicle and good perfusion after flap rotation.
6. A period of post-operative immobilization with splint to prevent undue tension and breakdown with excessive movement.

LIMITATIONS OF PEDICLED PERFORATOR FLAPS

While the benefits of perforator flaps have been listed above, there are several limitations. First while donor site morbidity related to a local or free muscle flap is decreased, local donor site morbidity remains. Skin grafting of the donor site is often required. The skin graft donor site may heal with a hypertrophic scar in some skin types. Wong *et al.*^[30] reported data on 61 pedicled-perforator flaps used for reconstruction of lower extremity defects with 50% of donor sites requiring skin grafts.

Another risk is flap necrosis. Gir *et al.*^[31] performed a systematic review of pedicle perforator flaps in 2012 that included 186 cases and reported an overall complication rate of 25.8% with the most common being partial flap loss (11.3%). The overall failure rate was low at 1.1%. Bekara *et al.*^[32] performed a meta-analysis of 428 perforator-pedicled propeller flaps and reported a similar overall complication rate of 25.2%. The authors further went on to identify three significant risk factors: age greater than 60, diabetes, and arteriopathy. Although these reported risks are significant, the senior author's experience is that proper patient selection, preoperative imaging, and careful intraoperative evaluation of the flap intra-operatively can reduce risk of partial flap necrosis.

CONCLUSION

Lower extremity soft tissue coverage proves challenging to reconstructive surgeons due to the complexity of wounds and paucity of available local soft tissue. Reconstructive options continue to evolve, through skin grafts, local flaps and free tissue transfer and more recently pedicled-perforator flaps. Compared with free tissue transfer, they can be performed without advanced microsurgical training, with basic surgical equipment, and with minimal donor site morbidity. Perforator flaps provide the surgeon with flexibility in design as they can be based off of any of the three main vascular territories of the lower extremity. These flaps have proved to be both safe and efficacious and can be used to reconstruct smaller lower extremity defects without the need for free tissue transfer.

DECLARATIONS

Authors' contributions

Synthesized literature review, performed most of manuscript drafting: Cohen-Shohet R

Contributed to literature review, manuscript formatting, and editing: McLaughlin M

Assisted with formatting and final editing: Kerekes D

Provided case series, expert knowledge, and final editing review: Chim H

Availability of data and materials

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Ethical approval and consent to participate

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Consent for publication

All photographs used had written formal consent.

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REFERENCES

- Topalan M. A new and safer anastomosis technique in cross-leg free flap procedure using the dorsalis pedis arterial system. *Plast Reconstr Surg* 2000;105:710-13.
- Ger R. The technique of muscle transposition in the operative treatment of traumatic and ulcerative lesions of the leg. *J Trauma* 1971;11:502-10.
- Pontén B. The fasciocutaneous flap: its use in soft tissue defects of the lower leg. *Br J Plast Surg* 1981;34:215-20.
- Quaba O, Quaba A. Pedicled perforator flaps for the lower limb. *Semin Plast Surg* 2006;20:103-11.
- Taylor GI, Palmer JH. The vascular territories (angiosomes) of the body: experimental study and clinical applications. *Br J Plast Surg* 1987;40:113-41.
- Salmon M. *Artères de la peau*. Paris: Masson et cie; 1936.
- Taylor GI, Pan WR. Angiosomes the leg: anatomic study and clinical implications. *Plast Reconstr Surg* 1998;102:599-616.
- Koshima I, Soeda S. Inferior epigastric artery skin flaps without rectus abdominis muscle. *Br J Plast Surg* 1989;42:645-8.
- Wei FC, Jain V, Suominen S, Chen HC. Confusion among perforator flaps: what is a true perforator flap? *Plast Reconstr Surg* 2001;107:874-6.
- Blondeel PN, Van Landuyt KH, Monstrey SJ, Hamdi M, Matton GE, et al. The “Gent” consensus on perforator flap terminology: Preliminary definitions. *Plast Reconstr Surg* 2003;112:1378-82.
- Saint-Cyr M, Wong C, Schaverien M, Mojallal A, Rohrich RJ. The perforasome theory: vascular anatomy and clinical implications. *Plast Reconstr Surg* 2009;124:1529-44.
- Moore KL, Agur AMR, Dalley AF. *Essential Clinical Anatomy*. Lippincott Williams & Wilkins; 2011.
- Drimouras G, Kostopoulos E, Agiannidis C, Papadodima S, Champsas G, et al. Redefining vascular anatomy of posterior tibial artery perforators a cadaveric study and review of the literature. *Ann Plast Surg* 2016;76:705-12.
- Wu WC, Chang YP, So YC, Yip SF, Lam YL. The anatomic basis and clinical applications of flaps based on the posterior tibial vessels. *Br J Plast Surg* 1993;46:470-9.
- Zhang X, Wang X, Wen S, Zhu H, Ning Z, et al. Posterior tibial artery-based multilobar combined flap free transfer for repair of complex soft tissue defects. *Microsurgery* 2008;28:643-59.
- Georgescu AV. Propeller perforator flaps in distal lower leg: Evolution and clinical applications. *Arch Plast Surg* 2012;39:94-105.
- Schaverien MV, Hamilton SA, Fairburn N, Rao P, Quaba AA. Lower limb reconstruction using the islanded posterior tibial artery perforator flap. *Plast Reconstr Surg* 2010;125:1735-43.
- Schaverien M, Saint-Cyr M. Perforators of the lower leg: analysis of perforator locations and clinical application for pedicled perforator flaps. *Plast Reconstr Surg*. 2008;122:161-70.
- Koshima I, Moriguchi T, Ohta S, Hamanaka T, Inoue T, et al. The vasculature and clinical application of the posterior tibial perforator - based flap. *Plast Reconstr Surg* 1992;90:643-9.
- Koshima I, Itoh S, Nanba Y, Tsutsui T, Takahashi Y. Medial and lateral malleolar perforator flaps for repair of defects around the ankle. *Ann Plast Surg* 2003;51:579-83.
- Maruyama Y, Iwahara Y, Ebihara H. V-Y advancement flaps in the reconstruction of skin defects of the posterior heel and ankle. *Plast Reconstr Surg* 1990;85:759-64.
- Venkataramakrishnan V, Mohan D, Villafane O. Perforator based V-Y advancement flaps in the leg. *Br J Plast Surg* 1998;51:431-5.

23. Hyakusoku H, Yamamoto T, Fumiiri M. The propeller flap method. *Br J Plast Surg* 1991;44:53-4.
24. Pignatti M, Ogawa R, Hallock GG, Mateev M, Georgescu AV, et al. The “tokyo” consensus on propeller flaps. *Plast Reconstr Surg* 2011;127:716-22.
25. Panse NS, Bhatt YC, Tandale MS. What is safe limit of the perforator flap in lower extremity reconstruction? Do we have answers yet? *Plast Surg Int* 2011;2011:1-7.
26. Huang J, Yu N, Long X, Wang X. A systematic review of the keystone design perforator island flap in lower extremity defects. *Med (United States)* 2017;96:e6842.
27. John JR, Balan JR, Tripathy S, Sharma RK, Jadhav C. The keystone-design perforator-based flap for leg defects: a synthesis of philosophies. *Plast Aesthetic Res* 2014;1:70.
28. Riccio CA, Chang J, Henderson JT, Hassouba M, Ashfaq F, et al. Keystone flaps. *Ann Plast Surg* 2019;83:226-31.
29. Zhang YX, Hayakawa TJ, Levin LS, Hallock GG, Lazzeri D. The economy in autologous tissue transfer: Part 1. the kiss flap technique. *Plast Reconstr Surg* 2016;137:1018-30.
30. Wong JKF, Deek N, Hsu CC, Chen HY, Lin CH, et al. Versatility and “flap efficiency” of pedicled perforator flaps in lower extremity reconstruction. *J Plast Reconstr Aesthetic Surg* 2017;70:67-77.
31. Gir P, Cheng A, Oni G, Mojallal A, Saint-Cyr M. Pedicled-perforator (propeller) flaps in lower extremity defects: a systematic review. *J Reconstr Microsurg* 2012;28:595-601.
32. Bekara F, Herlin C, Mojallal A, Sinna R, Ayestaray B, et al. A systematic review and meta-analysis of perforator-pedicled propeller flaps in lower extremity defects: Identification of risk factors for complications. *Plast Reconstr Surg* 2016;137:314-31.

Original Article

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Dynamic infrared thermography and smartphone thermal imaging as an adjunct for preoperative, intraoperative, and postoperative perforator free flap monitoring

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Abstract

Aim: The versatile application of perforator free flaps for coverage of any extremity has been well proven. Often, a “free-style”-like approach is used to design these flaps, as conventional imaging techniques for perforator identification may be too expensive or unavailable. As will be demonstrated, the recent application of a thermal imaging camera using a smartphone is a cheaper and therefore more universal means to better identify the requisite perforators upon which a free flap can be designed and then monitored.

Methods: Smartphone thermography can be used on any patient preoperatively to identify preferable perforators or vascular network “hot spots” within the desired donor site territory. Intraoperative management of the choice of perforators and subsequent flap dissection can be similarly facilitated. Intermittent postoperative monitoring based on changes of the thermal image color palette will provide a comparison that can be used to determine if perfusion across the microanastomosis is sustained.

Results: An overview of how to use a smartphone in concert with a thermal imaging camera is outlined. Dynamic infrared thermography represents a thermal stress necessary with a smartphone to better identify donor site “hot spots”.



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Conclusion: Smartphone thermography is an inexpensive and expeditious means for identification of “hot spots” that correlate with perforators that would suffice to insure perfusion to a free perforator flap. However, since perforator caliber and course cannot be determined, this should be considered to be only a complementary adjunct for conventional methods. Nevertheless, its simplicity will overall improve the safer design, harvest, and subsequent monitoring of free flaps.

Keywords: Smartphone, thermography, thermal image camera, perforator free flap, microvascular tissue transfer, monitor

INTRODUCTION

Thermal imaging is in reality not an esoteric principle of physics that should be feared, as multiple roles are already commonplace as this is the basis for night vision utilized by the military, or in civilian life a means to detect heat loss sources from construction sites or something as prevalent in the hospital setting as preexisting deep-tissue pressure injuries^[1]. It is amazing that more than 30 years ago, Theuvenet *et al.*^[2] actually applied this concept for assessment of perforator arteries of fasciocutaneous and musculocutaneous flaps! How this is possible is the intriguing aspect, and requires some understanding of human biophysiology, particularly as regards our homeostatic mechanisms for maintaining body temperature equilibrium.

Many factors actively influence skin temperature; however, assuming all else is constant, the principal mechanism for heat dissipation is via radiative heat loss from the skin to the environment^[3,4]. The medium used to transport heat throughout the body is blood circulation, thus a good correlation exists between the given skin temperature and the quality of its skin perfusion^[3]. From a basic physics standpoint, what is perceived as heat loss by the body is really infrared radiation whose wavelength falls within the non-visible range (700-1 mm) within the electromagnetic spectrum^[5]. The quantity of infrared radiation that is emitted will be manifested by increments in alterations of the skin temperature observed, and this is directly correlated to variations in the cutaneous blood flow^[5,6].

A thermal imaging camera will be essential for the desired analysis of the given cutaneous infrared emission, and more importantly variations in flap perfusion. Muntean *et al.*^[7] correctly pointed out that professional cameras are superior in their ability to do this, as these can pick-up temperature differences of as little as 0.04 °C that can be modulated by the cardiac rhythm itself^[8]! Such diminutive variations will allow detection of skin “hot spots”, where greater heat is being emitted and most likely via a dominant perforator, as well as the degree of thermal extension into the surrounding vascular network so served, which today we might call the perforasome of that perforator^[3-6,8-10]. Unfortunately, the widespread acquisition of this technology has been hampered by the extreme cost of these cameras.

Fortunately, however, technology has moved on, as today everyone has a smartphone. Incredibly inexpensive miniature thermal imaging cameras [FLIR ONE Pro (FLIR Systems, Inc., Willsonville, Oregon), FLIR.com/FLIRONE/Start] are available for ~ 1/100th the cost of a professional camera, or just a few hundred dollars. This may be plugged into any type of smartphone. Using an app provided by the vendor, rapid real time thermogram still images or videos can be digitally merged with the visible light camera photograph from the smartphone^[11]. Although the smartphone provides a lower resolution image and narrower temperature detection range than the more expensive professional cameras^[10,11], Pereira^[12] insisted that, for applications such as for perforator flaps, the accuracy thus far has proven to be enough.

Because of the lesser sensitivity of the smartphone thermal imaging camera, an initial thermal stress or “cold challenge” not required by the professional cameras will be more informative. This is why dynamic infrared thermography (DIRT) is a preferred adjunct^[3-5,13,14]. DIRT is simplest done preoperatively using Muntean’s method of spraying the proposed flap donor site with isopropyl alcohol followed by accelerated



Figure 1. Preoperative case example. Chronic skin graft breakdown and drainage from medial left lower leg, 20 years following a motorcycle accident that at that time had a failed free flap and then a cross-leg flap (left), thermal stress on left anterolateral thigh donor site induced by isopropyl alcohol spray with fan to accelerate evaporation and cooling (right)

evaporation for cooling with a high speed portable fan^[5]. Intraoperatively, a bag of ice instead can be used. This bedside test requires only a few minutes as the site rewarms using the thermal images observed as a valuable guide for further perforator identification with an audible Doppler probe or color Duplex ultrasound probe, if available.

METHODS

Begin by inserting the thermal imaging camera into the charging port of the smartphone. The vendor-provided thermography app is next selected. When the camera is turned on, a photo or video option may be chosen. With the latter positioned at a standard distance, about 70 cm from the flap itself^[12], images are observed and a thermogram taken as desired.

RESULTS

Preoperative

A thermal stress of the territory selected as the flap donor site is easily achieved by evaporation of an isopropyl alcohol spray accelerated with a portable fan [Figure 1]. A thermogram will confirm that this “cold challenge” is successful as darker colors on the color palette will be seen, implying lower skin temperatures [Figure 2]. During rewarming, “hot spots” appear that can be marked with a pen positioned as part of the thermal image [Figure 3]. These sites so rapidly delineated can then be further evaluated with the ubiquitous audible Doppler or color Duplex ultrasound to confirm the suspected presence of a perforator. A free flap can then be designed in the usual fashion as desired about those identified perforators.

Intraoperative

After the obligatory exploratory incision, if multiple possible perforator choices are found to exist, each in turn can be clamped temporarily with a microvascular clamp [Figure 4], and flap perfusion from each perforator assessed by evaluating the resulting thermogram [Figure 5]. If inadequate, perhaps more



Figure 2. Preoperative: photograph of left thigh thermal image as seen after “cold challenge”. Darker colors correspond to colder temperatures as seen on color bar below

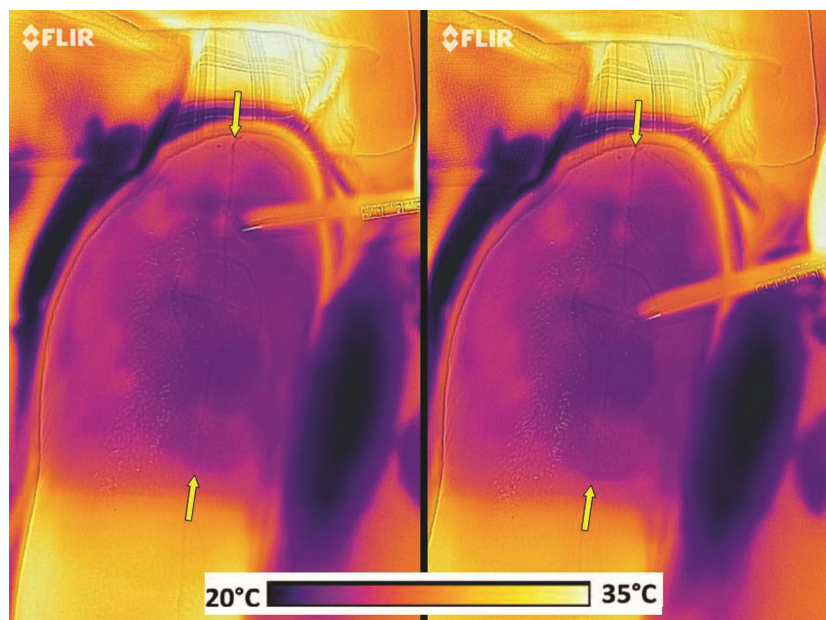


Figure 3. Preoperative: with rewarming, the brightest anterolateral thigh region “hot spot” denoted by marking pin held by assistant is observed proximal to a circle faintly seen drawn about midpoint of line (endpoints marked by yellow arrows) from anterosuperior iliac spine to superior lateral border of patella (left); and second “hot spot” in similar fashion seen more distal at center of that circle (right)

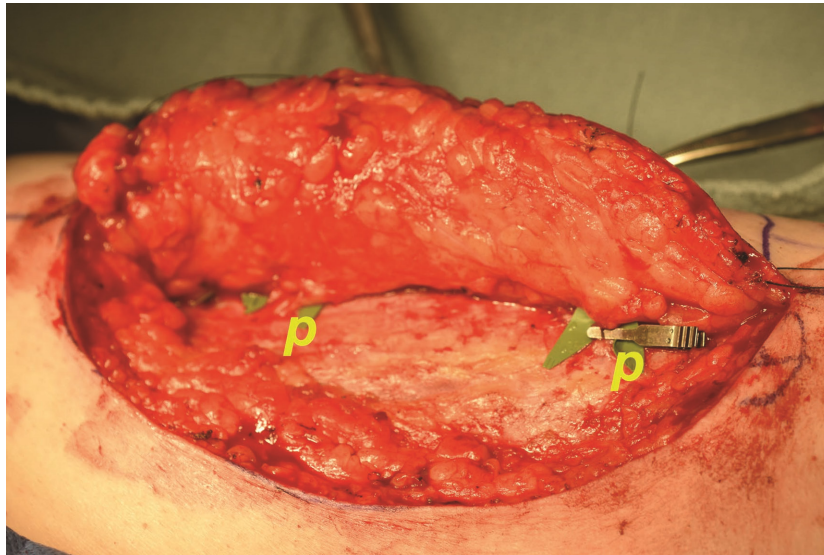


Figure 4. Intraoperative: exploratory incision revealed a perforator (p) exactly at the two sites marked on the thermogram in Figure 3 (proximal thigh at left)

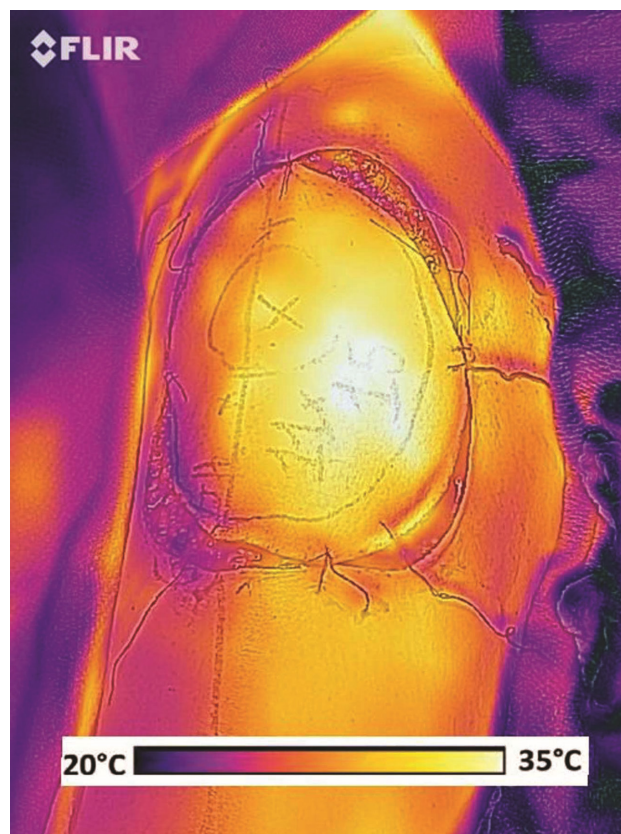


Figure 5. Intraoperative: thermogram with distal perforator clamped as in Figure 4 demonstrated virtually total anterolateral thigh flap perfusion via the proximal perforator alone, thus the second perforator could be discarded

than one perforator will need to be retained. Certainly, if the source pedicle of the flap itself is clamped, although the flap subjectively may appear well perfused, the corresponding thermogram will appropriately appear cool as expected [Figure 6]. Upon completion of the microanastomoses with flap revascularization, the flap should not only have a good appearance, but a correspondingly bright thermogram [Figure 7].

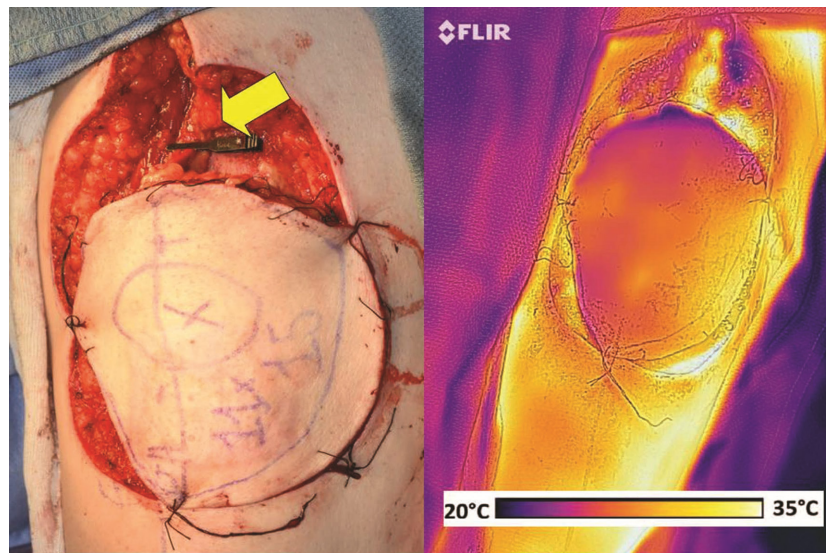


Figure 6. Intraoperative: subjectively, note “normal” appearance of anterolateral thigh flap, yet descending branch of lateral circumflex femoral source pedicle has been clamped (arrow) (left), but, as would be anticipated, the thermogram contradicts the observer’s assessment as the entire flap is cool, since indeed there was no perfusion and so no radiative heat loss (right)

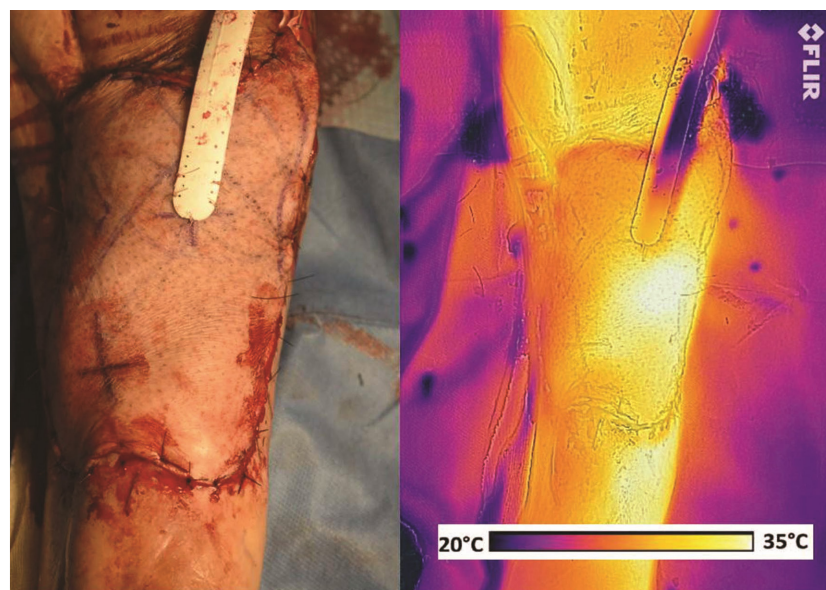


Figure 7. Intraoperative: anterolateral thigh flap inset on left lower leg (left), with thermogram confirming that revascularization was without compromise (right)

Postoperative monitoring

Routine monitoring protocols should always be followed. Maintenance of bright colors implying a warm flap as seen by the thermogram will confirm adequate perfusion and be consistent with satisfactory flow across the microanastomosis [Figure 8]. This, of course, will persist if successful long term [Figure 9].

A baseline thermal image at the time of completion of the procedure should always be available for comparison later while monitoring a free flap [Figure 10]. A change in the thermogram if the observed color is darker implies diminished flow. Venous congestion, with persistent arterial inflow to some degree, will result in a diffusely homogeneous thermogram [Figure 11]. This will be in distinction to a normal

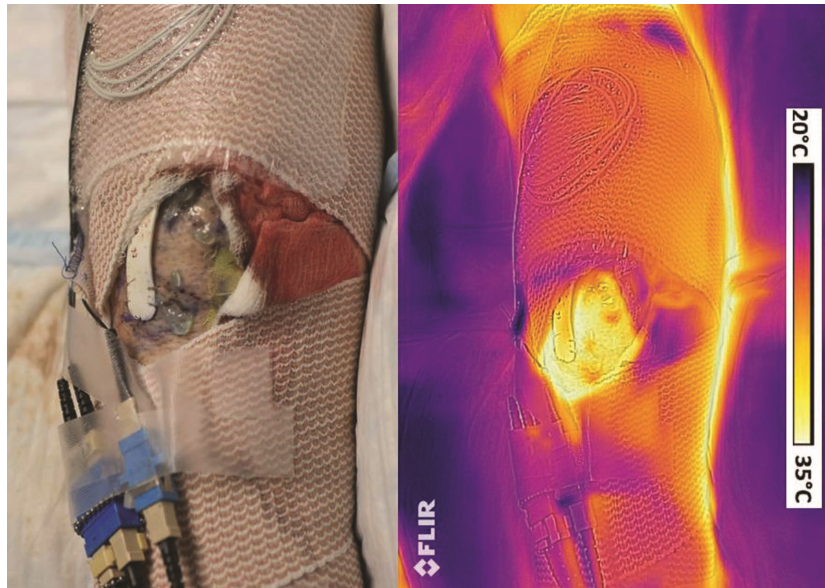


Figure 8. Postoperative monitoring: anterolateral thigh free flap appears satisfactory on inspection in dressing window on POD 2 (left). POD 2 thermogram shows variations of bright color pattern throughout flap, while dressings are dark, implying coolness, as they of course have no perfusion (right). POD: postoperative day



Figure 9. Postoperative monitoring: left leg anterolateral thigh free flap at POD 40 (left), and the POD 40 thermogram confirms flap adequately perfused and even warmer than toes (right). POD: postoperative day

perfusion pattern, as always present subtle differences in flow between encompassed vascular networks will be observed on the thermogram with some color variations throughout the flap [Figure 8]. Lack of inflow will result in a cold flap without any signs of perfusion [Figure 12].

DISCUSSION

Thermal imaging cameras have become incredibly inexpensive, thus, when attached to a smartphone, now anyone can assess free flap donor sites with virtually no learning curve^[6,11]. Following the simple preceding



Figure 10. Postoperative catastrophe: achilles tendon rupture covered with anterolateral thigh free flap had good visual color as seen intraoperatively (top), and intraoperative thermogram confirmed a warm flap with good perfusion comparable to surrounding leg skin (bottom)

guidelines, thermography can assist in the identification of perforators to facilitate the preoperative design of a free perforator flap. A concordance study by Pereira *et al.*^[6] compared preoperative detection of perforators by smartphone thermography with CT angiography, and showed high accuracy with a sensitivity of 100% and specificity of 98%. Recognized traditional imaging techniques for perforator identification in addition to CT angiography^[15] such as magnetic resonance angiography^[16], or color Duplex ultrasound^[17] remain reliable and sound alternatives, but may not be universally available. However, in contrast to thermography, all the aforementioned also may be expensive, perhaps require exposure to contrast media or ionizing radiation, and will be relatively time consuming^[3,17,18]. Certainly, thermography as a complementary procedure, if for no other attribute, can be done quickly to allow more intense focus on “hot spots” for follow-up with the ubiquitous audible Doppler, or perhaps color Duplex ultrasound.

Thermography also offers many insights to provide effective intraoperative management, including what perforators may be satisfactory to retain or what portion of the flap will be expected to be viable. The adequacy of flap perfusion following revascularization or any compromise upon inseting can be determined without the expense or demand for indocyanine green angiography^[19]. Finally, of course, the thermogram provides an additional means for postoperative monitoring. The same smartphone used to make the thermogram can be used to send these pictures wherever needed for corroboration. A thermogram is a near perfect monitor being simple to obtain, non-invasive, and accurate; however, it is not continuous and only semi-objective, as some interpretation of the color palette representing flap temperature is required.

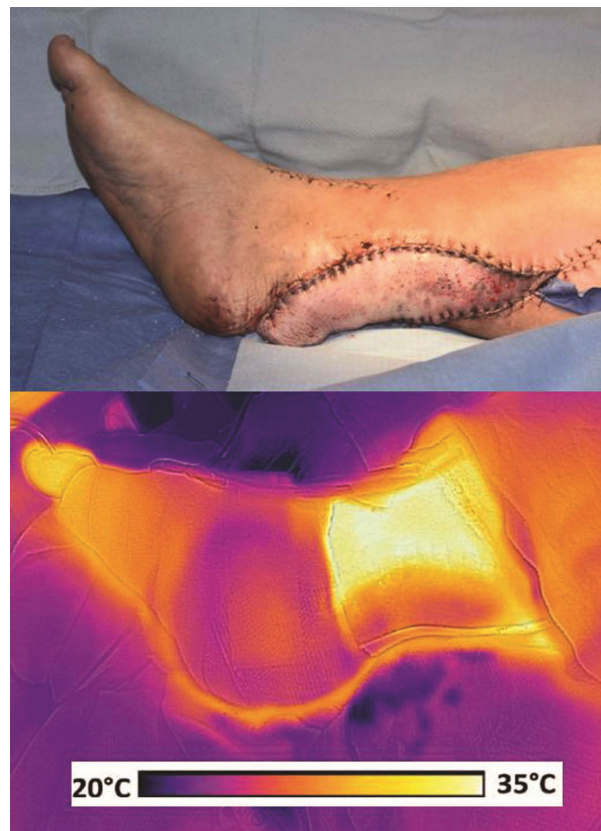


Figure 11. Postoperative catastrophe: violaceous hue of flap POD 1 (top). POD 1 thermogram of flap in dressing window had much darker color diffusely throughout than seen intraoperatively consistent with venous congestion (bottom). POD: postoperative day

Most studies to date using the principles of thermography have centered on detection of perforators of free flap donor sites or monitoring of microvascular tissue transfers^[4,8,13,14,18]. Only two previous reports have used a smartphone for thermography^[6,11], and both for the same purpose as here reviewed in greater detail. There is no reason that the same advantages of thermography cannot also be applied to local perforator flaps as well^[20,21]. Remember Georgescu *et al.*^[22]'s admonition that even local perforator flaps are microsurgical non-microvascular tissue transfers, and should be approached in a similar fashion as are free flaps using whatever resources are available.

An awareness of the limitations of thermal imaging cameras is also important. These can detect only the physiology due to alterations in surface body temperature, which is directly correlated to perforators; however, they cannot distinguish their morphology, thus there will be no recognition of the caliber, origin, or path of that perforator, which, after penetrating the deep fascia, could have an oblique course or diverge into multiple branches to result in multiple “hot spots” from a single perforator before reaching the skin^[5,8]. Professional thermal cameras, being more sensitive than smartphones, are less likely to be misled by any background thermal interference or artifacts such as the presence of cutaneous veins or heat hollows^[8]. In our experience, unlike with the professional thermal cameras, use of a smartphone has required a “cold challenge” to allow a thermal recovery to best determine the significance of “hot spots” in the preoperative detection of donor site perforators^[3,5]. Note also that the smartphone visible light photograph will always be offset slightly from the digital thermogram [Figure 13]^[7]. This must always be accounted for, especially if the exact location of perforators is essential.



Figure 12. Postoperative catastrophe: on re-exploration, venous congestion due to a venous thrombosis could not be reversed, and leech therapy was unsuccessful for flap salvage

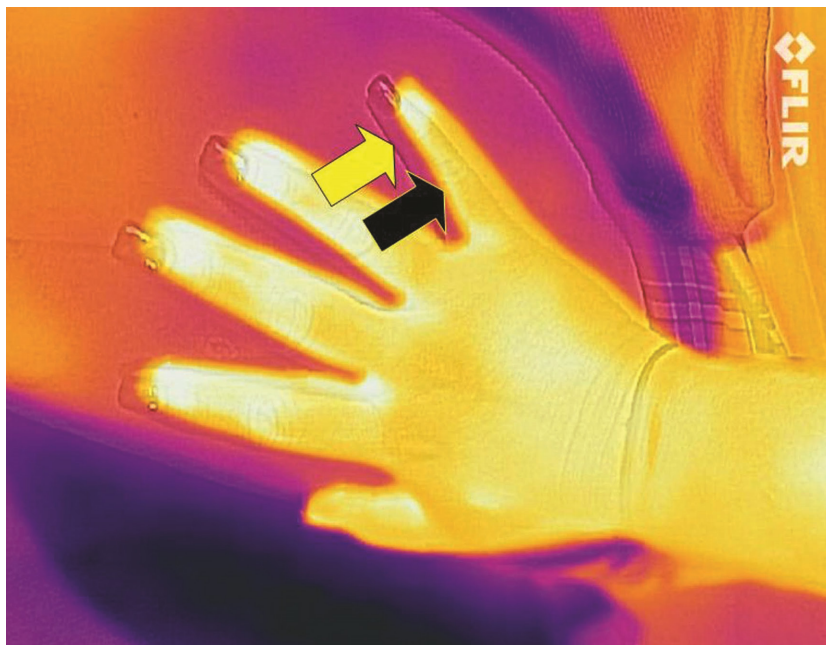


Figure 13. The observed thermal image (black arrow) can be offset from the visible camera image (yellow arrow) as seen here by almost 1 cm

In conclusion, despite the many attributes and plausible detriments enumerated above, the value and the ultimate role of using a smartphone and an inexpensive commercial thermal imaging camera for thermography has yet to be fully determined. Applications will surely not only be for free perforator flaps, but also local perforator flaps, and maybe someday muscle flaps as well. The learning curve is short, thus acquisition of a smartphone and a thermal imaging camera should universally better permit safer free flap designs, provide additional intraoperative management insight, and even be another means for postoperative free flap monitoring. Perhaps with more experience, someday thermography will be more than just a complementary adjunct in the use of perforator flaps in general.

DECLARATIONS

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Authors' contributions

The author contributed solely to the article.

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REFERENCES

- Koerner S, Adams D, Harper SL, Black JM, Langemo DK. Use of thermal imaging to identify deep-tissue pressure injury on admission reduces clinical and financial burdens of hospital-acquired pressure injuries. *Adv Skin Wound Care* 2019;32:312-20.
- Theuvsenet WJ, Koeyers GF, Borghouts MH. Thermographic assessment of perforating arteries: a preoperative screening method for fasciocutaneous and musculocutaneous flaps. *Scand J Plast Reconstr Surg* 1986;20:25-9.
- de Weerd L, Mercer JB, Weum S. Dynamic infrared thermography. *Clin Plast Surg* 2011;38:277-92.
- de Weerd L, Weum S, Mercer JB. The value of dynamic infrared thermography (DIRT) in perforator selection and planning of free DIEP flaps. *Ann Plast Surg* 2009;63:274-9.
- Muntean MV, Strilciuc S, Ardelean F, Georgescu AV. Dynamic infrared mapping of cutaneous perforators. *J Xiangya Med* 2018;3:16.
- Pereira N, Valenzuela D, Mangelsdorff G, Kufeke M, Roa R. Detection of perforators for free flap planning using smartphone thermal imaging: a concordance study with computed tomographic angiography in 120 perforators. *Plast Reconstr Surg* 2018;141:787-92.
- Muntean MV, Achimas-Cadariu PA. Detection of perforators for free flap planning using smartphone thermal imaging: a concordance study with computed tomographic angiography in 120 perforators. *Plast Reconstr Surg* 2018;142:604e.
- Tenorio X, Mahajan AL, Elias B, van Riepmst JS, Wettstein, et al. Locating perforator vessels by dynamic infrared imaging and flow doppler with no thermal cold challenge. *Ann Plast Surg* 2011;67:143-6.
- Saint Cyr M, Wong C, Schaverien M, Mojallal A, Rohrich RJ. The perforasome theory: vascular anatomy and clinical applications. *Plast Reconstr Surg* 2009;124:1529-44.
- Sheena Y, Jennison T, Hardwicke JT, Tittley OG. Detection of perforators using thermal imaging. *Plast Reconstr Surg* 2013;132:1603-10.
- Hardwicke JT, Osmani O, Skillman JM. Detection of perforators using smartphone thermal imaging. *Plast Reconstr Surg* 2016;137:39-41.
- Pereira N. Reply: detection of perforators for free flap planning using smartphone thermal imaging: a concordance study with computed tomographic angiography in 120 perforators. *Plast Reconstr Surg* 2018;142:605e.
- de Weerd L, Mercer JB, Setsá LB. Intraoperative dynamic infrared thermography and free-flap surgery. *Ann Plast Surg* 2006;57:279-84.
- Itoh Y, Arai K. Use of recovery-enhanced thermography to localize cutaneous perforators. *Ann Plast Surg* 1995;34:507-11.
- Masia J, Kosutic D, Clavero D, Larrañaga J, Vives L, et al. Preoperative computed tomographic angiogram for deep inferior epigastric artery perforator flap breast reconstruction. *J Reconstr Microsurg* 2010;26:21-8.
- Masia J, Kosutic D, Cervelli D, Clavero JA, Monill JM, et al. In search of the ideal method in perforator mapping: noncontrast magnetic resonance imaging. *J Reconstr Microsurg* 2010;26:29-35.
- Hallock GG. Doppler sonography and color duplex imaging for planning a perforator flap. *Clin Plast Surg* 2003;30:347-57.

18. Chubb D, Rozen WM, Whitaker IS, Ashton MW. Digital thermographic photography (“thermal imaging”) for preoperative perforator mapping. *Ann Plast Surg* 2011;66:324-5.
19. Holm C, Tegeler J, Mayr M, Becker A, Pfeiffer UJ, et al. Monitoring free flaps using laser-induced fluorescence of indocyanine green: a preliminary experience. *Microsurgery* 2002;22:278-87.
20. Muntean MV, Ardelean F, Strilciuc S, Pestean C, Georgescu AV, et al. Flap warming improves intraoperative indocyanine green angiography (ICGA) assessment of perfusion. an experimental study. *J Plast Reconstr Aesthet Surg* 2019;72:1150-6.
21. Pereira N, Hallock GG. SmartPhone thermagraphy for lower extremity local flap perforator mapping. *J Reconstr Microsurg* 2020;pub pend.
22. Georgescu AV, Matei I, Ardelean F, Capota I. Microsurgical non-microvascular flaps in forearm and hand reconstruction. *Microsurgery* 2007;27:384-94.

Review

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Progressive trends in timing and imaging of lower extremity reconstruction

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Abstract

The salvage of mangled lower-extremities after severe injury remains a daunting operative dilemma, but one that continues to evolve with advances in microsurgical and orthopedic techniques. Specifically, trends in clinical practice including the decision to salvage and timing of soft-tissue coverage are changing in concordance with improvements in wound care, flap selection for soft-tissue provision, and preoperative imaging. Due to these improvements, more complex wounds are increasingly eligible for reconstruction. It remains unclear, however, whether success in limb salvage confers improved functional patient outcomes. We present a review of the literature tracing recent advances in the salvage of mangled extremities following traumatic injury, with a focus on practice trends regarding timing of reconstruction, operative approaches, and preoperative imaging.

Keywords: Lower extremity, reconstruction, propeller flaps, amputation, microsurgery, trauma

INTRODUCTION

Complex high-energy trauma to the lower extremity often entails significant and devastating morbidity for patients. Lower extremity injury accounts for greater than 250,000 hospital admissions each year in the US; more than half involve open long-bone fractures, crush, or major soft-tissue injury^[1]. Return of function can be an arduous process requiring multidisciplinary care and ongoing therapy for months to years. Plastic surgeons involved in the care of these patients should be well versed in the unique demands required



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by reconstruction of these complex anatomic and functional deficits. Clinical decision-making should be guided by our developing understanding of tissue physiology, orthopedic reconstructive principles, and developing technology used to guide preoperative planning and intraoperative decision making. When effective, limb reconstruction can confer a close approximation of pre-morbid functionality. However, the calculus of when, how, and on whom to intervene remains incompletely defined and often plagued by equivocation. Fortunately, the tools used to assess the severity and distribution of injury, including expanding use of novel imaging techniques, as well as refinement of reconstructive approaches continue to develop. This review focuses on the advances made regarding approaches in surgical management and perioperative assessment of complex lower-extremity injuries. Advances in orthopedic fixation, as well as advances in the provision of soft-tissue reconstruction, guided by long-standing principles of surgical management continue to drive the functional, aesthetic, and patient-centered outcomes conferred by limb-salvage.

INITIAL ASSESSMENT AND DECISION TO PROCEED WITH LIMB SALVAGE

The inclination to salvage a mangled extremity, by any means necessary, is an understandable reflex for patients and physicians alike. This inclination, however, belies the utility of amputation in restoring functionality of patients. Data from the landmark, Lower Extremity Assessment Project (LEAP) group, published in 2002, provide the most thorough analysis to date of lower extremity trauma treatment and outcomes, including demographic data of the civilian population who suffer these injuries as well as their ultimate functional status and variables surrounding their recovery^[2]. The study found comparable functional outcomes among individuals who had undergone reconstruction versus those who had undergone amputation. Roughly one half of all patients followed for the duration of the study exhibited significant disability as objectively assessed by the Sickness Impact Profile score. The sobering conclusion gleaned from this multi-center study was that reconstruction conferred no functional benefit when compared with amputation, and outcomes from both groups were poor; little more than 30% of patients exhibited return to functionality compared with uninjured age-matched counterparts, and fewer than 60% of patients had returned to work at seven years post-injury. These conclusions, however, should be weighed critically, as subsequent analyses highlight the impact of socioeconomic factors, as opposed to treatment course, as predictors of ultimate outcomes^[3,4]. It should be emphasized that the LEAP trial focused on civilian patients. Much of the literature regarding advances in lower extremity reconstruction following high-energy trauma has been gleaned from the arena of combat. As such, treatment guidelines taken from one patient population, while informing of the other, cannot be translated without qualification, given distinct mechanisms of injury, concurrent trauma/injury, treatment setting, *etc.*^[5]. Despite the multitude of wound assessment and grading scales (discussed in more detail below), there remain no hard and fast rules regarding when a severely damaged limb should be amputated [Figure 1]. Despite previous orthodoxy, damage to posterior tibial nerve, and an insensate foot are no longer absolute contra-indications for limb salvage^[6,7]. Instead, reconstruction should be evaluated and approached on a case by case basis and must be in line with the ultimate goals of the patient.

ASSESSMENT OF INJURY AND PROGNOSIS OF RECONSTRUCTION

Multiple validated grading scales exist for the purposes of assessing extremities following traumatic injury and attempt to guide treatment accordingly. Unfortunately, all have demonstrated limited utility when applied in the clinical setting, and there remains no gold standard of a translatable universally applicable injury assessment tool. Nevertheless, the injury assessment scales, including the Mangled Extremity Severity Score^[7], Predictive Salvage Index^[8], Limb Salvage Index^[9], and the Nerve Injury, Ischemia, Soft Tissue Injury, Skeletal Injury, Shock, and Age of the Patient^[10] score, provide an objective and structured assessment of complex injuries. Each purportedly identifies unique variables predictive of ultimate amputation, including level of arterial injury, timing from injury to index operation, volume of soft tissue

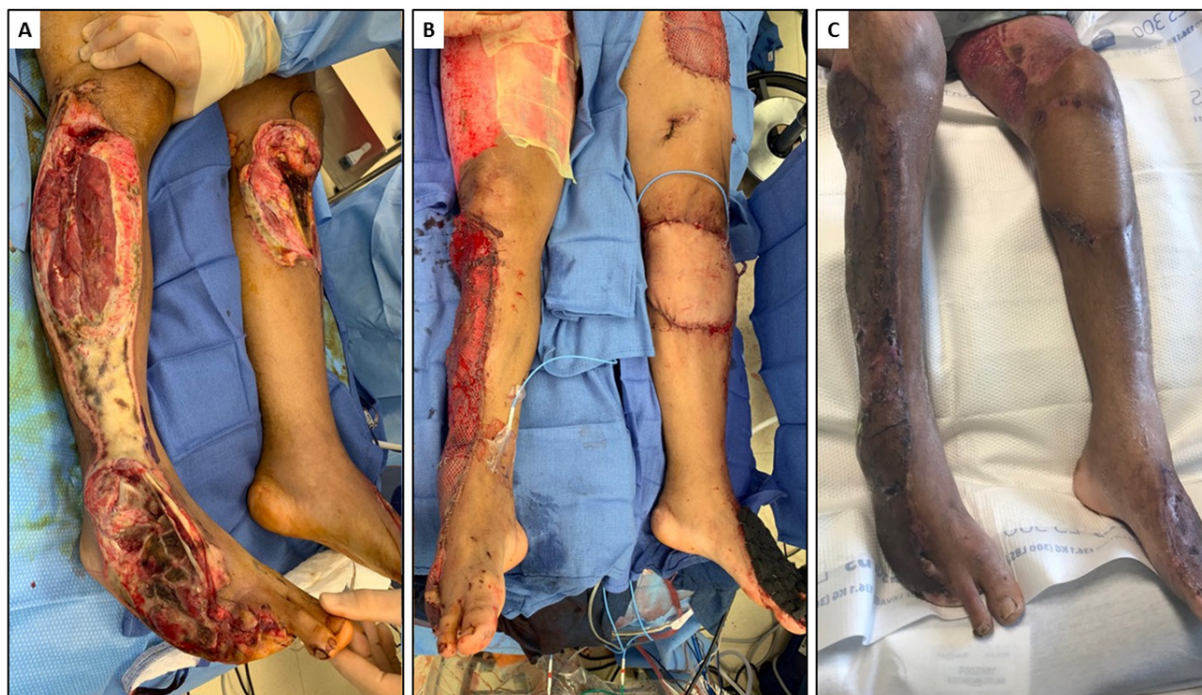


Figure 1. A: adult male struck by motor vehicle. Resulting degloving injuries included exposure of right femoral head, visible peroneal nerve, exposure of right metatarsals, and exposure of left proximal tibia; B: immediate reconstruction with lateral gastrocnemius pedicled flap with STSG to proximal right leg, free rectus abdominus flap with STSG to dorsal right foot, and free anterolateral thigh flap to proximal left leg. Dorsal left foot covered with integra, and subsequently skin grafted; C: patient six weeks after initial reconstruction. STSG: split thickness skin graft

lost, *etc.*, which are ostensibly essential in the characterization of the injury. However, using a dataset of over 500 patients with lower extremity trauma, Bosse *et al.*^[11] prospectively analyzed seven commonly used injury severity scales and found these scales to have limited utility in predicting amputation versus salvage. Each of these scales demonstrated adequate sensitivity, but limited specificity, in which low scores were concordant with salvage potential, but increasing values provided no indication regarding the likelihood of amputation in injuries thought to be more severe. This work serves to cement the salience of individualized assessment and care tailored to the unique circumstances of the patient.

The Gustilo-Anderson classification of open fractures remains a relevant and commonly used assessment tool, to grade open fractures in the setting of lower extremity injury. The classification system, and subsequent modification subdivide severity of injury into three categories, each with ascending level with increasing involvement of soft-tissue, and ultimate vascular injury^[12,13]. This classification system, however, was devised to assess risk of subsequent infection and does not aim to predict likelihood of amputation. Nonetheless, the Gustilo classification is an effective scale with demonstrated intra-observer reproducibility^[14].

The determinants of a patient's prognosis following reconstruction are multiple, varied, and not solely dependent on the wound itself, timing of reconstructions, or approach to treatment; as observed in the LEAP trial, most independent risk factors for poor functional outcomes and amputation include socioeconomic circumstance of the patient's and not the treatment plan initially employed^[3]. Again, the decision to proceed with reconstruction versus amputation is dependent on the gestalt of the patient and injury. Patients must not only overcome modifiable risk factors, and pathophysiologic sequelae of systemic disease; public perception and stigma regarding amputation continue to complicate the personal decision of whether to proceed with amputation, as well as the support network of the patient during their recovery^[15].

TIMING OF RECONSTRUCTION

Historically, surgeons have advocated for prompt soft-tissue coverage of lower-extremity defects following trauma^[16,17]. In his landmark study in 1986, Godina demonstrated improved rates of flap loss, infection, and length of hospital stay with soft-tissue coverage provided within the first 72-h of injury^[16]. Three days remains the benchmark goal for acute reconstruction. Indeed, despite a trend towards a more permissive timeline of soft-tissue coverage, recent analyses corroborate improved free-flap failure rates and reduced rates of infection with immediate reconstruction within the 72-h window, although these statistical analyses remain dependent on Godina's index cohort of over 500 patients, to date the most prolific of studies analyzed^[18]. Obviously, surgeons strive for prompt bony stabilization and soft-tissue coverage as soon as logistically possible; however, clinical reality and the presence of concomitant injury to vital organ systems often preclude definitive reconstruction in the acute setting. Facilitated by advances in wound care, this critical window has since been liberalized in the setting of recent studies demonstrating noninferior outcomes with reconstruction in the subacute and chronic phases of injury following serial debridement without compromise of flap survival rates or patient function^[17,19-25]. This trend has accelerated over the previous decade: the mean timing of definitive reconstruction has progressed from 6 to 12.5 days in the decade from 2002 to 2011^[26]. This trend also reflects the prioritization of adequate wound debridement to ensure adequate preparation of the recipient wound bed. As demonstrated by Karanas *et al.*^[20], definitive soft-tissue coverage should allow for serial debridement to minimize the risk of catastrophic deep-space, or bony infection, even if this process delays reconstruction outside of the acute window. Data from the armed combat literature also underlie the importance of ensuring a clean and adequately debrided wound bed^[27]. Pollak *et al.*^[27] found that time to initial operative debridement was not an independent risk factor for the risk of infection following high-energy low-extremity trauma; however, prompt admission to definitive trauma treatment center was protective, suggesting prompt global patient management and wound care is essential to favorable reconstructive outcomes.

Perhaps more than any other therapeutic advancement, the widespread use of negative pressure wound therapy (NPWT) has proven essential for the temporization of definitive reconstruction^[22,24,28]. Multiple hypotheses exist as to why the physiologic advantages of NPWT have facilitated the optimization of wound care including providing ideal wound healing environment via minimization of edema, reducing surface area of the wound, and providing reduced capillary afterload translating to increased perfusion of nascent granulation tissue^[29,30]. Indeed, the physiological benefits attributed to NPWT are felt to oppose the effects of tissue fibrosis, inflammation, and edema thought to potentially threaten microvascular anastomoses driving the emphasis of early reconstruction. The use of NPWT has extended the critical time to definitive soft-tissue coverage to as far out as weeks to months from the initial injury, with numerous studies documenting comparable rates of flap loss, infection, and hospital stay following soft tissue coverage. In fact, certain cohorts report improved outcomes approaching significance of chronically reconstructed wounds compared with more acute reconstruction, lending further credence to temporization of reconstruction outside of the acute window^[24]. As initially observed by Steiert *et al.*^[22], increasingly permissive time to definitive coverage appears concordant with the increasing complexity of the wounds being reconstructed, which helps to better understand the deviation from the 72-h orthodoxy. To be clear, when feasible, recent data still corroborate improved outcomes with earlier reconstruction. The work of Liu *et al.*^[23] demonstrated that, while delay to definitive reconstruction past seven days conferred increased risk for osteomyelitis and potential flap complications, NPWT was protective against reoperation and venous thrombosis in those populations unable to undergo acute reconstruction. Taken together, prompt reconstruction should remain the operative goal, but timing should involve nuanced considerations of the patient and injury, as excellent outcomes remain feasible long after the previously espoused 72-h window^[31]. Unfortunately, operative considerations are not the only determinants of timing to reconstruction; the work of Shammas *et al.*^[32] identified a number of sociodemographic risk factors, including older age, nonwhite race, and geographic region for delays to soft tissue coverage. Acute reconstruction should not

be performed at the expense of patient and wound optimization, as definitive soft-tissue coverage in the subacute, and chronic intervals have been demonstrated to be safe and effective.

Soft tissue coverage is similarly dependent on the integrity of bony fixation to provide adequate tension across joints for preservation of locomotion, and to prevent collapse of soft-tissues. Fortunately, the science and practice of orthopedic reduction and fixation has developed in parallel with microsurgical techniques. Amongst the most challenging operative dilemmas from orthopedic injury is the management of resulting segmental defects. Multiple surgical strategies exist and remain used in clinical practice to restore bony length and adequate union following traumatic bone loss or defects resulting from debridement. Techniques including distraction osteogenesis (Ilizarov Technique), autologous bone grafting, and mesh implants have demonstrated adequate results regarding ultimate restoration of bone length and stability^[33-35]. More recently, the Masquelet technique has emerged as a novel and reliable strategy for the purposes of restoration of bone defects^[36]. Initially described in results published in 2000, the strategy utilizes staged operations to induce a periosteum surrogate, “Inflammatory Membrane”, around a cement spacer, which is subsequently replaced with autologous bone graft^[37,38]. Amongst multiple retrospective studies, clinical success rates have been reported in up to 89%-93% of cases, despite bony defects greater than 10 cm^[39,40]. Despite the paucity of long-term functional outcomes, the technique has gained clinical traction, and has been used increasingly in concert with advances in provision of soft-tissue coverage for the purposes of lower extremity reconstruction.

OPERATIVE CONSIDERATIONS OF RECONSTRUCTION

Once the degree of injury has been appropriately assessed, the decision to proceed with reconstruction has been made, and the stability of the wound bed has been assured, considerations regarding the appropriate tissue to be transplanted must be made. General principles regarding the distribution of injury and corresponding donor site of soft-tissue coverage remain applicable and continue to guide surgical management. The tenets of the reconstructive ladder remain applicable when reconstructing lower extremity injuries. Often, despite significant fractures, local muscle flap coverage and skin grafting provide excellent results. However, given unique challenges posed at certain areas, namely around the knee and proximal tibia, as well as the distal leg, ankle, and foot, surgeons are increasingly utilizing more complex solutions, as espoused by the “reconstructive elevator” paradigm. As conceived and popularized by Gottlieb and Krieger^[41], the reconstructive elevator argues for skipping over simpler solutions in favor of a reconstructive approach that more accurately approximates the functional and anatomic deficits of the injury. For instance, given the paucity of tissue, and resulting exposure of bony and articulating surfaces, free-flap reconstruction has become the default surgical option for injuries of the distal lower extremity.

While certain micro-surgical principles have remained unchallenged, recent data have led to the liberalization of other reconstructive dogmas held by many practicing surgeons. The requirement of a clean wound bed for recipient tissue remains an immutable tenet of reconstruction. The translation of autologous tissue should only occur in a clean wound-bed free of necrotic or infected tissue, and preferably over appropriately reduced bony framework. In contrast, discussion regarding the selection of autologous tissue to be harvested as well as the selection of recipient vasculature continues to evolve. Recently, a trend towards the use of perforator fasciocutaneous flaps has proportionately displaced the use of bulkier myofasciocutaneous free-flaps^[42]. Improved understanding of perfasomes, and increasing facility with perforator dissection have resulted in the wide-spread adoption of using fasciocutaneous flaps for extremity reconstruction^[42,43]. Despite concerns that the use of fasciocutaneous flaps preclude the superior blood supply conferred by transferred muscle, these flaps are no more prone to ischemia and flap failure. Similarly, fasciocutaneous flaps are resistant to shear and breakdown in weight bearing areas when compared with muscle containing flaps^[44]. That being said, multiple “work-horse” flaps provide appropriate

tissue qualities for corresponding defects: the latissimus dorsi flap provides significant tissue bulk for large tissue deficits, the neurotized gracilis flap provides potential for restoration of active motion, *etc.* In a span of 30 years, microsurgical flaps have become common practice in lower extremity reconstruction. There remains a disproportionately high rate of complications of free-flaps in microsurgical reconstruction, with a 14% rate of major complications cited in a retrospective review of over 400 injuries. Independent risk factors for flap compromise include prolonged operative time, preoperative anemia, steroid use, and diabetes^[45].

Other considerations, including selection of recipient vessels, remain of paramount importance. Clinical orthodoxy favors selection of vessels proximal to the site of injury, given progressive decrease in size of available source vessels more distal in the leg. However, this orthodoxy has recently been challenged by select institutions, as selection of recipient vessels distal to the site of injury was recently demonstrated to be non-inferior in a retrospective review of 312 free-tissue transfers for soft-tissue reconstructions of open tibial fractures^[46]. This remains a point of contention, but feasibility provides an alternative in the event of complication precluding more proximal access.

A common paradigm in the reconstruction of lower extremity remains the anatomic subdivision of the leg into thirds: proximal, middle, and distal. The distal third provides unique reconstructive challenges due to paucity of local tissue available for local tissue rearrangement, and superficial distribution of structures requiring coverage. As such, the distal third of the leg manifests the opportunity to put the principles of the “reconstructive elevator”, into practice, yet remains plagued by higher rates of complications^[47]. Free-flaps remain the preferred option for reconstruction of substantial deficits in this region. However, comparison of free-flap coverage demonstrates increase rates of free-flap loss, and complications at the distal third of lower extremity injuries, when compared to more proximal leg injuries^[47,48]. The use of propeller flaps has arisen as a viable option for soft-tissue coverage when free-tissue transfer is contraindicated, or simply not feasible^[49] [Figure 2]. Propeller flaps provide substantial soft-tissue for coverage of essential structures via improved understanding of perfosome distribution without need for microanastomosis in precarious anatomic regions. Historically, perforator flaps had been thought to require thick cuffs of subcutaneous tissue to protect the pedicle from kinking, thereby restricting the arc of rotation, and often resulted in dog-ears at the axis of rotation. As understanding of perfasomes has advanced, including the course and distribution of these short branching vessels, local pedicled flaps have been used with increasing regularity for lower extremity reconstruction^[43,50]. Particularly in the distal third of the lower extremity, multiple local flaps including the reverse sural fasciocutaneous flaps can be used with regularity to reconstruct complex defects, and can be staged as delayed flaps without any question of tissue viability^[51,52]. More proximally, muscle flaps, such as the anterior tibial and soleus flaps, can be translated to cover bony defects following trauma, further establishing the role of local pedicled flaps in soft-tissue reconstruction of the lower extremity.

ADVANCES REGARDING IMAGING TECHNOLOGY TO ASSESS LOWER EXTREMITY INJURY

Imaging in the setting of complex injury can be used to not only evaluate the viability of limb salvage, but also to orient eventual reconstruction via the identification, localization, and qualitative assessment of potential recipient vessels for purposes of microvascular reconstruction. Hard signs of ischemia, including hemorrhage, expanding hematoma, and absent distal pulses, are sufficient to prompt operative intervention to ensure continued perfusion of the distal extremity; in the absence of obvious signs, however, modalities used for assessment of vascular injury remain variable and institution dependent.

The “gold standard” of evaluating vascular injury remains arteriography, but this modality is limited by persistent rates of iatrogenic injury, commonly cited at 1%-5%, as well as increased timing of

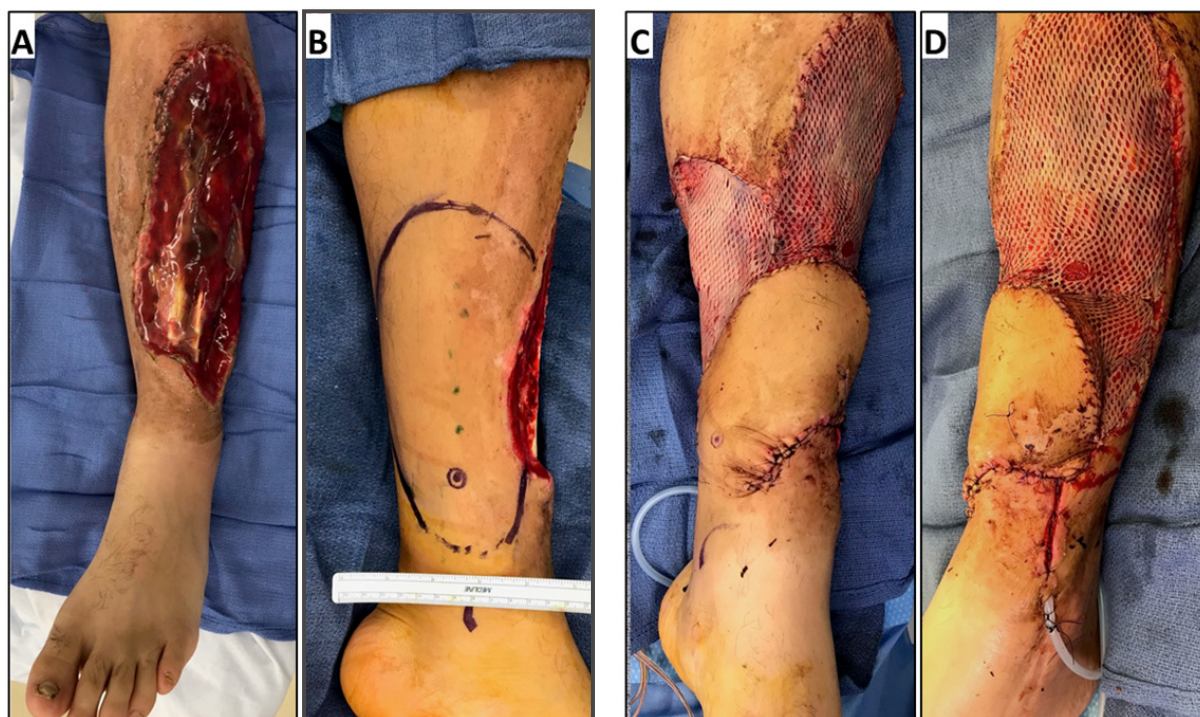


Figure 2. A: adult male following degloving injury to left lower extremity; B: preoperative marking for posterior tibial artery perforator propeller flap; C: immediate postoperative result, medial view; D: immediate postoperative result, lateral view

performance and cost to the hospital system^[53,54]. Since its introduction in clinical practice in the early 1990s, computed tomographic angiography (CTA) has become the de-facto diagnostic modality of choice to assess vascular injury in the setting of lower-extremity trauma^[55]. Due to a more favorable side-effect profile, as well as imaging resolution comparable to that of angiography, CTA has begun to replace arteriography as the preferred diagnostic modality to evaluate vascular injury^[56,57]. Despite the obvious advantage of predisposing patient's to less ionizing radiation and the avoidance of complications such as pseudoaneurysm, vessel thrombosis, and vessel injury, the routine use of CTA has long been continuously debated but has gained routine acceptance in clinical practice^[58]. While CT imaging may demonstrate vascular injury, and patency of residual vessels, this modality does little to evaluate flow in potential donor vessels to sustain microvascular reconstruction in the setting of collateral flow. Furthermore, the sensitivity of CTA is limited in the identification of vasospasm and local injury^[59]. For these reasons, many institutions continue to rely on arteriography for preoperative imaging and planning. In individuals whose renal function preclude administration of iodinated dyes, carbon dioxide angiography remains a viable and underutilized imaging modality^[60,61]. Compared with iodinated contrast, CO₂ angiography decreases the incidence of acute kidney injury from 11.1% to 4.7%. As such, CO₂ angiography may provide valuable diagnostic data in populations unable to receive large contrast loads secondary to compromised renal function or adverse reactions to iodinated contrast.

When microvascular reconstruction is required, recipient vessel selection outside the zone of injury is of paramount importance, made more so by the limitations conferred by the associated injury. Some institutions argue for the continued utility of obtaining formal arteriography, but primarily in the setting of chronic lower extremity wounds, as these studies may demonstrate previously unrecognized vascular pathology and allow for prompt endovascular intervention facilitating ultimate reconstruction^[62]. Others argue that any diagnostic imaging in the setting of trauma is superfluous, as thorough clinical examination and intraoperative adaptation are sufficient to conduct soft-tissue reconstruction^[63].

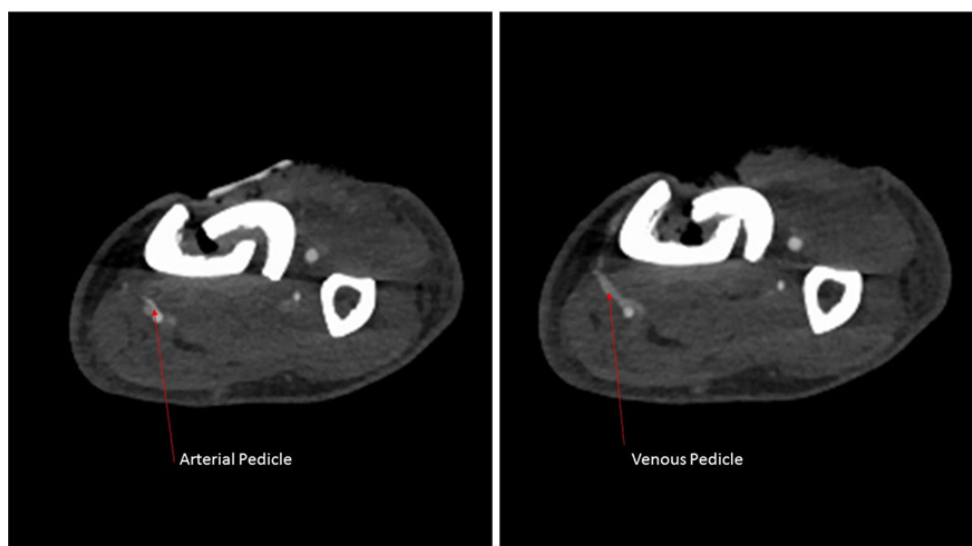


Figure 3. Computed tomographic angiography imaging of traumatized extremity with identification of potential recipient vessel prior to planned perforator flap for anterior tibial soft tissue

However, preoperative vessel imaging remains common practice in the traumatic setting. Similar to the evolution of imaging for the purposes of injury identification, vessel selection has evolved from the transition from angiography to CTA over the previous decade^[64,65]. For the purposes of free-flap planning, Duymaz *et al.*^[66] were able to demonstrate the utility of obtaining lower extremity CTAs in correlating arterial injury with eventual flap loss, although no direct comparisons were made to preoperative angiography. As previously mentioned, routine use of CTA provides excellent assessment of lower-extremity anatomy without the associated co-morbidities of formal angiography [Figure 3].

Development of ancillary imaging modalities to assess perforator vessel for preoperative planning continues to evolve. Recent work by Feng *et al.*^[67] suggests the use of color doppler ultrasound demonstrates greater fidelity of identifying and localizing dominant perforators of lower extremity flap when compared to CTA in a head-to-head comparison. The use of Indocyanine green (ICG) has also emerged as an adjunctive imaging modality to assess the microvasculature of perforator and local tissue flaps in microsurgical reconstruction. ICG is a cyanine dye with near-infrared spectral absorbance that binds circulating plasma proteins. As such, ICG in concert with near infrared imaging has been used across multiple medical disciplines for the purposes of vascular and lymph perfusion imaging. In the field of plastic surgery, ICG has been used with increasing frequency for the purposes of local, perforator, and free-flap perfusion distribution. Most published studies to date use ICG to assess viability of skin flaps of the trunk, head, and neck^[68-70]. The technology was recently demonstrated, albeit in a limited series of 23 patients, to significantly improve complication rates of tissue necrosis and deep-space infection in patients with Gustilo Type IIIB when used as an adjunct to guide initial debridement^[71]. While its use has yet to be routinely adopted, ICG has proven a reliable adjunct available to clinicians to assess tissue perfusion in the operating room.

CONCLUSION

Advances in microsurgical techniques, the advent of negative pressure wound technology in temporizing wound care, and improvements in preoperative imaging have facilitated changing treatment practices in the reconstruction of traumatic lower extremity injuries over the previous two decades. Despite persistent challenges, as evidenced by high rates of postoperative infection, flap loss, and poor functional recovery,

reconstruction has become increasingly available for injuries previously thought to be unsalvageable. The pre-existing dogma advocating for immediate soft-tissue reconstruction within a 72-h window has since been liberalized in the setting of improved wound-care, the widespread use of negative pressure wound therapy, and the advent of damage-control orthopedic surgery, allowing reconstruction of increasingly complex injuries in severely sick patients. The improved understanding of perfosomes and refinement of microsurgical technique have facilitated the paradigm of the reconstructive elevator to more closely approximate pre-morbid anatomy and function. The use of ancillary imaging including CTA, angiography, and doppler ultrasound has refined the identification and characterization of recipient vessels for free-tissue transfers. As technological advances continue to augment preoperative assessment, routine wound care, and intraoperative planning, reconstruction will continue to more closely approximate pre-injury functionality, improving patient outcomes and satisfaction.

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Authors' contributions

Share conceptualization and authorship of this review: Zhang AY, Cholok D, Lee GK
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REFERENCES

1. 2012 National Trauma Data Bank Annual Report (2012:146;table 29 page 65). Available from: <https://www.facs.org/-/media/files/quality-programs/trauma/ntdb/ntdb-annual-report-2012.ashx> [Last accessed on 13 Dec 2019].
2. Bosse MJ, MacKenzie EJ, Kellam JF, Burgess AR, Webb LX, et al. An analysis of outcomes of reconstruction or amputation after leg-threatening injuries. *N Engl J Med* 2002;347:1924-31.
3. MacKenzie EJ, Bosse MJ, Kellam JF, Pollak AN, Webb LX, et al. Early predictors of long-term work disability after major limb trauma. *J Trauma* 2006;61:688-94.
4. Higgins TF, Klatt JB, Beals TC. Lower Extremity Assessment Project (LEAP) - the best available evidence on limb-threatening lower extremity trauma. *Orthop Clin North Am* 2010;41:233-9.
5. Baechler MF, Groth AT, Nesti LJ, Martin BD. Soft tissue management of war wounds to the foot and ankle. *Foot Ankle Clin* 2010;15:113-38.
6. Momoh AO, Kumaran S, Lyons D, Venkatramani H, Ramkumar S, et al. An argument for salvage in severe lower extremity trauma with posterior tibial nerve injury: the ganga hospital experience. *Plast Reconstr Surg* 2015;136:1337-52.
7. Helfet DL, Howey T, Sanders R, Johansen K. Limb salvage versus amputation. Preliminary results of the Mangled Extremity Severity Score. *Clin Orthop Relat Res* 1990;80-6.
8. Howe HR, Poole GV, Hansen KJ, Clark T, Plonk GW, et al. Salvage of lower extremities following combined orthopedic and vascular

- trauma. A predictive salvage index. *Am Surg* 1987;53:205-8.
9. Russell WL, Sailors DM, Whittle TB, Fisher DF, Burns RP. Limb salvage versus traumatic amputation. A decision based on a seven-part predictive index. *Ann Surg* 1991;213:473-80; discussion 480-1.
10. McNamara MG, Heckman JD, Corley FG. Severe open fractures of the lower extremity: a retrospective evaluation of the Mangled Extremity Severity Score (MESS). *J Orthop Trauma* 1994;8:81-7.
11. Bosse MJ, MacKenzie EJ, Kellam JF, Burgess AR, Webb LX, et al. A prospective evaluation of the clinical utility of the lower-extremity injury-severity scores. *J Bone Joint Surg Am* 2001;83:3-14.
12. Gustilo RB, Anderson JT. Prevention of infection in the treatment of one thousand and twenty-five open fractures of long bones: retrospective and prospective analyses. *J Bone Joint Surg Am* 1976;58:453-8.
13. Gustilo RB, Mendoza RM, Williams DN. Problems in the management of type III (severe) open fractures: a new classification of type III open fractures. *J Trauma* 1984;24:742-6.
14. Brumback RJ, Jones AL. Interobserver agreement in the classification of open fractures of the tibia. The results of a survey of two hundred and forty-five orthopaedic surgeons. *J Bone Joint Surg Am* 1994;76:1162-6.
15. MacKenzie EJ, Bosse MJ, Kellam JF, Burgess AR, Webb LX, et al. Factors influencing the decision to amputate or reconstruct after high-energy lower extremity trauma. *J Trauma* 2002;52:641-9.
16. Godina M. Early microsurgical reconstruction of complex trauma of the extremities. *Plast Reconstr Surg* 1986;78:285-92.
17. Byrd HS, Spicer TE, Cierney G. Management of open tibial fractures. *Plast Reconstr Surg* 1985;76:719-30.
18. Qiu E, Kurlander DE, Ghaznavi AM. Godina revisited: a systematic review of traumatic lower extremity wound reconstruction timing. *J Plast Surg Hand Surg* 2018;52:259-64.
19. Francel TJ, Vander Kolk CA, Hoopes JE, Manson PN, Yaremchuk MJ. Microvascular soft-tissue transplantation for reconstruction of acute open tibial fractures: timing of coverage and long-term functional results. *Plast Reconstr Surg* 1992;89:478-87; discussion 488-9.
20. Karanas YL, Nigriny J, Chang J. The timing of microsurgical reconstruction in lower extremity trauma. *Microsurgery* 2008;28:632-4.
21. Lee ZH, Stranix JT, Rifkin WJ, Daar DA, Anzai L, et al. Timing of microsurgical reconstruction in lower extremity trauma: an update of the godina paradigm. *Plast Reconstr Surg* 2019;144:759-67.
22. Steiert AE, Gohritz A, Schreiber TC, Krettek C, Vogt PM. Delayed flap coverage of open extremity fractures after previous vacuum-assisted closure (VAC) therapy - worse or worth? *J Plast Reconstr Aesthetic Surg* 2009;62:675-83.
23. Liu DSH, Sofiadellis F, Ashton M, MacGill K, Webb A. Early soft tissue coverage and negative pressure wound therapy optimises patient outcomes in lower limb trauma. *Injury* 2012;43:772-8.
24. Hill JB, Vogel JE, Sexton KW, Guillamondegui OD, Corral GAD, et al. Re-evaluating the paradigm of early free flap coverage in lower extremity trauma. *Microsurgery* 2013;33:9-13.
25. Raju A, Ooi A, Ong YS, Tan BK. Traumatic lower limb injury and microsurgical free flap reconstruction with the use of negative pressure wound therapy: is timing crucial? *J Reconstr Microsurg* 2014;30:427-30.
26. Sheckter CC, Pridgen B, Li A, Curtin C, Momeni A. Regional variation and trends in the timing of lower extremity reconstruction: a 10-year review of the nationwide inpatient sample. *Plast Reconstr Surg* 2018;142:1337-47.
27. Pollak AN, Ficke JR, Extremity War Injuries III Session Moderators. Extremity war injuries: challenges in definitive reconstruction. *J Am Acad Orthop Surg* 2008;16:628-34.
28. Rinker B, Amspacher JC, Wilson PC, Vasconez HC. Subatmospheric pressure dressing as a bridge to free tissue transfer in the treatment of open tibia fractures. *Plast Reconstr Surg* 2008;121:1664-73.
29. Argenta LC, Morykwas MJ. Vacuum-assisted closure: a new method for wound control and treatment: clinical experience. *Ann Plast Surg* 1997;38:563-76; discussion 577.
30. Webb LX. New techniques in wound management: vacuum-assisted wound closure. *J Am Acad Orthop Surg* 2002;10:303-11.
31. Patterson CW, Stalder MW, Richardson W, Steele T, Wise MW, et al. Timing of free flaps for traumatic wounds of the lower extremity: have advances in perioperative care changed the treatment algorithm? *J Reconstr Microsurg* 2019;35:616-21.
32. Shammas RL, Mundy LR, Truong T, Weber JM, Grier AJ, et al. Identifying predictors of time to soft-tissue reconstruction following open tibia fractures. *Plast Reconstr Surg* 2018;142:1620-8.
33. Gubin A, Borzunov D, Malkova T. Ilizarov method for bone lengthening and defect management review of contemporary literature. *Bull Hosp Jt Dis (2013)* 2016;74:145-54.
34. Green SA. Skeletal defects. A comparison of bone grafting and bone transport for segmental skeletal defects. *Clin Orthop* 1994;111-7.
35. Attias N, Lindsey RW. Case reports: management of large segmental tibial defects using a cylindrical mesh cage. *Clin Orthop* 2006;450:259-66.
36. Masquelet A, Kanakaris NK, Obert L, Stafford P, Giannoudis PV. Bone repair using the masquelet technique. *J Bone Joint Surg Am* 2019;101:1024-36.
37. Masquelet AC, Fitoussi F, Begue T, Muller GP. Reconstruction of the long bones by the induced membrane and spongy autograft. *Ann Chir Plast Esthet* 2000;45:346-53.
38. Pelissier P, Bollecker V, Martin D, Baudet J. Foot reconstruction with the "bi-Masquelet" procedure. *Ann Chir Plast Esthet* 2002;47:304-7.
39. Giannoudis PV, Harwood PJ, Tosounidis T, Kanakaris NK. Restoration of long bone defects treated with the induced membrane technique: protocol and outcomes. *Injury* 2016;47 Suppl 6:S53-61.
40. Karger C, Kishi T, Schneider L, Fitoussi F, Masquelet AC, French Society of Orthopaedic Surgery and Traumatology (SoFCOT). Treatment of posttraumatic bone defects by the induced membrane technique. *Orthop Traumatol Surg Res* 2012;98:97-102.

41. Gottlieb LJ, Krieger LM. From the reconstructive ladder to the reconstructive elevator. *Plast Reconstr Surg* 1994;93:1503-4.
42. Cho EH, Shammass RL, Carney MJ, Weissler JM, Bauder AR, et al. Muscle versus fasciocutaneous free flaps in lower extremity traumatic reconstruction: a multicenter outcomes analysis. *Plast Reconstr Surg* 2018;141:191-9.
43. Hong JP, Shin HW, Kim JJ, Wei FC, Chung YK. The use of anterolateral thigh perforator flaps in chronic osteomyelitis of the lower extremity. *Plast Reconstr Surg* 2005;115:142-7.
44. Xiong L, Gazyakan E, Kremer T, Hernekamp FJ, Harhaus L, et al. Free flaps for reconstruction of soft tissue defects in lower extremity: a meta-analysis on microsurgical outcome and safety. *Microsurgery* 2016;36:511-24.
45. Veith J, Donato D, Holoyda K, Simpson A, Agarwal J. Variables associated with 30-day postoperative complications in lower extremity free flap reconstruction identified in the ACS-NSQIP database. *Microsurgery* 2019;39:621-8.
46. Stranix JT, Lee ZH, Jacoby A, Anzai L, Avraham T, et al. Not all gustilo type iib fractures are created equal: arterial injury impacts limb salvage outcomes. *Plast Reconstr Surg* 2017;140:1033-41.
47. Fischer JP, Wink JD, Nelson JA, Cleveland E, Grover R, et al. A retrospective review of outcomes and flap selection in free tissue transfers for complex lower extremity reconstruction. *J Reconstr Microsurg* 2013;29:407-16.
48. Cho EH, Garcia RM, Pien I, Kuchibhatla M, Levinson H, et al. Vascular considerations in foot and ankle free tissue transfer: analysis of 231 free flaps. *Microsurgery* 2016;36:276-83.
49. Nelson JA, Fischer JP, Brazio PS, Kovach SJ, Rosson GD, et al. A review of propeller flaps for distal lower extremity soft tissue reconstruction: is flap loss too high? *Microsurgery* 2013;33:578-86.
50. Saint-Cyr M, Wong C, Schaverien M, Mojallal A, Rohrich RJ. The perforasome theory: vascular anatomy and clinical implications. *Plast Reconstr Surg* 2009;124:1529-44.
51. Baumeister SP, Spierer R, Erdmann D, Sweis R, Levin LS, et al. A realistic complication analysis of 70 sural artery flaps in a multimorbid patient group. *Plast Reconstr Surg* 2003;112:129-40; discussion 141-2.
52. Parrett BM, Pribaz JJ, Matros E, Przylecki W, Sampson CE, et al. Risk analysis for the reverse sural fasciocutaneous flap in distal leg reconstruction. *Plast Reconstr Surg* 2009;123:1499-504.
53. Hessel SJ, Adams DF, Abrams HL. Complications of angiography. *Radiology* 1981;138:273-81.
54. Waugh JR, Sacharias N. Arteriographic complications in the DSA era. *Radiology* 1992;182:243-6.
55. Johansen K, Lynch K, Paun M, Copass M. Non-invasive vascular tests reliably exclude occult arterial trauma in injured extremities. *J Trauma* 1991;31:515-9; discussion 519-22.
56. Rubin GD, Schmidt AJ, Logan LJ, Sofilos MC. Multi-detector row CT angiography of lower extremity arterial inflow and runoff: initial experience. *Radiology* 2001;221:146-58.
57. Seamon MJ, Smoger D, Torres DM, Pathak AS, Gaughan JP, et al. A prospective validation of a current practice: the detection of extremity vascular injury with CT angiography. *J Trauma* 2009;67:238-43; discussion 243-4.
58. Klein MB, Karanas YL, Chow LC, Rubin GD, Chang J. Early experience with computed tomographic angiography in microsurgical reconstruction. *Plast Reconstr Surg* 2003;112:498-503.
59. Soto JA, Múnera F, Morales C, Lopera JE, Holguín D, et al. Focal arterial injuries of the proximal extremities: helical CT arteriography as the initial method of diagnosis. *Radiology* 2001;218:188-94.
60. Stegemann E, Tegtmeyer C, Bimpong-Buta NY, Sansone R, Uhlenbruch M, et al. Carbondioxide-aided angiography decreases contrast volume and preserves kidney function in peripheral vascular interventions. *Angiology* 2016;67:875-81.
61. Sharafuddin MJ, Marjan AE. Current status of carbon dioxide angiography. *J Vasc Surg* 2017;66:618-37.
62. Janhofer DE, Lakhiani C, Kim PJ, Akbari C, Naz I, et al. The utility of preoperative arteriography for free flap planning in patients with chronic lower extremity wounds. *Plast Reconstr Surg* 2019;143:604-13.
63. Lutz BS, Ng SH, Cabailo R, Lin CH, Wei FC. Value of routine angiography before traumatic lower-limb reconstruction with microvascular free tissue transplantation. *J Trauma* 1998;44:682-6.
64. May JW, Athanasoulis CA, Donelan MB. Preoperative magnification angiography of donor and recipient sites for clinical free transfer of flaps or digits. *Plast Reconstr Surg* 1979;64:483-90.
65. Chen HC, Chuang CC, Chen S, Hsu WM, Wei FC. Selection of recipient vessels for free flaps to the distal leg and foot following trauma. *Microsurgery* 1994;15:358-63.
66. Duymaz A, Karabekmez FE, Vrtiska TJ, Mardini S, Moran SL. Free tissue transfer for lower extremity reconstruction: a study of the role of computed angiography in the planning of free tissue transfer in the posttraumatic setting. *Plast Reconstr Surg* 2009;124:523-9.
67. Feng S, Min P, Grassetti L, Lazzeri D, Sadigh P, et al. A prospective head-to-head comparison of color doppler ultrasound and computed tomographic angiography in the preoperative planning of lower extremity perforator flaps. *Plast Reconstr Surg* 2016;137:335-47.
68. Holm C, Mayr M, Höfner E, Becker A, Pfeiffer UJ, et al. Intraoperative evaluation of skin-flap viability using laser-induced fluorescence of indocyanine green. *Br J Plast Surg* 2002;55:635-44.
69. Woodard CR, Most SP. Intraoperative angiography using laser-assisted indocyanine green imaging to map perfusion of forehead flaps. *Arch Facial Plast Surg* 2012;14:263-9.
70. Monahan J, Hwang BH, Kennedy JM, Chen W, Nguyen GK, et al. Determination of a perfusion threshold in experimental perforator flap surgery using indocyanine green angiography. *Ann Plast Surg* 2014;73:602-6.
71. Koshimune S, Shinaoka A, Ota T, Onoda S, Kimata Y. Laser-assisted indocyanine green angiography aids in the reconstruction of gustilo grade iib open lower-limb fractures. *J Reconstr Microsurg* 2017;33:143-50.

Original Article

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The technique of utilizing a single gracilis functional muscle transfer to restore quadriceps function following sarcoma surgery

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Abstract

Aim: Quadriceps strength and knee extension, the most important factors limiting the ability to rise from a chair, are crucial for walking at an appropriate speed, ascending and descending stairs, and performing activities such as running, dancing, and jumping. Resection of the anterior compartment of the thigh, including all four quadriceps muscles, for the treatment of a sarcoma is uncommon; however, when necessary, it is very debilitating and adversely affects a patient's quality of life without functional reconstruction. Currently, there are a limited number of complex and difficult reconstructions to restore quadriceps function that have been described with variable outcomes. We describe a simple technique that employs a single gracilis functional muscle transfer to replace essential quadriceps function.

Methods: This is a case series describing the use of either a free or pedicled single gracilis muscle to restore quadriceps function following sarcoma resection.

Results: Four patients underwent an anterior compartment sarcoma resection that resulted in a large segmental defect and/or denervation of all four quadriceps muscles such that no quadriceps function would remain without reconstruction. All four patients underwent a functional reconstruction using a single gracilis. Three of the living patients achieved British Medical Research Council Grade 4 strength, can achieve full knee extension, are able to



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navigate stairs, and are able to ambulate without a brace. The fourth patient unfortunately was deceased in under three months following his tumor resection.

Conclusion: Despite its small size in comparison to the quadriceps muscles, with physiotherapy and training, the gracilis muscle demonstrates the capacity to hypertrophy and replace quadriceps function following limb salvage surgery.

Keywords: Knee extension, re-animation, functional muscle transfer, free flap, pedicled flap, sarcoma, microsurgery, quadriceps, reconstruction

INTRODUCTION

It is not uncommon to have to resect one or more components of the four quadriceps muscles during sarcoma resection from the anterior compartment of the thigh^[1]. Pritsc *et al.*^[2] examined postoperative isometric strength and found that the strength of the quadriceps decreased by 22%, 33%, 55%, and 76%, respectively, when one, two, three, or more components of the quadriceps were resected^[2,3]. Functional thresholds of quadriceps strength below which essential quadriceps functions are impaired have been difficult to determine as there are many other factors in addition to muscle strength that affect ambulatory ability^[4].

At our institution, in the setting of anterior compartment resections of the thigh for malignant soft tissue tumors, we do not routinely proceed with functional reconstruction or augmentation of the quadriceps muscles if at least one of the four quadriceps muscle groups remain intact. In those patients who undergo complete resection or complete loss of continuity (central wide resections) and/or denervation of all four quadriceps, we have been successful in restoring essential quadriceps function utilizing a single gracilis muscle transfer, either as a free flap from the contralateral leg, or, more recently, as a simple pedicled gracilis muscle from the ipsilateral leg. With either technique, the gracilis muscle is transferred into the rectus femoris position. With training, the gracilis is able to hypertrophy enough to perform essential quadriceps function.

METHODS

Institutional research ethics approval was obtained for the study (Ethics #: HS23291). We retrospectively reviewed all patients at our institution who underwent complete resection and/or had complete denervation of all four quadriceps muscles as part of their sarcoma resection of the anterior thigh and reconstruction with a single gracilis muscle. All cases were performed by a single surgeon (Hayakawa TEJ). Patient demographics, surgical technique, and clinical outcomes such as British Medical Research Council (MRC) grading, knee extension, and ambulatory status is reported.

Surgical technique

The choice of free or pedicled gracilis is usually determined by the degree of cutaneous soft tissue reconstruction required. If there is a relatively small cutaneous defect, then both the functional quadriceps reconstruction and soft tissue reconstruction are accomplished by a single free contralateral gracilis myocutaneous flap. If the soft tissue or skin defect is too large for the gracilis skin paddle, then an ipsilateral pedicled gracilis is transferred into the rectus femoris position for the functional component of the reconstruction, and a larger cutaneous free tissue transfer such as an anterolateral thigh (ALT) or deep inferior epigastric perforator (DIEP) flap is added for coverage of the soft tissue defect.

In both scenarios, the inset of the gracilis is identical, and into the rectus femoris position. The gracilis will become the only “quadriceps” muscle and will provide both hip flexion and knee extension, which

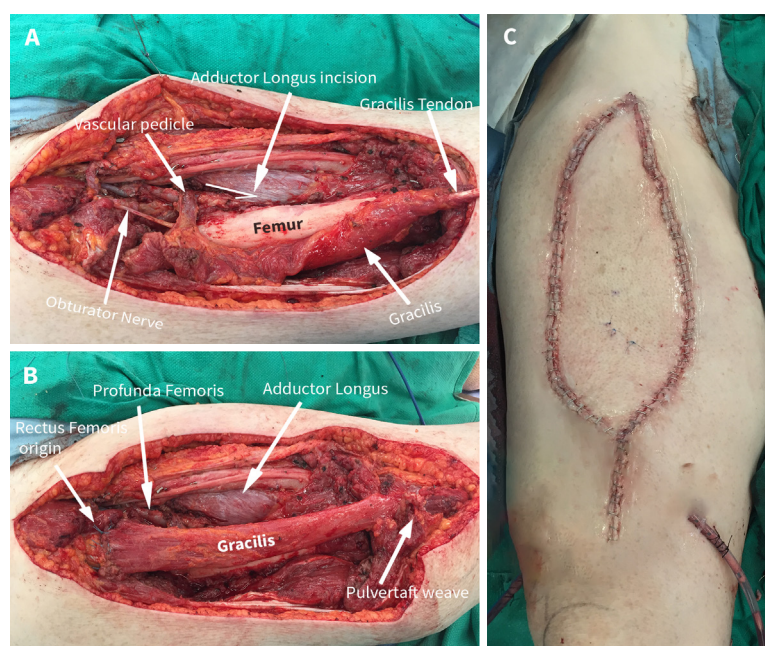


Figure 1. A: Pedicled gracilis harvest post-resection. Note the adductor longus releasing incision to prevent pedicle kinking following flap transposition allowing for tension-free inset; B: Gracilis inset in position of rectus femoris; C: Skin defect was covered with free anterolateral thigh flap

are both essential for normal gait. The entire length of the gracilis is harvested as previously described^[5] with care to harvest the proximal muscle directly off the periosteum of the ischium and the distal tendon off the pes anserine. There is almost always some of the rectus femoris tendon remaining proximally following the tumor resection. Occasionally additional rectus femoris muscle must be resected to get back to a solid tendinous portion that will allow several Krackow sutures as well as figure-of-eight sutures with 0 Ethibond™ (Ethicon Inc., Johnson & Johnson, Somerville, NJ, USA) to secure the proximal gracilis muscle origin to the stout rectus femoris tendinous origin. The long distal gracilis tendon is then woven in a Pulvertaft fashion into the remaining quadriceps tendon complex distally.

When performing an ipsilateral pedicled gracilis, the vascular pedicle is dissected and freed to the profunda femoris artery and vein beneath the adductor longus. The “tunnel”, deep to the adductor longus and superficial to the adductor brevis and magnus, may need to be elongated by making a “slit” or cut in the upper border of adductor longus that it is long enough to allow the gracilis muscle to be passed through from its normal position on the medial side of abductor longus to its new position on the lateral side. Care is taken to ensure there is no pressure or kinking of the gracilis vascular pedicle, which now must curve or arc up and over the profunda vessels as it follows the muscle during its transfer from the medial to the lateral side of the abductor longus. The gracilis is then placed into the rectus femoris position [Figures 1 and 2].

During flap harvest, we transect the motor branch of the obturator nerve to the gracilis and perform a neurorrhaphy to the most suitable available motor branch stump of the femoral nerve, which is ideally the remaining stump of the motor branch to the rectus femoris [Figure 3]. Of note, the sartorius muscle was resected in three cases and in no cases was it used for functional transfer. In no cases was nerve grafting to residual distal quadriceps elements performed.

The post-operative protocol consists of a five-day hospital stay to ensure flap viability and to educate patients in transfers in and out of a wheelchair. A Zimmer™ (Zimmer Biomet Holdings Inc. Warsaw, IN, USA) knee extension splint is fitted on the final hospital day with the knee in full extension. The patients are maintained in a wheelchair for two weeks post-operation to optimize wound healing and prevent seroma formation. At six weeks, the patients are switched from the Zimmer splint to an

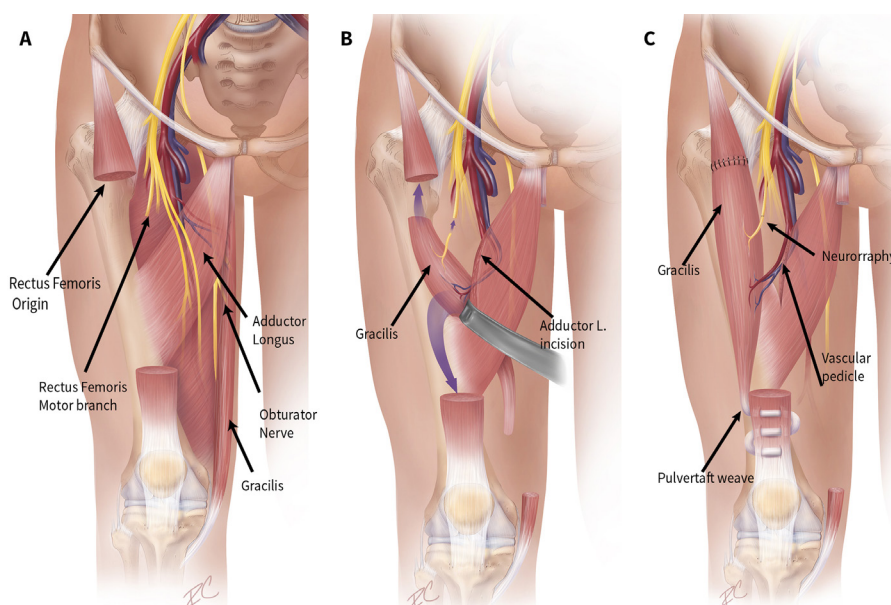


Figure 2. Artist rendition of surgical technique

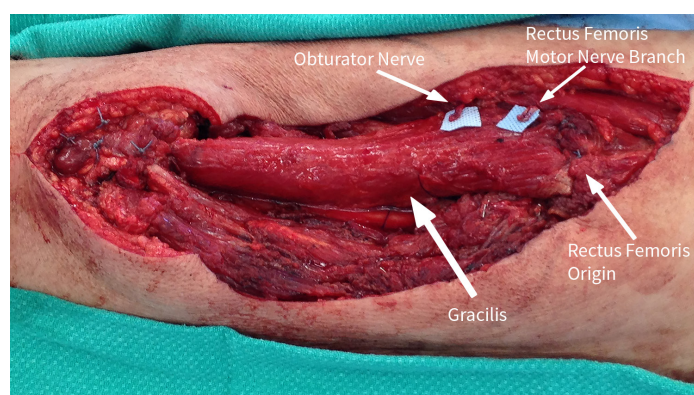


Figure 3. Neurotomy of motor branch of obturator nerve to motor nerve of rectus femoris

adjustable hinged knee splint and begin range of motion exercises that increase by 20° increments every week. Simultaneously motor frequency transcutaneous electrical nerve stimulation is begun. As soon as MRC grade 1 contraction is identified (a flicker of muscle contraction), the patients begin quadriceps strengthening exercises. Many standard strengthening techniques cannot be used because the knee is unstable from lack of quadriceps tone and therefore the ones shown in [Figure 4](#) allow the patient to vary the degree of force on the new muscle as it gets stronger while also allowing them to provide stability to their knee by offloading forces onto their upper extremities.

RESULTS

We performed a gracilis muscle transfer to replace total quadriceps function in four patients with large central sarcoma resections resulting in large central gaps and/or denervation of all four quadriceps muscles. Patient's age at the time of surgery ranged from 24 to 65 years. Follow up in the three patients still alive ranged 3-20 years, with the single deceased patient surviving under three months following surgery and dying as a result of metastatic disease. All patients had high grade sarcomas, Fédération Nationale des Centres de Lutte Contre le Cancer Grade 3, and all surviving patients had negative margins

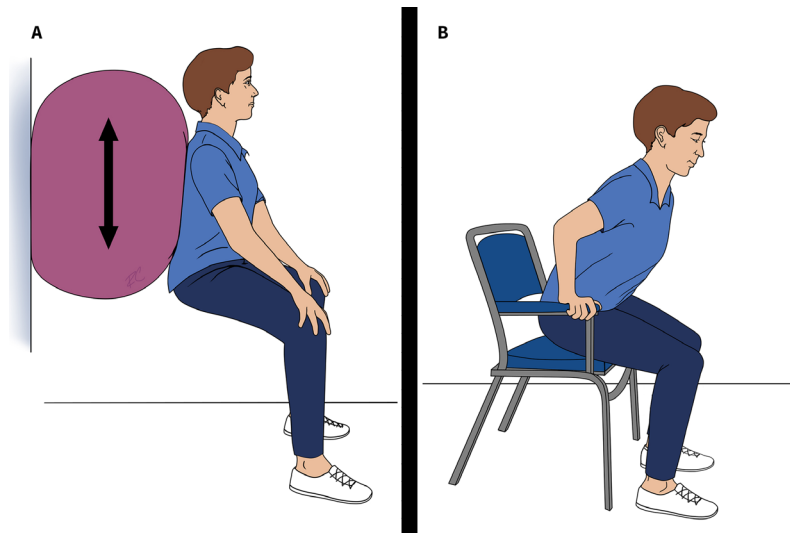


Figure 4. Quadriceps strengthening exercises post-reconstruction

at the time of initial resection. No patients had metastasis at the time of surgery. Two of the three patients continue to survive despite metastatic disease that occurred at three years following initial treatment in one, and eight years in the other. Both have pulmonary metastatic disease, and both have undergone treatment for their metastasis, one in the form of Video-Assisted Thoracoscopic Surgery and the other by Stereotactic Body Radiation Therapy. All patients underwent neoadjuvant radiation prior to surgery, and none of the surviving patients received chemotherapy. The reconstructions following resection included a free functional gracilis myocutaneous flap in one patient, a pedicled gracilis combined with an ALT flap in 2 patients, and a pedicled gracilis with a deep inferior epigastric artery perforator/superficial inferior epigastric artery (DIEP/SIEA) in one patient. The 3 surviving patients achieved MRC grade 4 muscle strength and were able to achieve full knee extension 12-18 months post-operation. The three surviving patients are able to ambulate without a brace and rise from the sitting position. All three of these patients demonstrated clinical signs of re-innervation with palpable muscle contraction beginning at, or just after 3 months post-operatively. Due to the clinical return of function, no electrophysiologic studies were performed. The exact length of the obturator nerve to the gracilis was not recorded, but in every case it was cut as short as possible to reduce re-innervation time yet still allow a tension free neurorrhaphy. One patient died from his disease less than three months post-operation, and therefore it was too early to demonstrate any contraction in the reinnervated functional reconstruction.

Case examples

The first case demonstrates a 50-year-old female with complete central resection of all four quadriceps [Figure 5]. At 18 months post-operation, this patient has enough strength from her gracilis to reach full extension, however she could not lock her knee into full extension for more than a short period of time until more strength and endurance was achieved after several additional months [Figure 6].

Her anticipated progress is demonstrated in the following videos. MRC grade 1 strength with contraction is noted at three months post-operation [Video 1]. MRC grade 2 contraction is noted at six months, which provides enough knee stability to discontinue the knee brace and allow the patient to ascend and descend stairs [Video 2]. MRC grade 3 strength is noted at nine months [Video 3]. MRC grade 4 strength is demonstrated at one year from surgery, which enables the patient to return to more vigorous sporting activities [Video 4]. Magnetic resonance imaging (MRI) demonstrates gracilis hypertrophy [Figure 7].

The second patient is a 22-year-old female with a large central resection of all four quadriceps muscles of left leg, reconstructed with a free gracilis muscle. Figure 8 demonstrates her “neo” quadriceps function with complete knee extension. She is able to complete a half marathon three years post-operation [Video 5].

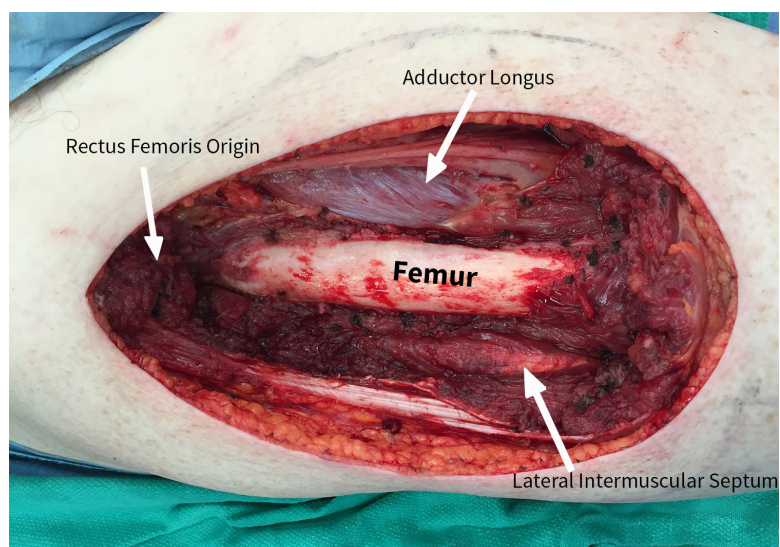


Figure 5. Post-oncologic resection of rectus femoris, vastus lateralis, vastus medialis, and vastus intermedius in a patient with a large high-grade sarcoma

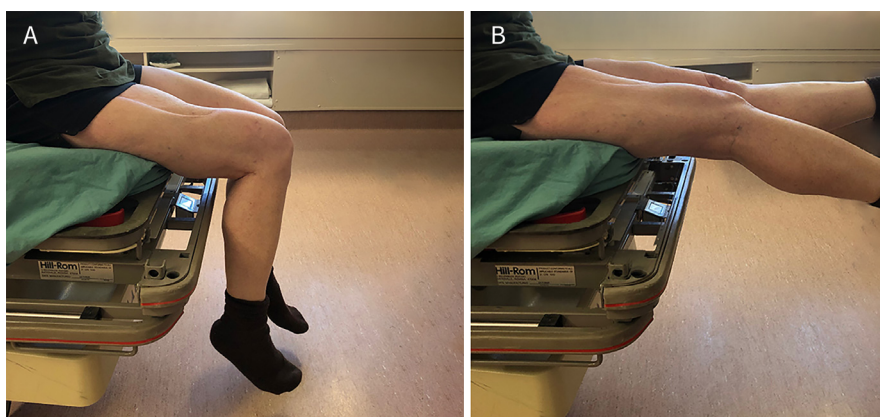


Figure 6. Grade 4 muscle strength at one year: extension of leg against gravity and resistance

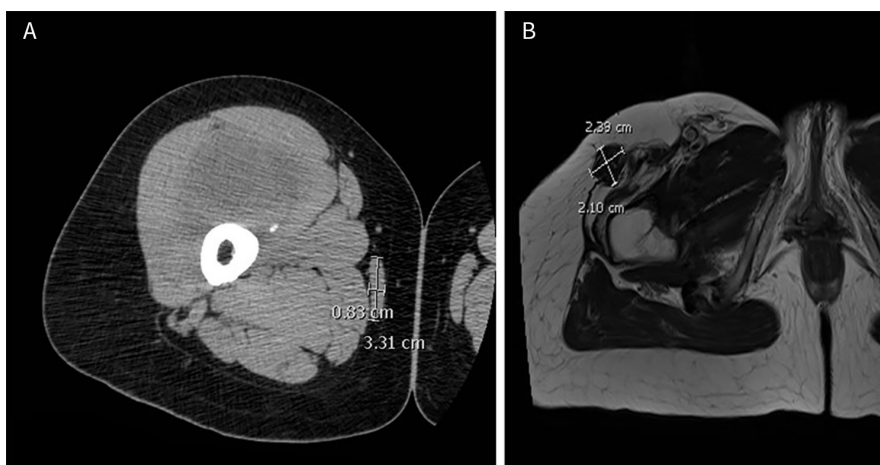


Figure 7. MRI showing right gracilis muscle hypertrophy post functional muscle transfer: (A) pre-operative MRI; and (B) 12-month post-operative MRI. MRI: magnetic resonance imaging

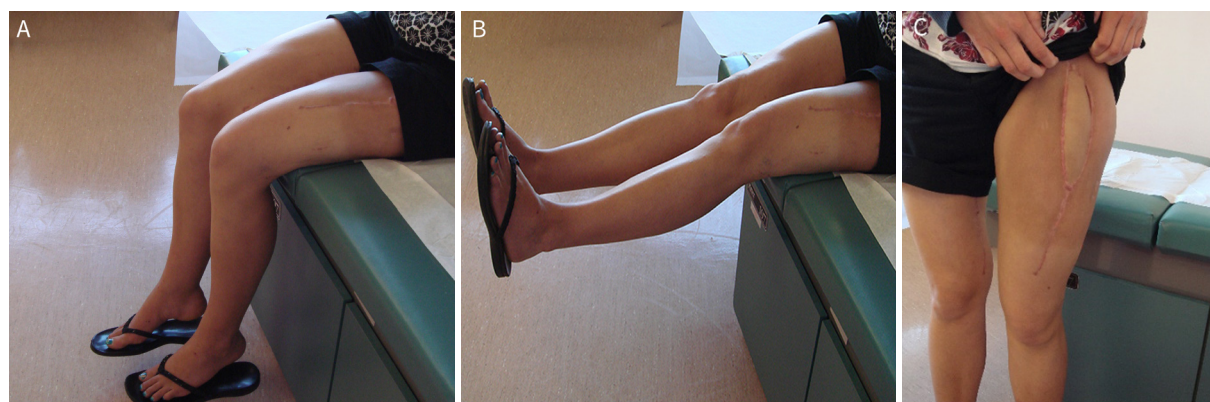


Figure 8. Demonstration of leg extension after free functional gracilis muscle flap to left quadriceps position at three years post-surgery: (A) leg at rest; (B) full active extension of leg; and (C) skin paddle of flap

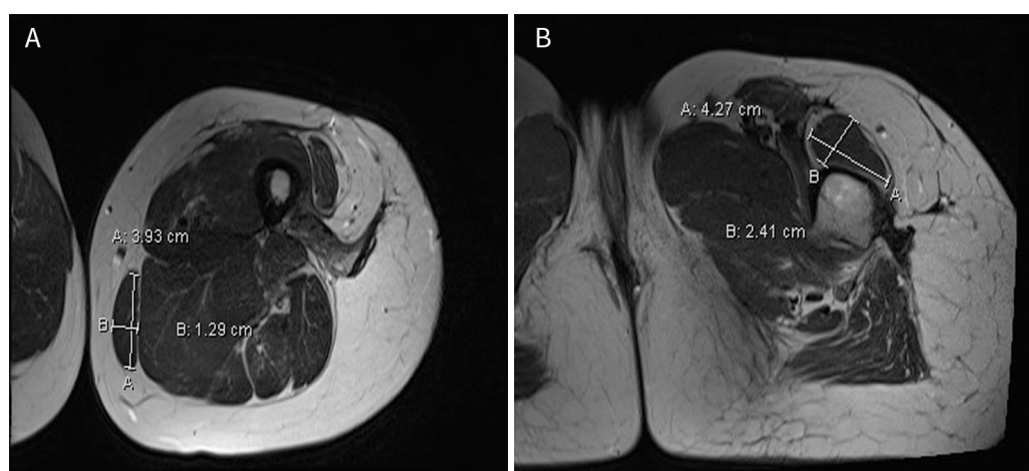


Figure 9. MRI showing gracilis muscle hypertrophy post free functional gracilis to left leg: (A) pre-operative MRI; and (B) 36-month post-operative MRI. MRI: magnetic resonance imaging

An MRI at three years post-surgery again shows that hypertrophy of the transferred gracilis muscle has occurred [Figure 9].

DISCUSSION

Although the anterior compartment of the thigh is the most common location for soft tissue sarcomas, complete resection of all four quadriceps muscles is uncommon^[1,2]. Several different techniques have been described to reconstruct or augment remaining quadriceps function after tumor extirpation. Willcox *et al.*^[6] described good functional results following latissimus dorsi reconstruction in a 21-year-old following complete quadriceps resection and femoral prosthesis placement. Muramatsu *et al.*^[7] had only MRC grade 2 strength return following latissimus for a total quadriceps resection, but better results in those in which the latissimus was used to augment partial quadriceps defects. Innocenti *et al.*^[8] described four cases of complete quadriceps reconstruction with latissimus dorsi, but in all cases augmented the latissimus dorsi with the sartorius muscle and a large fascia lata patch to augment the muscle tendon repair. Pritsch *et al.*^[2] described combinations of biceps femoris, semitendinosus muscles, and sartorius to reconstruct partial quadriceps resections with good to excellent results in 86.7% of patients. Fischer *et al.*^[9] also described local tendon transfers and utilized isolated biceps or a combination of biceps and semitendinosus or gracilis in

43 patients. In this series, 9 of the 17 patients that were available for follow up evaluation had resection of greater than $\frac{3}{4}$ of the quadriceps or complete femoral nerve loss. All 43 patients in this series attained full knee extension; however, 41% still required walking aids. Only 14% of all patients underwent pre-operative neoadjuvant radiation therapy^[9]. Despite its segmental innervation, Grinsell *et al.* described the use of the rectus abdominis muscle for complete quadriceps reconstruction. This group described dissecting 1-4 segmental intercostal nerves to the rectus abdominis over 10-12 cm and re-innervating the muscle to motor branches of the femoral nerve. They reported MRC Grade 4 power or greater in 6 of 11 patients^[10].

It has been our past practice not to proceed with functional reconstructions in those patients having at least one of the four quadriceps muscles remaining following tumor resection. Although these patients may be somewhat initially disabled, we noticed that with training and physiotherapy most are able to achieve unassisted ambulation, normal to near normal appearing gait, and full or nearly full knee joint extension. These findings are likely due at least in part to the well-established observation in both bodybuilding and powerlifting that muscles have the capacity for hypertrophy^[11,12]. Based on these findings, we believed the gracilis would have the ability to replace enough quadriceps function essential for activities of daily living: sitting, getting up from a chair, and unassisted gait. To be clear, the goal of the transfer was not to replicate the strength and power of all four quadriceps muscles with a single smaller muscle.

From a surgical perspective, the gracilis is a simple, straight forward transfer, particularly if it is pedicled. The gracilis is in the same surgical field as the resection and hence there is no additional donor site morbidity, and no change of positioning or awkward positioning is required. The gracilis flap can be pedicled into the defect with no ischemia time and no microvascular anastomosis. The stout proximal fascia and long distal tendon make the gracilis perfectly suited for insertion into the rectus femoris origin proximally and into the quadriceps tendons distally with a strong Pulvertaft weave. The obturator nerve can be cut short for more rapid reinnervation if a long femoral nerve stump exists or tailored to be longer if the nerve was involved with the tumor more proximally. Thus far, we have always reinnervated the gracilis with the rectus femoris motor nerve branch of the femoral nerve, which is tagged during resection. Failure of reinnervation has not been a problem. Although not performed for sarcoma surgery, we have successfully performed pedicled functional gracilis leaving the obturator nerve to gracilis intact. We have utilized this in combination with a nerve transfer for complete femoral nerve injuries. In this case, the muscle dissection and placement are the same, but the obturator branch to the gracilis is left intact and the gracilis is “piggybacked” onto the medial side of rectus femoris. In this case, the obturator branch to the adductor longus is transected and used as a simultaneous nerve transfer to reinnervate the rectus femoris. Therefore, simply leaving the motor nerve to the gracilis intact during pedicled gracilis transfer may be another technique option but we do not have experience utilizing this in our sarcoma reconstructions.

There are advantages to the gracilis over the other free muscle transfers: its donor site functional deficit is likely less than that of a rectus abdominis, latissimus dorsi, or contralateral rectus femoris, and the recipient vessel location or the necessity of vein grafts in a radiated vessel depleted field does not become a factor when trying to accurately position the pedicled muscle transfer as compared to a free tissue transfer.

There are certainly situations in which other muscle transfers should be considered. For example, if the resection necessitates a femoral prosthesis, a latissimus dorsi or rectus abdominis is probably better suited to provide more complete coverage of the prosthesis. If the sartorius remains following resection, then it should also be considered in addition to the gracilis as described by Willcox *et al.*^[6] and Innocenti *et al.*^[8]. Local tendon transfers can certainly be considered in institutions whose protocol does not include pre-operative neoadjuvant radiation therapy. The risk of post-operative wound dehiscence and lymphedema with these techniques is not insignificant even in the non-irradiated setting^[9].

We choose to place the gracilis in the rectus femoris position for several reasons. The ability to stand from a seated position is one of the most important measures of physical function and is essential for independent living^[4,13]. The biarticulated rectus femoris is critically important in the sit-to-stand transition, as well as stepping and gait^[14,15]. The rectus femoris is a two-joint muscle that acts both as a flexor of the hip and an extensor of the knee and is active during two phases of the gait cycle; in other words, it has bimodal activity^[16-20]. The first burst of activity occurs during the loading response phase where it acts with the vasti by acting at the knee during load bearing to stabilize it^[21]. The second burst occurs during the pre- and initial-swing phase of the gait cycle where it acts as a hip flexor in propelling the limb forward into swing^[21]. These unconscious complex sets of coordinated movements are the reason we chose to reinnervate the gracilis with the motor nerve to rectus femoris rather than simply transfer it with its obturator innervation intact and hope that retraining could occur. The three vasti muscles are important for standing function and they extend the knee without flexing the thigh^[22]. Likely because of this, two of our functional gracilis patients did have symptoms of fatigue if standing for longer periods of time. The vastus lateralis and intermedius are the strongest vasti; however, the vastus medialis is important for locking the knee in terminal extension and preventing patellar drift and lateral subluxation^[22]. Considering this, our patients could all reach complete knee extension while seated on a bench but only one could hold their knee in full extension for more than a brief period of time. Interestingly, we did not have any problems with patellar subluxation or drift, and this may be attributed to the long distance distally that we weaved the gracilis tendon into the quadriceps tendon complex as well as some stabilizing fibrosis from the neo adjuvant radiotherapy that may have occurred.

In summary, the required amount of quadriceps strength necessary to maintain quality of life has not been accurately established^[4]. It remains unclear which muscle or muscle transfers in the body are suitable to replace enough quadriceps strength and function to achieve this endpoint. Although the gracilis muscle is clearly not as strong as the quadriceps muscle complex, there are other clinical examples where a much smaller and weaker muscle can replace the essential functions of a much larger muscle group. An example would be the scenario of total biceps and brachialis resection or denervation in which a much smaller and weaker brachioradialis can adequately compensate for elbow flexion such that no additional reconstruction is usually required. Our experience suggests that with physiotherapy and training, and in the appropriate patient, the gracilis has enough capacity to provide essential quadriceps function following complete resection and/or denervation associated with limb salvage sarcoma surgery.

DECLARATIONS

Authors' contributions

Concept study design, literature search, and manuscript writing: Hayakawa TEJ
 Manuscript preparation, data acquisition: Nguyen CM, Ratanshi I
 Manuscript review: Giuffre JL, Buchel EW

Availability of data and materials

IRB approved retrospective study based on University of Manitoba Health Sciences Centre hospital charted data.

Financial support and sponsorship

None.

Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

IRB approval prior to data acquisition and study design (HS23291).

Consent for publication

A written informed consent for publication of videos and photos were obtained.

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REFERENCES

1. Enneking WF, Spanier SS, Malawer MM. The effect of the anatomic setting on the results of surgical procedures for soft parts sarcoma of the thigh. *Cancer* 1981;47:1005-22.
2. Pritsch T, Malawer MM, Wu CC, Squires MH, Bickels J. Functional reconstruction of the extensor mechanism following massive tumor resections from the anterior compartment of the thigh. *Plastic Reconstr Surg* 2007;120:960-9.
3. Markhede G, Stener B. Function after removal of various hip and thigh muscles for extirpation of tumors. *Acta Orthop Scand* 1981;52:373-95.
4. Ploutz-Snyder LL, Manini P, Ploutz-Snyder RJ, Wolf DA. Functionally relevant thresholds of quadriceps femoris strength. *J Gerontol A Biol Sci Med Sci* 2002;57:B144-52.
5. Giuffre JL, Bishop AT, Shin AY. Harvest of an entire gracilis muscle and tendon for use in functional muscle transfer: a novel technique. *J Reconstr Microsurg* 2012;28:349-58.
6. Willcox TM, Smith AA, Beauchamp C, Meland NB. Functional free latissimus dorsi muscle flap to the proximal lower extremity. *Clin Orthop Relat Res* 2003;285-8.
7. Muramatsu K, Ihara K, Miyoshi T, Yoshida K, Hashimoto T, Taguchi T. Transfer of latissimus dorsi muscle for the functional reconstruction of quadriceps femoris muscle following oncological resection of sarcoma in the thigh. *JPRAS* 2011;64:1068-74.
8. Innocenti M, Abed YY, Beltrami G, Delcroix L, Balatri A, et al. Quadriceps muscle reconstruction with free functioning latissimus dorsi muscle flap after oncological resection. *Microsurgery* 2009;29:189-98.
9. Fischer S, Soimaru S, Hirsch T, Kueckelhaus M, Seitz C, et al. Local tendon transfer for knee extensor mechanism reconstruction after soft tissue sarcoma resection. *JPRAS* 2015;68:729-35.
10. Grinsell D, Lonie S, Wilson KC, Choong PFM. The innervated rectus abdominis flap for quadriceps reconstruction. *JPRAS* 2019;72:941-5.
11. Schoenfeld BJ. The mechanisms of muscle hypertrophy and their application to resistance training. *J Strength Cond Res* 2010;24:2857-72.
12. Schoenfeld BJ. Potential mechanisms for a role of metabolic stress in hypertrophic adaptations to resistance training. *Sports Med* 2013;43:179-94.
13. Riley PO, Schenkman ML, Mann RW, Hodge WA. Mechanics of a constrained chair-rise. *J Biomech* 1991;24:77-85.
14. Kobetic R, Triolo RJ, Uhlir JP, Bieri C, Wibowo M, et al. Implanted functional electrical stimulation system for mobility in paraplegia: a follow-up case report. *IEEE Trans Rehabil Eng* 1999;7:390-8.
15. Sharma M, Marsolais EB, Polando G, Triolo RJ, Davis JA Jr, et al. Implantation of a 16-channel functional electrical stimulation walking system. *Clin Orthop Relat Res* 1998;236-42.
16. Perry J, Davids JR. Gait analysis: normal and pathological function. *J Pediatr Orthop* 1992;12:815.
17. Murray MP, Mollinger LA, Gardner GM, Sepic SB. Kinematic and EMG patterns during slow, free, and fast walking. *J Orthop Res* 1984;2:272-80.
18. Shiavi R, Bugle HJ, Limbird T. Electromyographic gait assessment, Part 1: Adult EMG profiles and walking speed. *J Rehabil Res Dev* 1987;24:13-23.
19. Ericson MO, Nisell R, Ekholm J. Quantified electromyography of lower-limb muscles during level walking. *Scand J Rehabil Med* 1986;18:159-63.
20. Csongradi J, Bleck E, Ford WF. Gait electromyography in normal and spastic children, with special reference to quadriceps femoris and hamstring muscles. *Dev Med Child Neurol* 1979;21:738-48.
21. Annaswamy TM, Giddings CJ, Della Croce U, Kerrigan DC. Rectus femoris: its role in normal gait. *Arch Phys Med Rehabil* 1999;80:930-4.
22. Gustafson KJ, Pinault GCJ, Neville JJ, Syed I, Davis JA Jr, et al. Fascicular anatomy of human femoral nerve: implications for neural prostheses using nerve cuff electrodes. *J Rehabil Res Dev* 2009;46:973-84.

Letter to Editor

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Classification of negative pressure wound therapy

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Since relatively new negative pressure wound therapy (NPWT) has become an integral part of simple to complex wound management, effective price transparency of NPWT should include the release of clear, accurate, and actionable information for patients to determine their cost of treatment and remove the guesswork. The amount and type of material used, number of hours of negative pressure application, cost of maintaining negative pressure for a definite period, *etc.*, usually determine the cost of NPWT. With this idea of price transparency, the author attempted to classify NPWT in different ways. The author believes that, with similar attempts by various authors in the future, a better classification would evolve.

A. Depending on the schedule of negative pressure and type of environment produced under the NPWT device, it may be classified as:

1. Continuous NPWT [Vacuum Assisted Closure (VAC)]^[1] (KCI Medical, San Antonio, Texas) and Versatile-1 Wound Vacuum System (Versatile-1 WVS) (Blue Sky Medical, La Costa Calif)^[2].
2. Intermittent NPWT [Limited access dressing (LAD)]^[3,4].

B. Depending on the interface material used between the tissue and device, NPWT may be classified as:

1. NPWT with interface such as foam, gauze, or other porous material that helps to distribute the negative pressure uniformly over wound surface. Examples include VAC^[1] and Suction Assisted Dressing (SAD)^[4]. In this type of NPWT devices, granulation grows in the pores of interface material and does not provide favorable environment for epithelialization.
2. NPWT without interface material. An example is LAD. This type of NPWT is better for epithelialization.



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The single use portable NPWT dressing used for outdoor (OPD) patients is PICO (Smith and Nephew Healthcare, Hull, United Kingdom) that requires fewer dressing changes and is an adjuvant therapy to hasten wound healing. PICO is better accepted by OPD patient with reduced financial burden^[5].

C. Depending on sealing of the device, NPWT may be classified as:

1. NPWT with occlusive dressing: such dressings provide moist healing environment with enormous capacity to remove soakage. Examples include VAC and LAD. Moist healing becomes more effective in intermittent negative pressure regimen, such as in LAD^[3,4].
2. NPWT with semi-occlusive dressing. Such dressings, apart from negative pressure, provide wet to dry environment, and are effective in wounds with relatively small amount of soakage. An example is SAD^[4].

D. Depending on area of dressing, NPWT may be classified as:

1. Small area dressing.
2. NPWT over a part of a region of the body, e.g., foot.
3. NPWT over a region of the body, e.g., inferior or superior extremity.
4. Separate NPWT over multiple regions of the body, e.g., both limbs separately, one upper limb and one lower limb, *etc.*
5. Extra large and complex NPWT, e.g., upper limb and adjacent chest.
6. Whole body dressing, e.g., in extensive burn areas.
7. Special area NPWT, e.g., perineum, face and scalp, or over area with external fixator.

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The author contributed solely to the article.

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Ethical approval and consent to participate

Not applicable.

Consent for publication

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REFERENCES

1. Morykwas MJ, Argenta LC, Shelton-Brown EI, McGuirt W. Vacuum-assisted closure: a new method for wound control and treatment: animal studies and basic foundation. *Ann Plast Surg* 1997;38:553-62
2. Campbell PE. Surgical wound closure case studies with the versatile 1 wound vacuum system for negative pressure wound therapy. *J Wound Ostomy Continence Nurs* 2006;33:176-85; discussion 185-90.
3. Kumar P. Limited access dressing. *Wounds* 2008;20:49-59.
4. Kumar P. Exploiting potency of negative pressure in wound dressing using limited access dressing and suction-assisted dressing. *Indian*

J Plast Surg 2012;45:302-15.

5. Payne C, Edwards D. Application of the single use negative pressure wound therapy device (PICO) on a heterogeneous group of surgical and traumatic wounds. *Eplasty* 2014;14:e20.

Review

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The methodology of lymphatic anatomy studies in a cadaver model: an overview

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Abstract

The lymphatic system is the area least investigated in the field of anatomical science. The major reason for this is the technical difficulty in identifying the lymphatics in the surrounding tissue in post-mortem specimens. As a result, the medical illustration masterpieces crafted by pioneer anatomists on the basis of cadaver dissections remain a vital component of current anatomical textbooks. Several innovative techniques were developed in the past to allow anatomists to distinguish the transparent lymphatic structures from their surroundings and enable thorough investigation of the lymphatic system in a cadaver model. This paper focuses on these techniques, including the current technique developed by the authors themselves.

Keywords: Anatomy, lymphatic system, cadaver, mercury, indocyanine green

INTRODUCTION

Since lymphangiography was introduced by Kinmonth^[1] in the 1950s, several other imaging techniques have been developed to provide imaging of the lymphatic system in the clinical setting. Lymphoscintigraphy^[2,3] is the current gold standard procedure, but indocyanine green (ICG) lymphography^[4-6], magnetic resonance lymphography^[7,8], and single-photon emission computed



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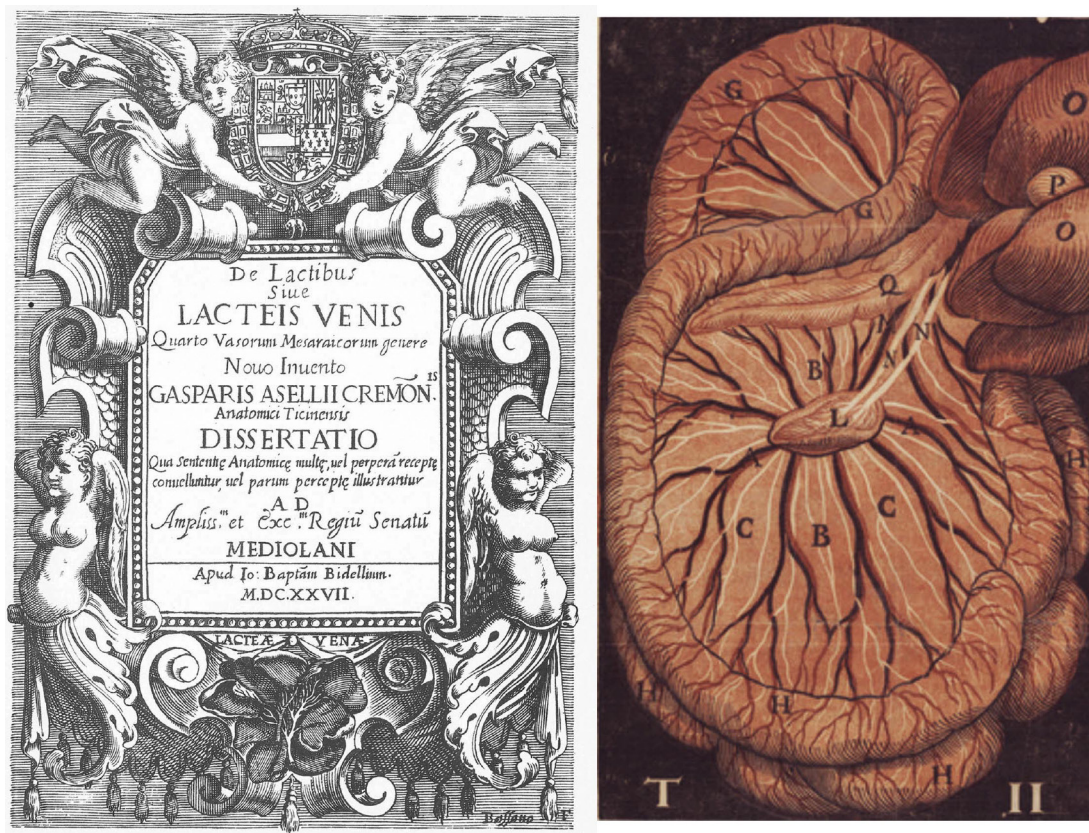


Figure 1. Aselli's^[10] publication in 1627. This image shows white lacteal cords in the dog mesentery (right)

tomography (SPECT)/CT^[9] are emerging imaging techniques to visualise the lymphatics. The tracers used for these examinations vary according to the procedure and are carried spontaneously via the lymphatic system after being injected into the skin or subcutaneous tissue. Understanding the precise anatomy of the lymphatic system is fundamental for providing a normal control view of the particular body region being examined that in turn enables doctors and researchers to identify changes in patients.

Despite the range of clinical imaging examination techniques, studies of lymphatic anatomy are very limited. The spontaneous transit of lymph fluid terminates in post-mortem specimens and valvular structures inside the lymphatic vessel are located at intervals of a few millimetres. These characteristics mean that retrograde injection from the proximal to the distal is not possible, so injections must be done from distal to proximal. In addition, the lymphatic vessels are transparent and lymph fluid is colourless as it contains no red blood cells, thus it is difficult for anatomists to distinguish lymphatic structure from the surrounding soft tissue. However, pioneer anatomists overcame these difficulties and created detailed medical drawings of the lymphatic system based on their dissections. These drawings continue to be a feature of current anatomical textbooks.

In this article, we provide an overview of the historical techniques used in the study of lymphatic anatomy and introduce our own contribution to this field.

HISTORICAL REVIEWS

Dissection of living animals - discovery of the lymphatic system

Discovery of the lymphatic system is credited to the Italian anatomist Aselli^[10] [Figure 1]. When Aselli was asked by his colleague to demonstrate the recurrent nerve in a living dog, he noticed by chance that

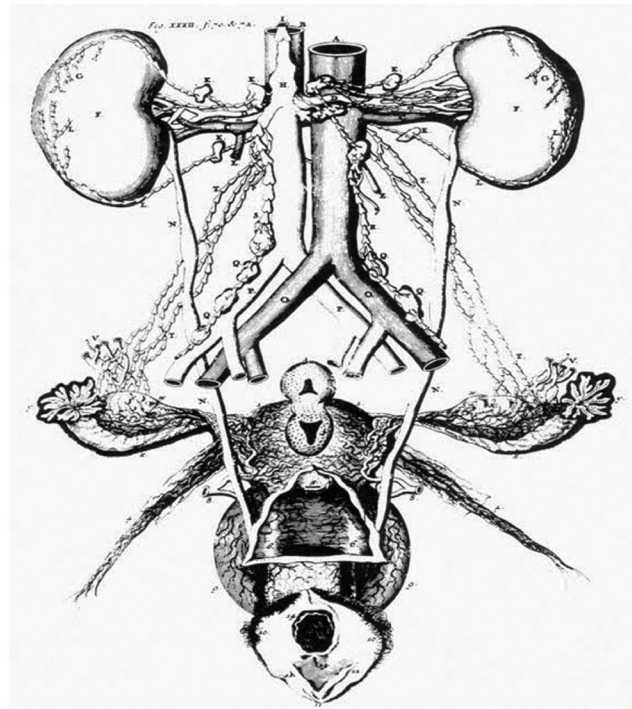


Figure 2. Nuck's^[13] publication in 1696. Mercury injection was applied to the lymphatic vessels in the female reproductive organs (right)

there were many white cords running in the mesentery. Initially, he thought that these cords were nerves, but when he cut them with scissors, he observed milky liquid (lacteal) gushing from the vessels. Aselli attempted to reproduce his findings on another day, but could not find the same type of structure. He then realised that these structures correlated with the absorption of nutrients from the small intestine, because being able to see the vessels depended on the timing of feeding^[11].

Aselli's findings were magnificent and shed light on a new body system. However, the dissection of living animals had limitations for further investigation and led him to the misconception that these vessels connected to the liver, rather than the thoracic duct.

Mercury injection

Malpighi used mercury to observe the arterioles, because he knew mercury was a slippery agent that could penetrate into smaller vessels^[12]. Nuck^[13] made an amalgam by mixing mercury with tin and lead. He used this mixture to identify the lymphatics and his illustrations of the lymphatic vessels are very well detailed [Figure 2]^[13]. Mercury injection became the standard technique for anatomical investigation of the lymphatic system for the next three centuries^[14].

Mascagni^[15] was one of the anatomists who used mercury injection and published his extensive studies in 1787^[16]. His contribution to the field is not only his book containing detailed anatomical illustrations, but also the life-size wax models he created. Mascagni supervised modellers Felice Fontana and Clemente Susini in creating wax models for anatomical teaching^[17,18]. These masterpiece models are well preserved and are still on display at the La Specola Museum in Florence and Josephinum Museum in Vienna.

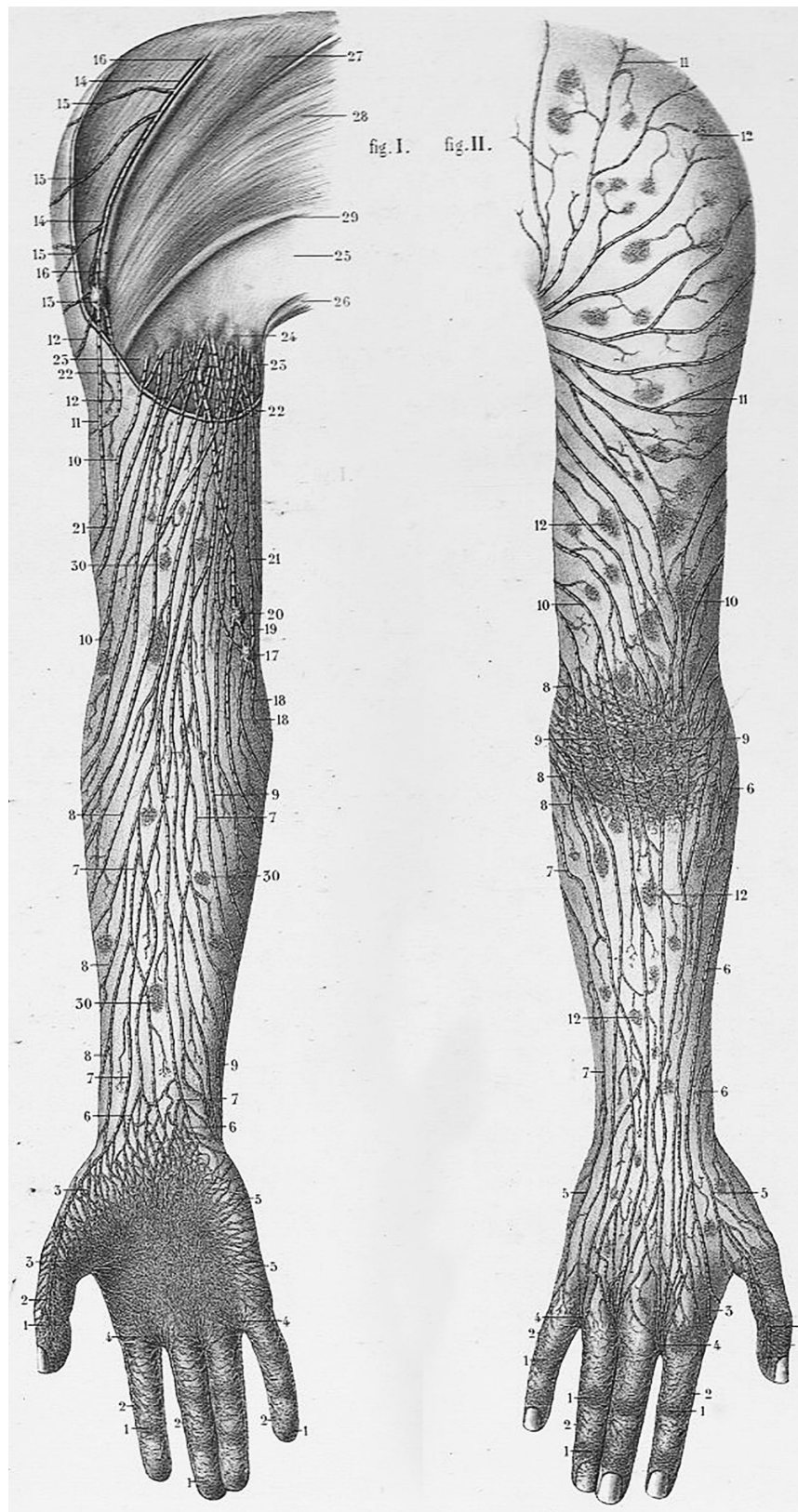


Figure 3. Illustration from Sappey's^[19] book showing lymphatic vessels in the upper extremity identified using the mercury injection technique



Figure 4. Illustration from Bartels'^[24] book showing lymphatic vessels in the upper extremity identified using Gerota's method

Sappey^[19] also used the mercury injection technique and published his findings in 1874 [Figure 3]. His book provided a comprehensive understanding of the human lymphatics, but his superb illustrations were more of artistic than scientific value. Sappey was probably the first anatomist to understand the idea of lymphatic territories defined by a watershed at the midline and a horizontal line crossing the umbilicus in the torso.

To date, anatomical findings with mercury injection were the mainstay of our understanding of the lymphatic system. Anatomists injected mercury directly into the lymphatic vessels or indirectly into the skin in cadaveric specimens using stretched glass tubes or fine needles. The excellent illustrations made by the early anatomists led to the belief that mercury was an ideal material for demonstrating the lymphatics, but it has several downsides. Firstly, mercury is a toxic substance and its use in anatomical investigation was discontinued in the early twentieth century due to concerns about health issues. Secondly, mercury

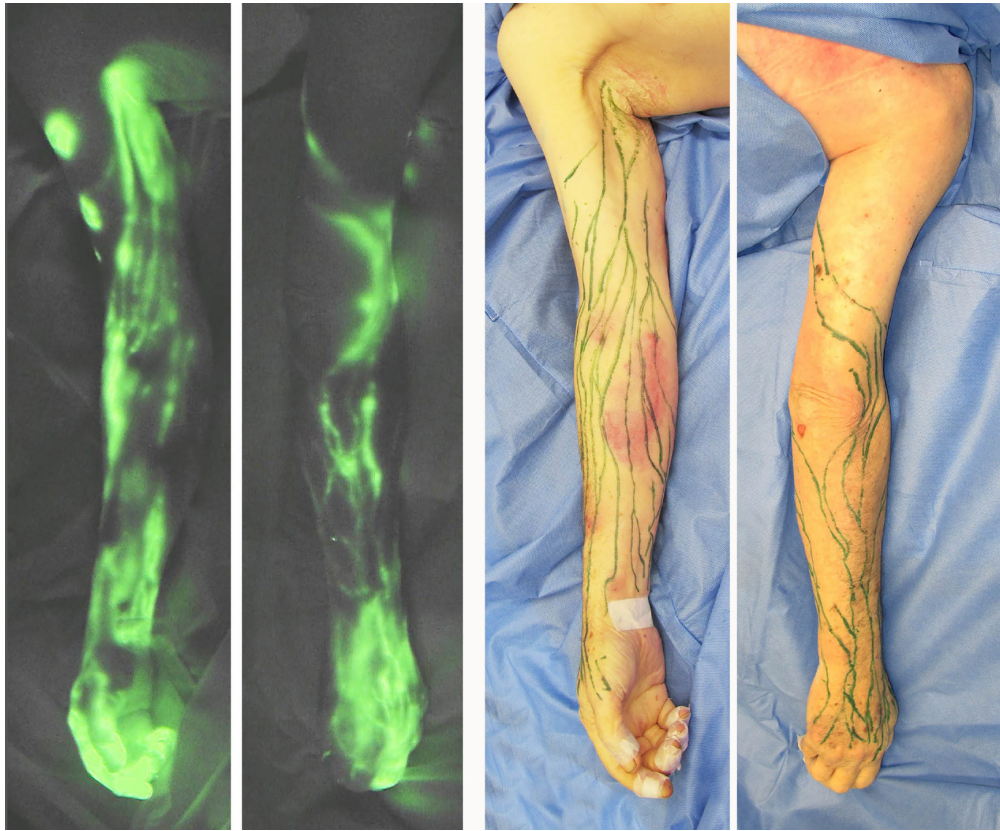


Figure 5. Indocyanine green lymphography image in the upper extremity in a fresh cadaver (left). Lymphatic mapping in the same specimen (right)

was an imperfect tool for identifying the lymphatics. A young male cadaver that had been studied using a mercury injection in the 18th century, possibly by Alexander Monro the Second (1733-1817), was stored at the University of Edinburgh^[20]. When this cadaver was later submitted to radiographic investigation, the radiographs revealed that the mercury had entered not only the lymphatic vessels, but also the veins^[21]. This finding suggests that the anatomists doing the illustrations must have spent a lot of time and effort in manually extracting the information about the lymphatics to create their drawings. Finally, the mercury injection technique was limited in the number of lymphatic vessels that could be identified in each specimen. Hence, Sappey needed to combine findings from multiple specimens to compose a single diagram.

Despite these several downsides of the technique, the painstaking efforts made by pioneer anatomists who used mercury injection succeeded in establishing the solid foundation of lymphatic anatomy for three centuries, and our current knowledge still relies heavily on their achievement.

Dye injection

As a potential replacement for mercury injection, a dye injection method for demonstrating the lymphatics was developed by Gerota^[22] in a technique known as Gerota's method. Gerota's original medium was composed of Prussian blue diluted with turpentine and ether and his method was used by Rouvière^[23] and Bartels^[24] and contributed to their publications [Figure 4].

While studies using mercury injection used mainly adult cadaver specimens, Gerota's method required the use of foetal and child cadavers. The reason for this is that the slippery nature of mercury allowed

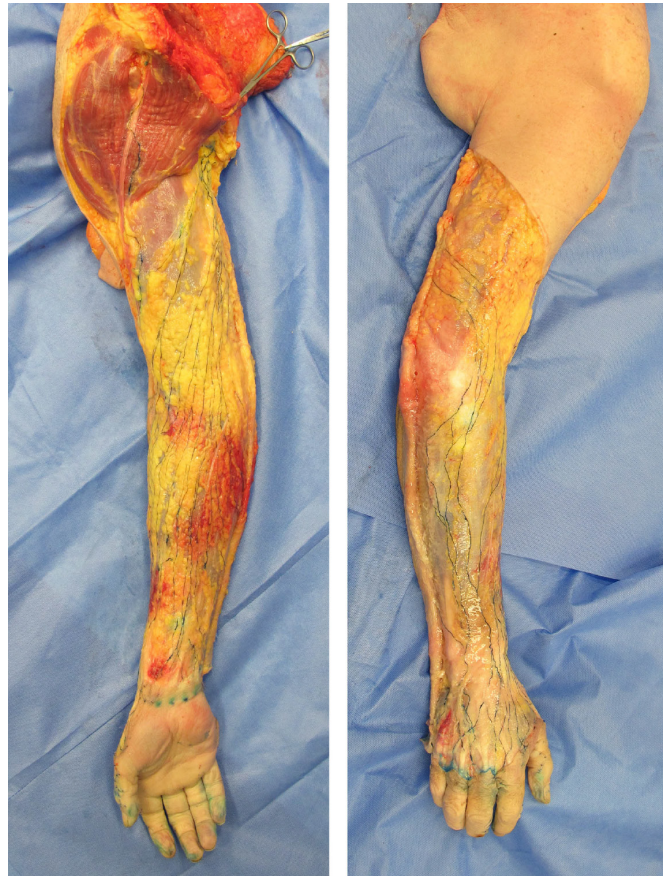


Figure 6. Lymphatic vessels in the specimen in Figure 5 shown using the microinjection technique

it to travel long distances inside the lymphatic vessels, but the dye used in Gerota's method could only travel much shorter distances. To overcome this limitation, anatomists began using smaller bodies, but the difficulty of acquiring a steady supply of foetal specimens became a barrier to anatomical study and was the major factor in the decline of lymphatic anatomy research in the twentieth century. Foetal studies using Gerota's method still continue at the Department of Anatomy at the University of Buenos Aires, where the method is combined with the Spalteholz technique to render tissues translucent^[25].

Microinjection technique with hydrogen peroxide

A new technique to investigate the lymphatic system in adult cadaver specimens without using mercury was developed by Suami *et al.*^[26,27]. In contrast to arteries and veins that contain red blood cells, transparent lymphatic vessels cannot be identified with the naked eye post-mortem because they collapse. Initially, patent blue violet was injected into the cadaver to identify the lymphatic vessels. The dye succeeded in demonstrating some lymphatic vessels, but it also stained the surrounding tissue and prevented any further investigation. After this, hydrogen peroxide was used and found to be an ideal substance to distinguish the lymphatic vessels from the surrounding soft tissue without any contamination. When hydrogen peroxide is injected into the skin and subcutaneous tissue around the area of investigation, its reaction with tissue enzymes produces fine bubbles of oxygen. These bubbles inflate the lymphatic vessels so they can be identified under a surgical microscope. When the location of the vessels has been determined, a fine stretched glass tube or needle is directly cannulated into them and a contrast agent (a radiocontrast medium or dye) is injected to stain them with colour. Once coloured, the vessels can easily be dissected out from the soft tissue. The whole procedure is performed under a surgical microscope and therefore has become known as the microinjection technique. Compared to both the mercury injection technique and

Gerota's method, the microinjection technique requires more dextrous skills in manipulating lymphatic vessels under the microscope.

When a radiocontrast medium is selected as the contrast agent, the prospective radiographic images are similar to those produced by lymphoangiography in live subjects. Lymphangiography is an invasive procedure requiring a small surgery consisting of cutting the skin and cannulating a fine needle into a lymphatic vessel under local anaesthesia^[1]. Usually, only one lymphatic vessel is cannulated. In contrast to lymphoangiography, the microinjection technique in cadaver specimens has no limitation on the number of lymphatic vessels that can be identified, so has the advantage of allowing the researcher to obtain a comprehensive picture of the lymphatics in each specimen. The disadvantage of the microinjection technique is that the contrast medium stops at the sentinel node, so further cannulation in the efferent vessel of the node is essential if the proximal areas are to be investigated. However, the invention of the microinjection technique enabled anatomists to undertake the study of lymphatic anatomy in adult cadavers and contributed to better lymphatic mapping of the body regions^[28-31].

Indocyanine green lymphography

ICG lymphography was initially developed to map the sentinel lymph nodes for breast cancer treatment^[32]. Its application was then expanded to provide imaging for the diagnosis of lymphoedema^[4-6]. ICG is a water-soluble agent that emits near infrared-rays when it combines with protein in the human body. When ICG is injected into the skin, it automatically enters the lymphatic vessels. The infrared camera then scans the limb and captures the emitted signals, causing the vessels to glow green so that they can be identified in real time to a depth of 2 cm from the surface of the skin.

The authors injected ICG into fresh cadavers and confirmed that it was able to identify the lymphatic vessels in post-mortem specimens^[33,34]. ICG lymphography was found to be consistent in identifying the lymphatics and the dye was able to travel long distances from the injection site if fresh, non-frozen cadavers were used. The technique has demonstrated several advantages in anatomical study in a cadaver model. Firstly, lymphatic vessels can be identified without a skin incision, so ICG injections do not disrupt the embalming process to follow and the bodies can be reutilised for anatomical dissection after study of the lymphatics. Secondly, ICG mapping has helped make the microinjection technique more effective, as it provides a more efficient way of locating the lymphatic vessels than injecting hydrogen peroxide, the most time-consuming part of the process. Finally, it has enabled fast mapping of the course of lymphatic vessels and allowed the capture of imaging data from multiple cadaver specimens^[35].

AUTHOR'S CURRENT METHOD

Finally, this paper briefly introduces the specific method we currently use for anatomical investigation of the lymphatic system in a cadaver model. Cadaver specimens are obtained from the institutional willed body program with appropriate approval for their use in scientific investigation. Fresh, non-embalmed and non-frozen specimens are ideal, but previously frozen and thawed specimens can also be used. ICG (Verdye 25 mg, Diagnostic Green GmbH, Germany) is mixed with 20 mL of saline. Taking the investigation in an upper extremity as an example, 0.1 mL doses of ICG solution are injected intradermally into the sides of fingers and several spots in the anterior wrist. After a few minutes of massage at the injection sites, the ICG dye starts entering the lymphatic vessels. Inside the lymphatic vessel, the dye is moved from the distal to proximal by massaging the skin in an axial direction. If the specimen is within a few days post-mortem, the ICG moves all way to the axillary nodes and the course of the vessels is demonstrated with the infrared camera (Photodynamic Eye Neo II, Hamamatsu K.K., Japan). A marker pen is used to mark the lymphatic vessels on the surface of the skin [Figure 5].

If the specimens are needed for further dissection and for use in an anatomical teaching workshop, the microinjection technique is then applied^[33]. Five per cent hydrogen peroxide with/without dye is injected

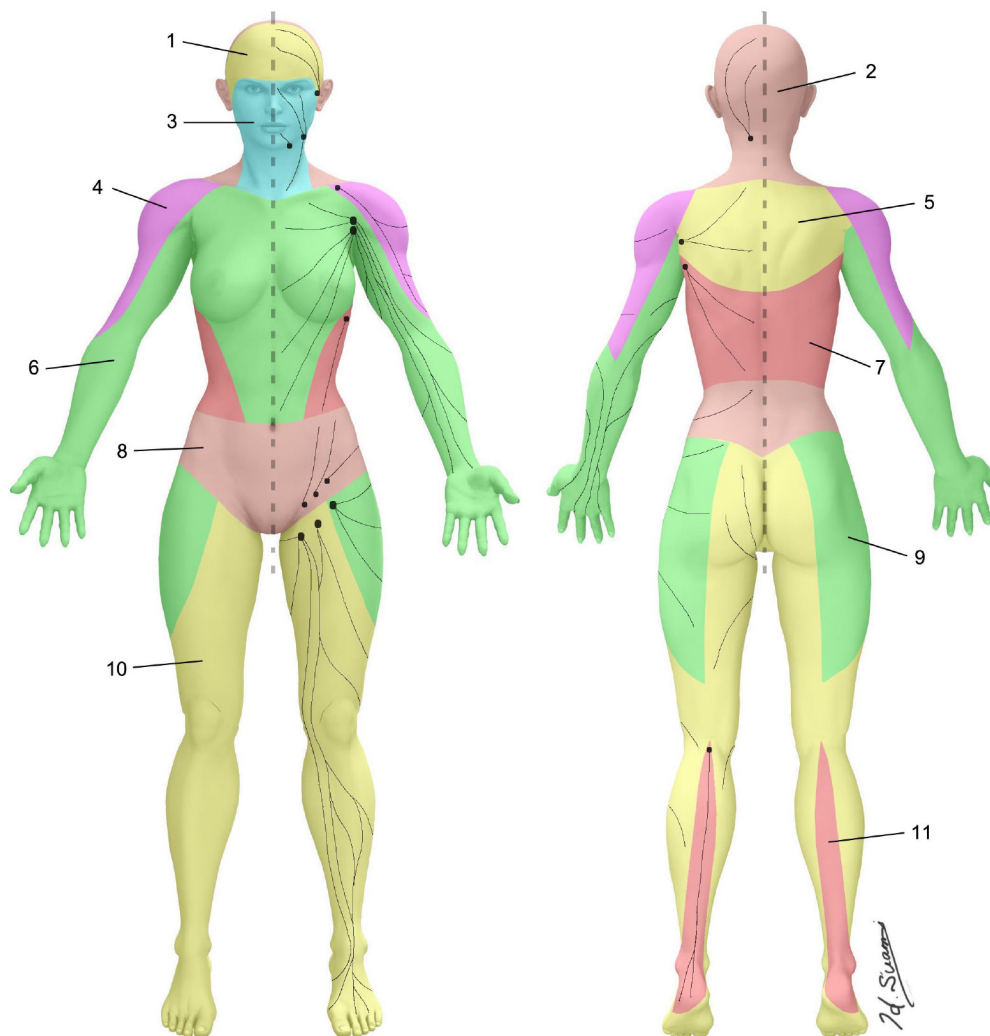


Figure 7. Lymphosomes of the body. The lymphatic territories are demarcated according to their corresponding lymphatic basins: (1) temporal; (2) occipital; (3) submental; (4) subclavicular; (5) subscapular; (6) lateral axillary; (7) pectoral; (8) superior inguinal; (9) lateral inguinal; (10) inferior inguinal; and (11) popliteal. (Reproduced with permission of Suami^[37], 2018)

around the lymphatic vessels identified by the ICG mapping to inflate them for cannulation. The inflated vessels are easily identified in the subcutaneous tissue below the area that has been marked. A 30 G needle connected to an extension tube and 1 mL syringe is set with a micromanipulator (UMM-3FC and UM-1PFC, Narishige Group Co., Japan) and cannulated into the lymphatic vessel. A coloured substance with/without a radiocontrast medium is injected into the lymphatic vessels by manually pumping the 1 mL syringe. After removing the skin just above the stained lymphatic vessels, the lymphatic course is traced until the vessels reach their corresponding lymph nodes [Figure 6].

The combination of ICG lymphography and the microinjection technique works effectively in fresh adult cadavers. We applied this technique to map the lymphatics and found that the skin can be demarcated into groups of lymphatic vessels that connect to the same regional nodes. The author coined the word “lymphosome” to describe these separate lymphatic territories [Figure 7]^[36,37].

Significant anatomical changes occur in lymphoedema^[38-40]. Understanding the normal anatomy of the lymphatics is essential to allow doctors and researchers to distinguish how lymphatic structures altered by lymphoedema differ from the original condition. New imaging techniques continue to be developed and

provide new types of lymphatic images. Physicians need to be able to interpret these images accurately to specify the pathology of lymphatic dysfunction, and anatomical study of the lymphatics is essential to provide the required baseline information.

CONCLUSION

This paper focuses on the techniques that have enabled anatomists to investigate the lymphatic system in cadavers over the past several hundred years. Mercury injection was the mainstay of lymphatic study for many years and our current knowledge still largely depends on findings from more than 100 years ago. New imaging techniques are being developed in the clinical setting, and anatomical research needs to be updated to incorporate these new techniques to provide further information about the lymphatic system.

DECLARATIONS

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Authors' contributions

Study concept and data acquisition: Suami H

Data interpretation and manuscript drafting: Suami H, Shinaoka A

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All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

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REFERENCES

1. Kinmonth JB. Lymphangiography in man; a method of outlining lymphatic trunks at operation. *Clin Sci* 1952;11:13-20.
2. Weissleder H, Weissleder R. Lymphedema: evaluation of qualitative and quantitative lymphoscintigraphy in 238 patients. *Radiology* 1988;167:729-35.
3. Golueke PJ, Montgomery RA, Petronis JD, Minken SL, Perler BA, et al. Lymphoscintigraphy to confirm the clinical diagnosis of lymphedema. *J Vasc Surg* 1989;10:306-12.
4. Ogata F, Narushima M, Mihara M, Azuma R, Morimoto Y, et al. Intraoperative lymphography using indocyanine green dye for near-infrared fluorescence labeling in lymphedema. *Ann Plast Surg* 2007;59:180-4.
5. Unno N, Inuzuka K, Suzuki M, Yamamoto N, Sagara D, et al. Preliminary experience with a novel fluorescence lymphography using indocyanine green in patients with secondary lymphedema. *J Vasc Surg* 2007;45:1016-21.
6. Suami H, Chang DW, Yamada K, Kimata Y. Use of indocyanine green fluorescent lymphography for evaluating dynamic lymphatic status. *Plast Reconstr Surg* 2011;127:74e-6e.
7. Liu NF, Yan ZX, Wu XF, Luo Y. Magnetic resonance lymphography demonstrates spontaneous lymphatic disruption and regeneration in obstructive lymphedema. *Lymphology* 2013;46:56-63.

8. Arrive L, Derhy S, Dlimi C, El Mouhadi S, Monnier-Cholley L, et al. Noncontrast magnetic resonance lymphography for evaluation of lymph node transfer for secondary upper limb lymphedema. *Plast Reconstr Surg* 2017;140:806e-11e.
9. Baulieu F, Bourgeois P, Maruani A, Belgrado JP, Tauveron V, et al. Contributions of SPECT/CT imaging to the lymphoscintigraphic investigations of the lower limb lymphedema. *Lymphology* 2013;46:106-19.
10. Aselli G. De lactibus, sive lacteis venis, quarto vasorum mesaraicorum genere novo inuento. Milan, Italy; 1627.
11. Leeds SE. Three centuries of history of the lymphatic system. *Surg Gynecol Obstet* 1977;144:927-934.
12. Young J. Malpighi's "De Pulmonibus". *Proc R Soc Med* 1929;23:1-11.
13. Nuck A. Adenographia curiosa et uteri foemineae anatomie nova. Lugduni Batavorum, P. vander Aa; 1692.
14. Handriksen MM. Anatomical mercury: changing understandings of quicksilver, blood, and the lymphatic system, 1650-1800. *J Hist Med Allied Sci* 2015;70:516-48.
15. Mascagni P. Vasorum lymphaticorum corporis humani historia et ichnographia. Sienna: P Carli; 1787.
16. Bertelli R. Paolo Mascagni (1755-1815). *J Cardiovasc Surg (Torino)* 1961;2:414-21.
17. Riva A, Conti G, Solinas P, Loy F. The evolution of anatomical illustration and wax modelling in Italy from the 16th to early 19th centuries. *J Anat* 2010;216:209-22.
18. Hilloomala R, Renahan J. 18th-Century anatomical models at La-Specola, Florence. *Anat Anzeiger* 1985;159:141-58.
19. Sappey MPC. Anatomie, physiologie, pathologie des vaisseaux lymphatiques consideres chez l'homme et les vertebres. Paris A 1885.
20. Kaufman MH. Observations on some of the plates used to illustrate the lymphatics section of Andrew Fyfe's compendium of the anatomy of the human body, published in 1800. *Clin Anat* 1999;12:27-34.
21. Kaufman MH, Best JJ. Monro Secundus and 18th century lymphangiography. *Proc R Coll Physicians Edinb* 1996;26:75-90.
22. Gerota D. Zur technik der lymphgefassinjection. Eine neue injectionmasse für lymphgefasse. Polychrom injection. *Anat Anz* 1896;12:216-24.
23. Rouvière H. Anatomie des lymphatiques de l'Homme. Paris; 1981.
24. Bartels P. Das lymphgefäßsystem. In: BARDELEBEN, Handbuch der Anatomie des Menschen. Jena: Gustav Fischer; 1909.
25. Amore M, Tapia L, Mercado D, Pattarone G, Ciucci J. Lymphedema: a general outline of its anatomical base. *J Reconstr Microsurg* 2016;32:2-9.
26. Suami H, Taylor GI, O'Neill J, Pan WR. Refinements of the radiographic cadaver injection technique for investigating minute lymphatic vessels. *Plast Reconstr Surg* 2007;120:61-7.
27. Suami H, Taylor GI, Pan WR. A new radiographic cadaver injection technique for investigating the lymphatic system. *Plast Reconstr Surg* 2005;115:2007-13.
28. Suami H, Taylor GI, Pan WR. The lymphatic territories of the upper limb: anatomical study and clinical implications. *Plast Reconstr Surg* 2007;119:1813-22.
29. Pan WR, Suami H, Taylor GI. Lymphatic drainage of the superficial tissues of the head and neck: anatomical study and clinical implications. *Plast Reconstr Surg* 2008;121:1614-24; discussion 25-6.
30. Suami H, O'Neill JK, Pan WR, Taylor GI. Superficial lymphatic system of the upper torso: preliminary radiographic results in human cadavers. *Plast Reconstr Surg* 2008;121:1231-9.
31. Suami H, Pan WR, Mann GB, Taylor GI. The lymphatic anatomy of the breast and its implications for sentinel lymph node biopsy: a human cadaver study. *Ann Surg Oncol* 2008;15:863-71.
32. Kitai T, Inomoto T, Miwa M, Shikayama T. Fluorescence navigation with indocyanine green for detecting sentinel lymph nodes in breast cancer. *Breast Cancer* 2005;12:211-215.
33. Scaglioni MF, Suami H. Lymphatic anatomy of the inguinal region in aid of vascularized lymph node flap harvesting. *J Plast Reconstr Aesthet Surg* 2015;68:419-27.
34. Shinaoka A, Koshimune S, Yamada K, Kumagishi K, Suami H, et al. A fresh cadaver study on indocyanine green fluorescence lymphography: a new whole-body imaging technique for investigating the superficial lymphatics. *Plast Reconstr Surg* 2018;141:1161-4.
35. Shinaoka A, Koshimune S, Yamada K, Kumagishi K, Suami H, et al. Correlations between tracer injection sites and lymphatic pathways in the leg: a near-infrared fluorescence lymphography study. *Plast Reconstr Surg* 2019;144:634-42.
36. Suami H. Lymphosome concept: anatomical study of the lymphatic system. *J Surg Oncol* 2017;115:13-7.
37. Suami H, Scaglioni MF. Anatomy of the lymphatic system and the lymphosome concept with reference to lymphedema. *Semin Plast Surg* 2018;32:5-11.
38. Suami H, Pan WR, Taylor GI. Changes in the lymph structure of the upper limb after axillary dissection: radiographic and anatomical study in a human cadaver. *Plast Reconstr Surg* 2007;120:982-91.
39. Suami H, Koelmeyer L, Mackie H, Boyages J. Patterns of lymphatic drainage after axillary node dissection impact arm lymphoedema severity: a review of animal and clinical imaging studies. *Surg Oncol* 2018;27:743-50.
40. Suami H, Heydon-White A, Mackie H, Czerniec S, Koelmeyer L, et al. A new indocyanine green fluorescence lymphography protocol for identification of the lymphatic drainage pathway for patients with breast cancer-related lymphoedema. *BMC Cancer* 2019;19:985.

AUTHOR INSTRUCTIONS

1. Submission Overview

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2. Submission Preparation

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Manuscript Type	Definition	Abstract	Keywords	Main Text Structure
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Original Article	An Original Article describes detailed results from novel research. All findings are extensively discussed.	Structured abstract including Aim, Methods, Results and Conclusion. No more than 250 words.	3-8 keywords	The main content should include four sections: Introduction, Methods, Results and Discussion.
Review	A Review paper summarizes the literature on previous studies. It usually does not present any new information on a subject.	Unstructured abstract. No more than 250 words.	3-8 keywords	The main text may consist of several sections with unfixed section titles. We suggest that the author include an "Introduction" section at the beginning, several sections with unfixed titles in the middle part, and a "Conclusion" section in the end.
Case Report	A Case Report details symptoms, signs, diagnosis, treatment, and follows up an individual patient. The goal of a Case Report is to make other researchers aware of the possibility that a specific phenomenon might occur.	Unstructured abstract. No more than 150 words.	3-8 keywords	The main text consists of three sections with fixed section titles: Introduction, Case Report, and Discussion.
Meta-Analysis	A Meta-Analysis is a statistical analysis combining the results of multiple scientific studies. It is often an overview of clinical trials.	Structured abstract including Aim, Methods, Results and Conclusion. No more than 250 words.	3-8 keywords	The main content should include four sections: Introduction, Methods, Results and Discussion.
Systematic Review	A Systematic Review collects and critically analyzes multiple research studies, using methods selected before one or more research questions are formulated, and then finding and analyzing related studies and answering those questions in a structured methodology.	Structured abstract including Aim, Methods, Results and Conclusion. No more than 250 words.	3-8 keywords	The main content should include four sections: Introduction, Methods, Results and Discussion.
Technical Note	A Technical Note is a short article giving a brief description of a specific development, technique or procedure, or it may describe a modification of an existing technique, procedure or device applied in research.	Unstructured abstract. No more than 250 words.	3-8 keywords	/
Commentary	A Commentary is to provide comments on a newly published article or an alternative viewpoint on a certain topic.	Unstructured abstract. No more than 250 words.	3-8 keywords	/
Editorial	An Editorial is a short article describing news about the journal or opinions of senior editors or the publisher.	None required	None required	/
Letter to Editor	A Letter to Editor is usually an open post-publication review of a paper from its readers, often critical of some aspect of a published paper. Controversial papers often attract numerous Letters to Editor.	Unstructured abstract (optional). No more than 250 words.	3-8 keywords (optional)	/
Opinion	An Opinion usually presents personal thoughts, beliefs, or feelings on a topic.	Unstructured abstract (optional). No more than 250 words.	3-8 keywords	/
Perspective	A Perspective provides personal points of view on the state-of-the-art of a specific area of knowledge and its future prospects. Links to areas of intense current research focus can also be made. The emphasis should be on a personal assessment rather than a comprehensive, critical review. However, comments should be put into the context of existing literature. Perspectives are usually invited by the Editors.	Unstructured abstract. No more than 150 words.	3-8 keywords	/

2.3 Manuscript Structure

2.3.1 Front Matter

2.3.1.1 Title

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protein names are included, the abbreviated name rather than full name should be used.

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Authors' full names should be listed. The initials of middle names can be provided. Institutional addresses and email addresses for all authors should be listed. At least one author should be designated as corresponding author. In addition, corresponding authors are suggested to provide their Open Researcher and Contributor ID upon submission. Please note that any change to authorship is not allowed after manuscript acceptance.

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Methods should contain sufficient details to allow others to fully replicate the study. New methods and protocols should be described in detail while well-established methods can be briefly described or appropriately cited. Experimental participants selected, the drugs and chemicals used, the statistical methods taken, and the computer software used should be identified precisely. Statistical terms, abbreviations, and all symbols used should be defined clearly. Protocol documents for clinical trials, observational studies, and other non-laboratory investigations may be uploaded as supplementary materials.

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This section should discuss the implications of the findings in context of existing research and highlight limitations of the study. Future research directions may also be mentioned.

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It should state clearly the main conclusions and include the explanation of their relevance or importance to the field.

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Organization as author	Diabetes Prevention Program Research Group. Hypertension, insulin, and proinsulin in participants with impaired glucose tolerance. <i>Hypertension</i> 2002;40:679-86. [PMID: 12411462]

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Books	Sherlock S, Dooley J. Diseases of the liver and billiary system. 9th ed. Oxford: Blackwell Sci Pub; 1993. pp. 258-96.
Book chapters	Meltzer PS, Kallioniemi A, Trent JM. Chromosome alterations in human solid tumors. In: Vogelstein B, Kinzler KW, editors. The genetic basis of human cancer. New York: McGraw-Hill; 2002. pp. 93-113.
Online resource	FDA News Release. FDA approval brings first gene therapy to the United States. Available from: https://www.fda.gov/NewsEvents/Newsroom/PressAnnouncements/ucm574058.htm . [Last accessed on 30 Oct 2017]
Conference proceedings	Harnden P, Joffe JK, Jones WG, editors. Germ cell tumours V. Proceedings of the 5th Germ Cell Tumour Conference; 2001 Sep 13-15; Leeds, UK. New York: Springer; 2002.
Conference paper	Christensen S, Oppacher F. An analysis of Koza's computational effort statistic for genetic programming. In: Foster JA, Lutton E, Miller J, Ryan C, Tettamanzi AG, editors. Genetic programming. EuroGP 2002: Proceedings of the 5th European Conference on Genetic Programming; 2002 Apr 3-5; Kinsdale, Ireland. Berlin: Springer; 2002. pp. 182-91.
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