**Plastic and
Aesthetic Research**

Review

Management of digital neuromas: an update on current nonoperative and operative interventions

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Abstract

Digital neuromas can be psychologically and functionally debilitating. While typically the result of penetrating traumatic injury, neuromas also stem from blunt trauma, chronic irritation, or prior inadequate repair. Abnormal axonal regeneration without an appropriate distal target following nerve injury results in the formation of end-neuromas, often leading to significant pain. Conservative management is centered around a combination of pharmacological interventions and therapeutic modalities. In the setting of failed conservative management, surgical intervention is employed with the goals of excising the neuroma and redirecting axonal growth into healthy tissue. This article focuses on painful digital neuromas and options for both nonoperative and operative management.

Keywords: Hand surgery, digital neuroma, coaptation, nerve repair, nerve transposition, RPNI

INTRODUCTION

Digital neuromas are the result of abnormal nerve regeneration following peripheral nerve injury typically caused by traumatic lacerations, amputations, or crush injuries. Approximately 5% of digital neuromas are symptomatic[1,2]. However, more than half of symptomatic patients will undergo surgical intervention for relief of symptoms. Painful neuromas have debilitating psychological and functional sequelae, including

chronic pain, depression, and anxiety[3]. Therefore, a multidisciplinary approach to management is imperative in this patient population.

Pathophysiology

Following complete transection, the commonly encountered bulbous nerve ending comprised of disorganized Schwann cells, fibroblasts, connective tissue, and axons with mixed myelination is known as an end-neuroma[4]. Internal fascicular damage in the absence of complete transection from blunt trauma or repetitive nerve injury (pressure, irritation, or entrapment) triggers a similar bulbous overgrowth known as a neuroma-in-continuity[4,5]. Disorganized axonal regeneration following peripheral nerve injury is the hallmark of neuroma formation.

Etiology

Digital nerve injuries may be acute or chronic but are typically the result of acute trauma. Acute injuries are typically the result of either penetrating or blunt trauma. Penetrating trauma may result in partial or complete transection of the nerve, while blunt trauma results in crush or stretch injury. Chronic nerve injury results from repetitive nerve injury from either stretch, pressure, or irritation[4]. A well-known, chronic nerve injury is Bowler's thumb, a condition resulting from repetitive compression and friction of the ulnar digital nerve of the thumb[6-8]. Patients typically present with pain, paresthesia, and a mass effect of the digital nerve well described as perineural fibrosis[6,8]. Histologically, the masses in Bowler's thumb exhibit perineural scar formation with interfascicular fibrosis, which differs from the disorganized axonal and Schwann cells typically found in traumatic neuromas[8]. While predominantly described in the bowling community, case reports have also described this condition in other athletes and therapists[9,10]. Additional causes of nerve injury may be iatrogenic as a result of prior surgical interventions.

Diagnosis

Correctly identifying the etiology, timeline, and location of injury is imperative to developing an appropriate plan for intervention. Patient history and physical exam may localize the injury and assess functional sequelae of injury. Patient interviews should reveal the mechanism and timing of injury, associated symptoms, functional deficits, and prior attempts at treatment, if any. It is also important to obtain hand dominance and occupation in addition to clarifying patient goals prior to planned interventions. For physical exams, inspection is a powerful tool. Swelling, atrophy, ecchymosis, scars, lacerations, open wounds, abnormal hand postures, or contractures can both localize injury and assess the severity of local tissue injury. Sensation assessments via palpation, two-point discrimination, or Semmes-Weinstein monofilaments may establish the degree of nerve injury[11]. The most commonly utilized test for the painful neuroma is a positive Tinel's sign, which produces paresthesias when tapping over the nerve[11,12]. One should carefully note altered sensations including hyperesthesia, allodynia, or hypoesthesia surrounding the site of injury[13]. An additional finding on physical exam is cold intolerance, which is frequently reported by patients with symptomatic neuromas[14]. A useful adjunct to the physical exam is local anesthesia, which can be injected into the area of the mass lesion [either seen on an exam or by ultrasound (US)] to both localize the affected portion of the nerve and confirm nerve injury as the source of symptomatology.

Additional diagnostic tools include imaging and functional modalities. Both high-definition nerve US - also known as neurosonography - and magnetic resonance imaging (MRI) have been debated regarding their abilities to effectively visualize peripheral neuromas[15,16]. There are a limited number of reports exploring the use of US or MRI in digital nerve injuries. Though neurosonography is limited by user dependence, it is easy to operate, non-invasive, cost-efficient, and effective in identifying space-occupying lesions or sites of compression[17,18]. In cases of inconclusive ultrasonographic studies, MRI is a useful tool to stratify patients

by severity of nerve injury as it provides evaluators with information regarding nerve morphology. Changes to nerve morphology as a result of injury are seen earlier with MRI as opposed to electrodiagnostic testing, which may not be altered for weeks[19]. Such findings on MRI can classify a lesion as more severe, prompting earlier surgical intervention[8,19]. Classic functional diagnostic modalities for larger peripheral nerve injuries include nerve conduction studies (NCS) and electromyography (EMG)[11,15]. However, these have a limited role and are rarely used in the evaluation of digital nerve injuries[20]. Ultimately, the best diagnostic tool is operative exploration to identify involved nerves and assess the local tissue environment [Figure 1].

NONOPERATIVE MANAGEMENT

The development of neuropathic pain is multifactorial, and management goes beyond the use of any single modality. Nonoperative management can be divided into pharmacologic agents and therapy modalities that aim to desensitize affected nerves, alleviate pain, or decrease local inflammation and fibrosis[13]. Pharmacologic agents encompass oral, systemic, topical, and injectable therapies. Physical therapy modalities include a variety of interventions that aim to alter pain perception via desensitization. The goal of the surgeon, in collaboration with pain specialists and occupational/physical therapists, is to create a multimodal regimen that is specific to each patient.

Pharmacologic agents
Oral agents
The most commonly employed first-line oral agents for neuropathic pain include gabapentinoids and antidepressants[21]. Gabapentinoids include gabapentin and pregabalin and work via calcium channel blockade. Gabapentin is dose-dependent and should be taken three times a day. Pregabalin touts the benefit of higher bioavailability due to dose independence and is typically dosed twice daily. Both medications should be weaned as abrupt cessation may lead to withdrawal with common side effects including dizziness, somnolence, and fatigue. Though historically employed as anticonvulsant medications, they are now commonly utilized for peripheral neuropathy and postherpetic neuropathy. A small body of literature has explored the role of gabapentinoids for neuropathy in the setting of painful neuromas and post-amputation pain[22]. In preclinical trials, gabapentin has been shown to improve neuropathic pain following traumatic nerve injury[23]. However, studies in adults following traumatic nerve injury have had varied results, with some studies showing little to no effect following a short trial[21]. Additionally, gabapentin has additional side effects of gastrointestinal distress and peripheral edema. Pregabalin, though less widely studied, has shown promising results in the adult population following traumatic nerve injury[24]. In a randomized, double-blind, placebo-controlled phase III trial, Markman *et al.* showed statistically significant improvement in secondary outcomes following a 15-week trial of pregabalin following traumatic nerve injury[25]. These outcomes centered around improvements in quality of life, such as decreased sleep interference and improved pain interference according to the Brief Pain Inventory[26].

The role of antidepressants has been heavily studied for the management of neuropathic pain, with a focus on tricyclic antidepressants (TCAs) and serotonin-norepinephrine reuptake inhibitors (SNRIs)[13]. TCAs, including amitriptyline and nortriptyline, act via serotonin and norepinephrine reuptake inhibition but are less selective than SNRIs. Amitriptyline is more commonly studied in traumatic nerve injury among TCAs, and in various pain algorithms, it is still considered a first-line agent that should be employed under a 4-6-week trial[27,28]. Commonly studied SNRIs in the pain literature include duloxetine and venlafaxine for various causes of peripheral neuropathy[29]. Duloxetine has been studied for peripheral nerve injury and phantom limb pain with successful results, specifically in combination with pregabalin[30]. Anxiety and depression are common among patients with neuropathic pain. These concomitant mood disorders both decrease patient's quality of life and alter their experience of pain, making them less likely to respond to
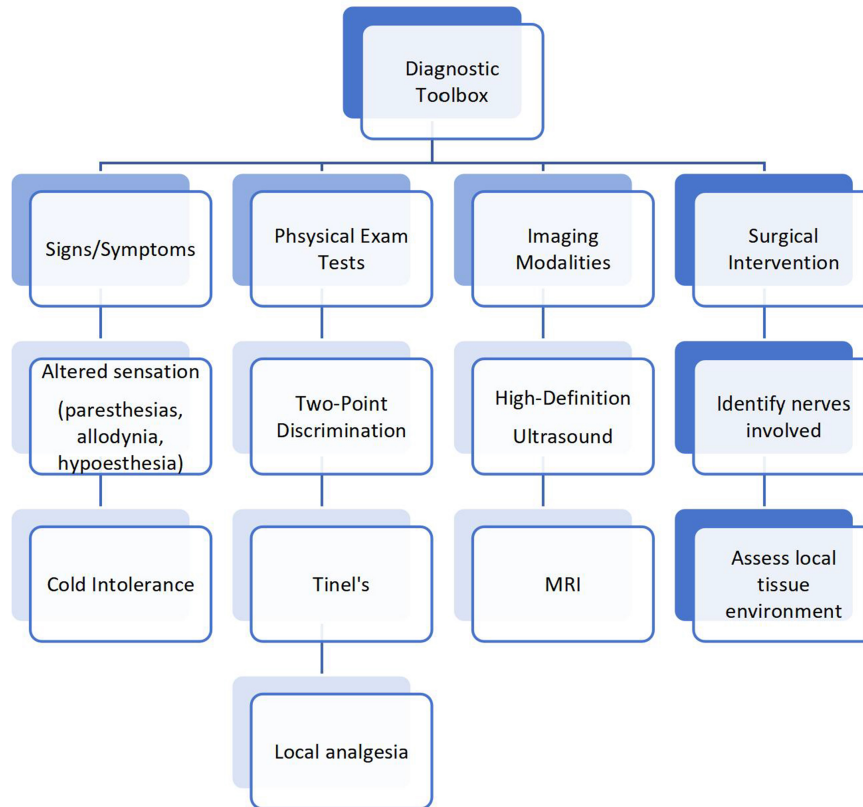
Figure 1. Schematic demonstrating various tools for diagnosing a digital neuroma.

surgical interventions[31-33]. Therefore, it is important to screen for mood disorders and implement the appropriate therapies when indicated.

Topicals/injections
Capsaicin and lidocaine have been described as topical and local agents for peripheral neuropathy, though not well studied in traumatic nerve injuries[22]. Capsaicin is a transient receptor potential vanilloid 1 (TPVR1) receptor agonist typically employed in an 8% formulation. As a topical, capsaicin has been shown to decrease stump pain and allodynia following limb amputation[34]. Though typically employed topically in an 8% formulation, it has also been studied as an injectable, specifically for Morton's neuroma - an interdigital neuroma between the third and fourth toes - with patients showing significant improvement in pain scores and improved functional interference scores 2-3 weeks following initial injection[35]. Morton's neuroma is the result of a degenerative neuropathy and differs from traumatic neuromas. Therefore, capsaicin injections for traumatic digital neuromas must be further studied.

The role of lidocaine in peripheral neuropathy is both diagnostic and therapeutic. Lidocaine blocks nerve transmission via voltage-gated sodium channel blockade and is utilized by both surgeons and anesthesiologists in the perioperative period. It can be administered topically, locally, or intravenously. For the purpose of diagnosis via local injection, the timing of onset is within 90 s and lasts 20 min when administered in a plain formulation without a vasoconstrictor[36]. Relief of neuropathic pain following injection can successfully localize a painful neuroma and is easily utilized in the clinical outpatient setting. Topical lidocaine is typically administered in a 5% formulation and has been well studied in the management of neuropathic pain for postherpetic neuropathy, trigeminal neuralgia, and diabetic

neuropathy[37,38]. Its use for painful digital neuromas is not well studied but could be a helpful topical adjunct in this patient population.

Therapeutic modalities

Close coordination with hand therapy is imperative for surgical patients with a painful neuroma. While comprehensive physical and occupational therapeutic protocols are outside of the scope of this article, we will briefly review commonly utilized interventions and exercises for patients with neuropathic pain. Though Fisher and Boswick described three nonoperative therapies for painful digital neuromas in 1983, these are still commonly utilized[39]. Scar massage, percussion, and US continue to have roles in hand therapy for patients with painful neuropathic pain. Scar massage can be employed at the surgeon's discretion but is typically initiated once surgical incisions are well healed. Scar massage has been extensively studied in burn literature and has been found to not only increase the pliability of hypertrophic scars but also decrease sensitivity[40]. Percussion follows similar principles of altering afferent nerve signaling. Low-intensity pulsed US has shown promising results in peripheral neuropathy and is a commonly employed modality in therapy protocols[41,42]. Finally, transcutaneous electrical nerve stimulation (TENS) is an additional modality often used in hand therapy. TENS works via activation of opioid receptors in the central nervous system, leading to desensitization in the area of treatment[43]. It is important to note that there are a number of interventional pain therapies extensively described in the amputee population, including preoperative analgesia, continuous peripheral nerve blocks, neurolysis, and neuromodulation. However, these have not yet been studied in the digital neuroma population[44].

Nonoperative management of peripheral neuropathy following traumatic peripheral nerve injury encompasses a small portion of the literature outlining the algorithms for neuropathic pain [Figure 2]. Therefore, multidisciplinary management of painful neuromas is imperative to effectively trial nonoperative management in this patient population. When nonoperative therapies prove ineffective, surgical interventions should be explored.

OPERATIVE MANAGEMENT

In the case of failed nonoperative management or debilitating peripheral neuropathy secondary to a painful neuroma, surgical intervention provides the most promising outcomes. Initial management of painful neuromas was simple neurectomy performed by sharp division of the distal nerve ending just proximal to the neuroma in the case of end-neuroma. Early outcomes in the absence of surgical alternatives were promising, with excellent or satisfactory patient outcomes reported in approximately two-thirds of patients following crush, semi-sharp, or sharp injuries following initial neurectomy[45]. However, later studies exhibited increasingly high rates of re-operation following simple neurectomy[4]. The introduction of nerve transposition into veins, muscle, and bone rendered simple neurectomy less than ideal for definitive management of painful neuromas. Surgical interventions for painful neuromas continue to evolve, evidenced by the recent advent of targeted muscle reinnervation (TMR) and regenerative peripheral nerve interface (RPNI)[46,47] [Figure 3].

Nerve coaptation

Direct end-to-end neurorrhaphy has proven successful in both the prevention of neuroma formation at initial surgery and the improvement of neuropathic pain following secondary surgery. In a retrospective study of 289 partial hand and digital amputations in 54 patients, Maslow *et al.* found that direct coaptation resulted in significant improvement of postoperative pain compared to patients who had undergone simple neurectomy[12]. Taras *et al.* conducted a retrospective study on patient outcomes following dorsal coaptation after the excision of digital neuromas and found that 84% of patients reported complete relief of stump
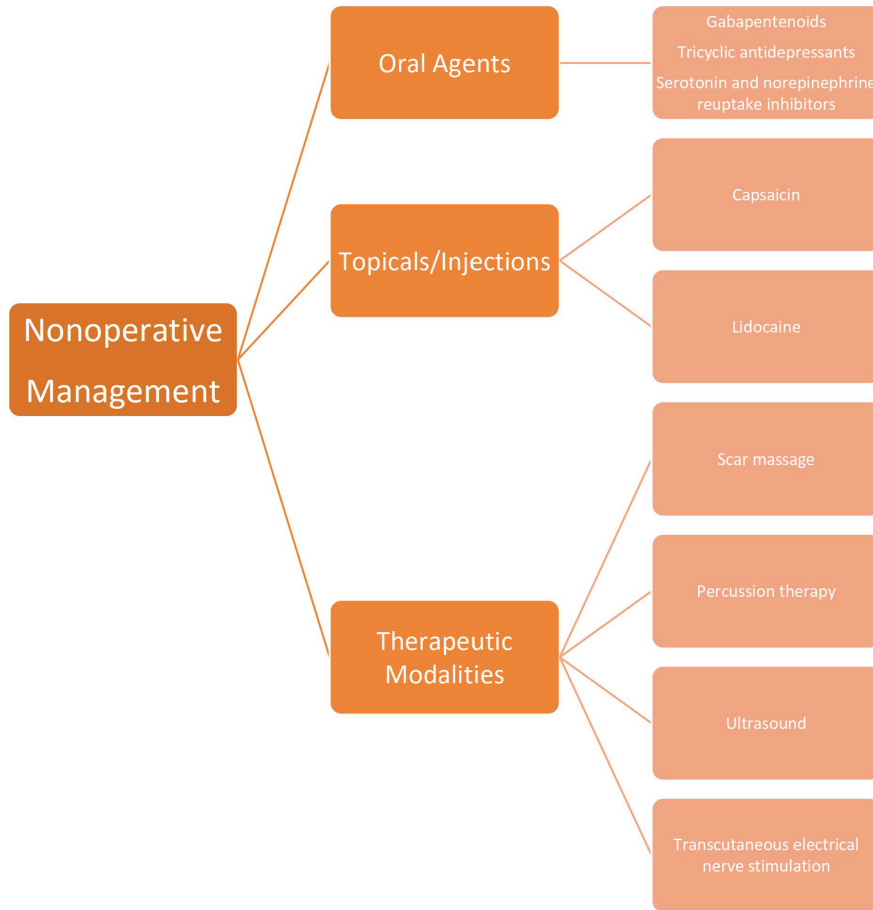
Nonoperative Management

Oral Agents
- Gabapentenoids
- Tricyclic antidepressants
- Serotonin and norepinephrine reuptake inhibitors

Topicals/Injections
- Capsaicin
- Lidocaine

Therapeutic Modalities
- Scar massage
- Percussion therapy
- Ultrasound
- Transcutaneous electrical nerve stimulation

Figure 2. Schematic summary of nonoperative interventions.

Nerve Coaptation	Transposition	RPNI	TMR	Nerve Capping
• Direct end-to-end neurorrhaphy • Dorsal nerve coaptation	• Vein • Muscle • Bone	• Flexor digitorum superficialis • Brachioradialis	• Interossei • Lumbricals • Thenar muscles	• Silicone • Collagen • Bioengineered

Figure 3. Schematic of options for surgical intervention.

pain[2]. The surgical technique for nerve coaptation begins with tourniquet hemostasis and direct visualization under loupe magnification. Both radial and ulnar digital nerves should be identified and traced proximal outside of the zone of injury. Existing neuromas should be excised at the level of digital nerve bifurcation or trifurcation, commonly located at the distal interphalangeal joint[48]. Distal nerve endings of the radial and ulnar digital nerves should then be transposed dorsally and coapted with a 9-0 epineural suture [Figure 4]. The dorsal location removes the regenerating nerve from an area of repeated trauma and out of the original zone of injury likely plagued by inflammation or fibrosis.
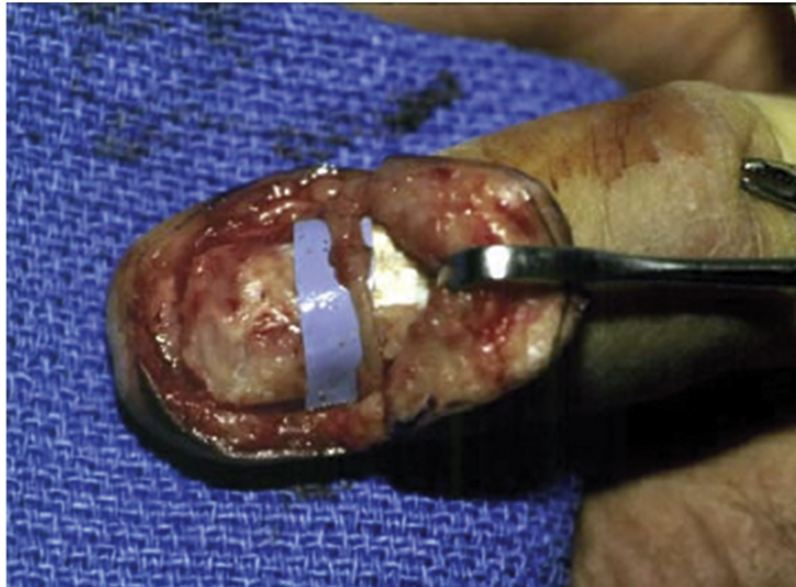
Figure 4. Intraoperative photo of dorsal coaptation of radial and ulnar artery digital nerves.

Transposition

Nerve transposition to adjacent tissue (i.e., vein, muscle, bone) is a historical technique for painful neuromas of the hand, which quickly replaced simple neurectomy[49,50]. In 1998, Sood *et al.* described three zones of the hand to simplify options for transposition of end-neuromas in the hand[51]. Zone 1 includes dorsal and volar neuromas located distal to the metacarpophalangeal joint, thereby including neuromas of the proper digital nerves. The distal location of digital nerves, small caliber of surrounding vasculature, and absence of local muscle limits options for transposition in Zone 1 injuries. Therefore, the most common transposition of digital nerves in Zone 1 is into the proximal phalanx or metacarpal[52,53]. When possible, the authors' preferred method for neuromas in Zone 1 is dorsal coaptation, as described in the previous section. Areas of minimal trauma or motion are preferred to stabilize the free nerve ending and prevent neuroma formation, obviating the use of local intrinsic muscles.

RPNI

RPNI was developed by Cederna and Chestek in 2012 as a novel technique to improve neuropathic pain[46]. The surgical technique includes sharp proximal transection of the affected nerve and implantation into a free muscle graft. RPNI touts the benefits of improving neuropathic pain and improving prosthetic control. RPNI may be employed for the painful digital neuroma by harvesting a free muscle graft via a separate incision in the proximal hand, most commonly the flexor digitorum superficialis or brachioradialis[46]. More distant donor sites from the lower extremity may be employed in the setting of polytrauma and the immediate availability of muscle graft obviates the need for a second proximal incision. Harvest of the muscle graft should be in line with muscle fibers and inset should result in an epineural attachment to the central portion of the graft. A nonabsorbable monofilament suture should be utilized (e.g., 6-0 Nylon). The literature surrounding RPNI in the upper extremity has shown promising outcomes. In 2020, Hooper *et al.* conducted a retrospective study of 30 therapeutic RPNIs in symptomatic neuromas of the hand and digits, showing an 85% considerable improvement in the complete resolution of neuropathy by final clinic follow-up[46]. RPNI may additionally be employed as a preventative measure in the setting of digital amputations, given the ease of technique and proven benefits.

Targeted muscle reinnervation

Initially described in 2009 by Kuiken *et al.*, TMR is a novel surgical technique originally designed to improve functional control of myoelectric prostheses[47]. Over the past decade, TMR has been increasingly employed in the prevention of post-amputation neuropathic pain and associated neuromas[54-57]. The operative goal is to redirect sensory peripheral nerves transected following amputation into motor entry points of newly denervated adjacent muscles. Though more commonly employed for more proximal nerve injuries, it has recently been described following digital amputations[58]. Indications for TMR in digital nerve injuries following amputation include chronic, painful neuropathy or prophylaxis at the time of revision amputation to prevent neuroma formation. In the hand, the most commonly utilized expendable muscles (i.e., muscles previously directed into the now amputated segment) include the palmar and volar interossei for index, long, ring, and small fingers[58,59]. The interossei have 1-1.4 motor entry points that originate from the deep branch of the ulnar nerve, which travels radially within the deep palmar space after exiting Guyon's canal[59,60]. Additionally, utilized motor entry points include those entering the lumbricals for index, long, ring, and small fingers. Thenar muscle motor entry points are utilized for thumb amputations and hypothenar muscle motor entry points for small finger amputations[59].

Nerve capping

Though less commonly utilized in the setting of adequate local tissue coverage, nerve caps still play a small role in the management of painful digital neuromas. Nerve capping employs synthetic materials to contain the proximal nerve ending following neuroma excision. Nerve caps are theorized to prevent neuroma formation by (1) decreasing interaction with locally inflamed or fibrous tissue and (2) mechanically blocking axonal growth, thereby allowing the epineurium to heal over transected fascicles in a more organized manner. Early reports of synthetic nerve caps were centered around silicone caps[45]. These lost favor in the setting of varied patient outcomes and re-explorations in the setting of failure that revealed dislodgement or ineffective containment of axonal outgrowth. Recent literature has shown an influx of various bioengineered materials for use, including porcine, acellular nerve allograft, and polyglycolic acid[61-64]. In a narrative literature review of all studies employing the use of nerve caps, Sisti *et al.* found promising outcomes with the use of Neurocap and collagen[65]. Neurocap is a bioresorbable copolyester poly(DL-lactide-e-caprolactone) that has been shown to improve pain scores associated with end-neuromas of the median and superficial radial sensory nerve. Collagen caps recently employed are typically derived from type I collagen and have had excellent outcomes in the lower extremities[66]. Uemura *et al.* describe a successful case of a collagen conduit for nerve capping of a long finger digital neuroma following the excision of a recurrent fibroma. Patients had a significant reduction in the Visual Analogue Scale and the quick Disabilities of the Arm, Shoulder and Hand questionnaire[67].

Surgical interventions for digital neuromas continue to evolve with the advancement of research and technology. It is important to understand the risks and benefits of various techniques in order to guide patient management. Oftentimes, surgical interventions are supplemented with medications and therapeutic modalities. The author's preferred algorithm for management involves optimizing medical management and attempting therapeutic modalities for patients with mild to moderate symptoms. If these nonoperative interventions fail, we will proceed with surgery. For those with moderate to severe symptoms, we will proceed with surgery employing one of the above methods. If pain persists postoperatively, we maintain consistent follow-up and optimize medical management in collaboration with specialists in pain management and hand therapy.

CONCLUSION

The painful digital neuroma is a challenge for both patients and surgeons. The impact on patients' quality of life as a result of poorly managed neuropathic pain can be functionally and psychologically debilitating. It is

imperative from a surgical standpoint to have a thorough understanding of the patient's symptomatology and physical exam in order to both localize the neuroma and create a treatment plan that addresses the patient's specific goals. While nonoperative interventions have been less thoroughly studied for digital neuromas, the surgeon should be aware of their options and understand that multimodal interventions are more likely to achieve pain relief compared to the use of a single agent. In the case of refractory neuropathic pain, operative intervention will be most successful for pain relief. Operative techniques for digital neuromas continue to evolve and preliminary studies have shown promising results, especially with the newer techniques such as RPNI and TMR. While the painful digital nerve can be a challenge to the hand surgeon, the options are extensive and the body of literature for management continues to grow.

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Authors' contributions
Performed extensive literature review and executed manuscript drafting: Turner A
Contributed significantly to editing and discussions regarding surgical technique: Woodberry K, Taras JS

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Ethical approval and consent to participate
The study included by Taras *et al.* with use of Figure 4 was approved by the Institutional Review Board.

Consent for publication
Not applicable.

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Hand+Surgery&ots=eFgQCjvlbv&sig=QWZCPr5s0WTbWPehWp335gg75E8#v=onepage&q=Isaacs%20J.%20Nerve%20Repair.%20In%3A%20Green%E2%80%99s%20Operative%20Hand%20Surgery&f=false. [Last accessed on 19 Aug 2024].

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