Plastic and Aesthetic Research

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

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 payed 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

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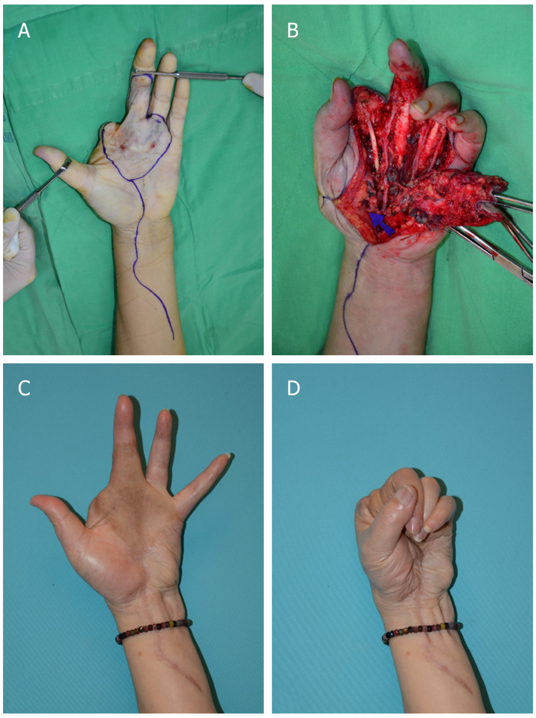

Figure 1. A: The 45-year-old woman was affected by arteriovenous malformation of the left hand. The index finger had been previously amputated due to recurrent and excessive bleeding. Before surgery, the residual lesion was marked according to angiography study; B: the arteriovenous malformation was 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 fasciocutanous 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 factures 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

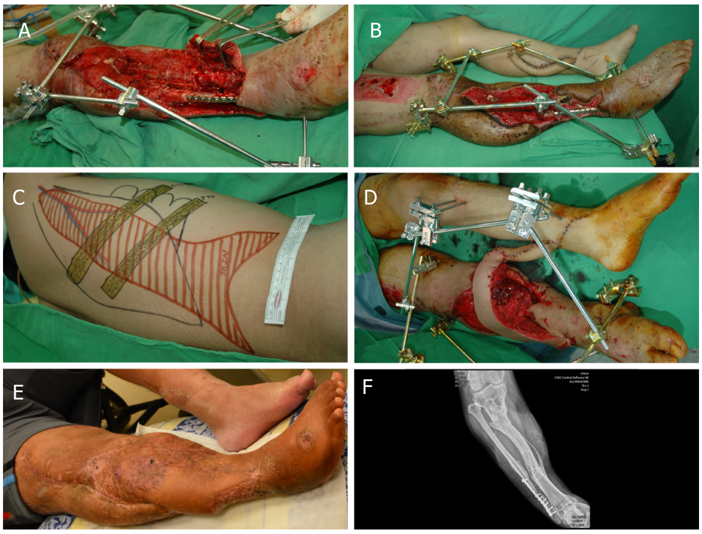

Figure 3. A: The 25-year-old patient had a severe crush injury to his right lower limb in a car accident. The leg survived after thrombectomy of the right femoral artery. There was a 12 cm defect of the right tibia after debridement, and the fractured fibula was plated as shown; B: there was no available 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 myocutanous 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 form 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.

Financial support and sponsorship

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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