

A Practical Approach to Nerve Grafting in the Upper Extremity

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In this era of tissue bioengineering an autogenous nerve graft may be considered the ultimate biocompatible, resorbable nerve conduit, with a basil lamina, preformed guidance channels, a reserve of viable Schwann cells, and nerve growth factors. In addition, it is capable of developing an intrinsic circulation. The nerve graft provides a regenerating axon with a means for passage to the distal nerve stump, while protecting it from the surrounding environment. There is no foreign body reaction and no graft-versus-host response. An enterprising biotechnology company undoubtedly would have no difficulty marketing this product. The results obtained with nerve autografts constitute the gold standard by which nerve conduits are designed and measured. Despite this seemingly utopian picture, the donor site morbidity and the limitations of nerve grafting have led to a search for alternate methods. This search has been addressed eloquently by Strauch and Chui and their coauthors elsewhere in this issue. This article focuses on the ways in which the nerve responds to injury and how it regenerates, followed by some practical considerations for autologous nerve grafting.

Nerve response to injury

Cell body

The neuron consists of a central cell body, located within the central nervous system, and a peripheral axon. The axon represents a tremendously elongated process attached to the nerve cell body. Thousands of axons make up the substance of a peripheral nerve. The axon contains 90% of the axoplasmic volume. When a nerve is severed, one immediate consequence is loss of this vital fluid [1]. The normal retrograde transport of neurotrophic factors from the target organ ceases. The cell body undergoes chromatolysis, which includes mitochondrial swelling, migration of the nucleus to the periphery, and dispersal of Nissl substance. The more proximal the site of transection, the more intense the reaction, which peaks by 2 to 3 weeks. The cell body may die and is lost from the neuron pool. If it survives, however, the cell body shifts its resources toward replacing the axoplasm and rebuilding the axon.

Distal axon

The distal axon cannot survive without its connection to the cell body and disintegrates (ie, wallerian degeneration). Endoneurial edema occurs within a few hours [2]. The microtubules and neurofilaments of the distal axon, which are responsible for axoplasmic transport, undergo proteolysis by a calcium-activated neutral protease [3]. At 72 hours, the Schwann cells can be seen digesting the myelin sheath and axonal subcomponents [4]. Endoneurial collagen

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production from Schwann cells and fibroblasts increases, causing progressive shrinkage of the distal tubules [5]. The Schwann cells rapidly proliferate, forming columns (the bands of Büngner) that appear to stimulate the direction and magnitude of axonal growth.

Proximal axon

After transection, there is demyelination of the distal stump. The axons degenerate to one or more proximal internodes. The distance varies with the severity of injury, ranging from a few millimeters with mild trauma to several centimeters with severe injury [6]. The endoneurial tube lies empty, consisting mostly of the Schwann cell basal lamina.

Axon regeneration

Nerve regeneration does not involve mitosis and multiplication of nerve cells. Instead the cell body restores nerve continuity by growing a new axon. Axon sprouting has been shown 24 hours after nerve transection. One axon sends out multiple unmyelinated axon sprouts from the tip of the remaining axon or collateral sprouts from a nearby proximal node of Ranvier. The distal sprout contains the growth cone; this sends out filopodia [7], which adhere to sticky glycoprotein molecules in the basal lamina of Schwann cells, such as laminin and fibronectin (neurite-promoting factors) [8]. The filopodia contain actin, which aids in pulling the growth cone distally [9]. The basal lamina of two abutting Schwann cells forms a potential endoneurial tube into which the regenerating axon grows. These axons deteriorate if a connection with a target organ is not reached. There are 50 advancing sprouts from one axon. Initially, there are many more nerve fibers crossing a nerve repair than in the parent nerve [10]. Although more than one axon may enter the same endoneurial tube, there is eventual resorption of the multiple sprouts, leaving one dominant axon.

Axons grow 1 to 2 mm/day [11]. The normal 16-day turnover rate of acetylcholine receptors is shortened in denervated muscle to about 4 days [12]. For practical purposes, the maximum length that a nerve can grow to restore motor function is approximately 35 cm. This fact in part accounts for the poor motor recovery when grafting nerve defects proximal to the elbow in adults. Sensory end organs remain viable because there is no end plate and retain the potential for reinnervation [13]. Nerve grafting a digital nerve defect may provide protective sensation even after many years.

Role of the Schwann cell

The importance of maintaining Schwann cell viability in the nerve graft is evident. After nerve transection, the Schwann cell removes the axonal and myelin debris in the severed nerve ends and the nerve graft. Schwann cells produce an immediate source of nerve growth factor, which helps to support the proximal stump [14,15]. The Schwann cell expresses nerve growth factor receptors, which aid in directing the advancing growth cone [16]. It also increases its production of other neurotrophic factors, including ciliary neurotrophic factor, brain-derived neurotrophic factor, and fibroblast growth factor, which promote axonal growth [17]. The laminin and fibronectin in the Schwann cell basal lamina act as a rail for the advanced axon sprouts to grow down. The Schwann cell produces a myelin sheath for the immature axon sprout. Cell biologists have attempted to mimic these functions by incorporating Schwann cells, laminin, fibronectin, and nerve growth factors into synthetically engineered nerve conduits.

Role of the nerve graft

The nerve graft acts to provide a source of empty endoneurial tubes through which the regenerating axons can be directed. Any tissue that contains a basal lamina, such as freeze-dried muscle or tendon, can be substituted [18], but only the autogenous nerve graft also provides a

source of viable Schwann cells. To be effective, the graft must acquire a blood supply. If the nerve graft survives, the Schwann cells also survive [19].

Graft incorporation

When separated from its blood supply, the graft undergoes wallerian degeneration. Schwann cells can survive 7 days, depending purely on diffusion [19a]. By 3 days after implantation, there is invasion of the nerve graft by endothelial buds from the surrounding tissue bed, with evidence of high nerve blood flows by 1 week [20,21]. This segmental vascular sprouting from extraneural vessels is not limited by the length of the graft [22,23]. The length of the graft is, within certain limits, of no significance to the end result, provided that there is a tension-free anastomosis [24]. The ingrowth of vessels from the ends of the graft (inosculation) does not seem to be of major importance, unless the recipient bed is poorly vascularized [23]. The late phase of nerve graft incorporation shows migration of Schwann cells from the proximal nerve end into the graft and from the graft into both host nerve ends [25].

Graft diameter

Small-diameter grafts spontaneously revascularize, but large-diameter grafts do so incompletely [26]. Thick grafts undergo central necrosis with subsequent endoneurial fibrosis. This fibrosis ultimately impedes the advancement of any ingrowing axon sprouts. Cable nerve grafts are similar to thick grafts. They consist of numerous nerve grafts that are sutured or glued together to match the caliber of the recipient nerve. Because a large percentage of the surface is in contact with another graft and not in contact with the recipient bed, the central portions may not revascularize. With large-diameter recipient nerves, it is preferable to use multiple smaller caliber grafts to bridge fascicular groups in the proximal and distal stumps to increase the surface area that is in contact with the recipient bed.

Nerve biomechanics

A normal nerve has longitudinal excursion, which subjects it to a certain amount of stress and strain in situ. Peripheral nerve is initially easily extensible. It rapidly becomes stiff with further elongation as a result of the stretching of the connective tissue within the nerve [27]. Chronically injured nerves become even stiffer [28]. Elasticity decreases by 50% in the delayed repair of nerves in which wallerian degeneration has occurred [29]. Experimentally, blood flow is reduced by 50% when the nerve is stretched 8% beyond its in vivo length. Complete ischemia occurs at 15% [30]. Suture pullout does not occur until a 17% increase in length; this suggests that ischemia and not disruption of the anastomosis is the limiting factor in acute nerve repairs [31]. This observation also is applicable to nerve grafting.

Nerve is a viscoelastic tissue in that when low loading in tension is applied over time, the nerve elongates, without a deterioration in nerve conduction velocities. Stress relaxation results in recovery of blood flow within 30 minutes at 8% elongation [29]. Intriguing experimental work has been done with gradual nerve elongation to overcome nerve gaps using tissue expansion [32] and external fixation [33], but this cannot be considered an accepted standard of treatment as yet.

A normal nerve can compensate for the change in length with limb flexion and extension because it is surrounded by gliding tissue that permits longitudinal movement. The change in length is distributed over the entire nerve so that the elongation of each nerve segment is small. A nerve graft becomes welded to its recipient bed by the adhesions through which it becomes vascularized. As a consequence, the nerve graft is exquisitely sensitive to tension because it has no longitudinal excursion. The harvested length of the graft must be long enough to span the nerve gap without tension while the adjacent joints are extended; this is also the position of temporary immobilization. If the limb or digit is immobilized with joint flexion, the graft becomes fixed in this position. When the limb is mobilized at 8 days, the proximal and distal stumps are subject to tension even though the graft initially was long enough. Early attempts at lengthening the graft lead to disruption of the anastomosis.

Grafting versus primary repair

A tension-free repair is the goal for any nerve anastomosis. When there is a clean transection of the nerve and the gap is caused by elastic retraction, an acute primary repair is indicated. When treatment of a nerve laceration is delayed, fibrosis of the nerve ends prevents approximation, and nerve grafting is indicated even though there is no loss of nerve tissue. As a general rule, primary nerve repair yields superior results to nerve grafting, provided that there is no tension across the anastomotic site [34]. Grafting can obtain similar results to primary repair under ideal conditions [35]. If a nerve is repaired under tension, however, the results are superior with an interpositional graft [36]. Axon sprouts are able to cross two tension-free anastomotic sites more easily than crossing one anastomosis that is under tension [37].

Nerve grafting is indicated to bridge a defect when greater than 10% elongation of the nerve would be necessary to bridge the gap [29]. This is a better indication for grafting than the nerve gap per se, although 4 cm is often used as the critical defect for grafting in the limb [38]. Defects less than this may be overcome by nerve rerouting and transposition in some instances.

Nerve gap

There is a difference between the nerve gap and a nerve defect. A *nerve gap* refers to the distance between the nerve ends, whereas a *nerve defect* refers to the actual amount of nerve tissue that is lost. With simple nerve retraction after division, the fascicular arrangement is similar. As the defect between the proximal and distal stumps increases, there is a greater fascicular mismatch between the stumps, which leads to poorer outcomes. Gaps greater than 5 cm have been reported to affect the result adversely [39].

Considerations for donor nerve grafts

Many conditions must be met for a nerve to be considered as a potential graft. First, the relationship between the surface area and the diameter of the graft must be optimal to allow rapid revascularization. The donor site defect from sacrifice of any given nerve must be acceptable for the patient. The harvested nerve must be long enough to ensure a tension-free anastomosis with the adjacent joints in full extension. Finally, the cross-sectional area and number of fascicles should match those of the recipient nerve at the level of injury as closely as possible. For these reasons, most of the available grafts are cutaneous nerves.

Most donor grafts are imperfect matches of the recipient nerve. The fascicular arrangement of the nerve graft is dissimilar to the nerve being repaired in size, number, and fascicular topography. The branching pattern of the grafts usually changes from an oligofascicular pattern proximally to a polyfascicular pattern distally, which typically corresponds to the branching pattern of the recipient nerve. There may be some loss of axon sprouts owing to growth down peripheral branches that leave the nerve graft. Some authors have recommended inserting the grafts in a retrograde manner for this reason, but others believe this is not warranted [24]. The choice of nerve graft is dictated by the length of the nerve gap, the cross-sectional area of the recipient nerve, the available expendable donor nerves for that particular nerve injury, and the surgeon's preference.

Donor nerve grafts

As a general rule, it is good practice to divide the donor nerve in an intermuscular plane rather than in the subcutaneous tissue to diminish the risk of a painful neuroma. Innovative surgeons continue to provide novel ways in which to bridge nerve gaps, such as using the fascicular group to the third web space as a source of nerve graft material for bridging median nerve gaps [40] and the distal anterior interosseous nerve to reconstruct neuromas of the recurrent motor branch of the median nerve [41]. Some commonly used donor nerves are summarized here.

Upper extremity grafts

Medial antebrachial cutaneous nerve

The medial antebrachial cutaneous nerve (MABCN) arises from either the medial cord or the lower trunk of the brachial plexus. It travels down the arm medial to the brachial artery, then pierces the deep fascia with the basilic vein about the middle of the arm. More than 90% of the time, the MABCN bifurcates into anterior and posterior branches proximal to the medial epicondyle [42], which provide sensation to the medial forearm and posteromedial elbow. It is preferable to use the anterior branch to avoid a bothersome sensory loss over the elbow. The anterior branch crosses the elbow between the medial epicondyle and the biceps tendon usually in front of the cubital vein, then travels superficial to the flexor carpi ulnaris muscle, ending 10 cm from the wrist. It is approached through an anteromedial incision on the proximal forearm. It provides a graft of 20 cm.

Lateral antebrachial cutaneous nerve

The lateral antebrachial cutaneous nerve (LABCN) is the distal continuation of the musculocutaneous nerve. It exits from underneath the biceps tendon, then divides into anterior and posterior branches at the elbow crease. The donor site defect corresponds to the anterolateral forearm, but it also may innervate the volar radial or dorsoradial thumb. For this reason, it is not harvested for grafting a sensory nerve deficit to the thumb [43]. There is a partial or complete overlap of the sensory territory of the superficial radial nerve 75% of the time [44]. The nerve is approached through an anterolateral incision on the proximal forearm, as it passes deep to the cephalic vein (Fig. 1). The LABCN provides a nerve graft of 5 to 8 cm.

Posterior cutaneous nerve of the forearm

The posterior cutaneous nerve of the forearm (PCNF) is a sensory branch of the radial nerve that rarely may be used as a source of graft material. It arises from the radial nerve in the spiral groove and pierces the lateral head of the triceps. It descends the lateral side of the arm, then travels down the dorsal forearm to the wrist, where it communicates with terminal branches of the LABCN. It supplies sensation to the posterolateral forearm. It is identified via a dorsolateral incision at the elbow between the junction of the brachioradialis and the extensor carpi radialis longus. The PCNF provides 2 to 5 cm of graft material [45].

Superficial radial nerve

The superficial radial nerve (SRN) is prone to painful neuroma formation after trauma; it is not a first-line choice of graft. It may be used for proximal radial nerve injuries, where it is excluded from grafting, unless it can be separated from the motor fibers; this is to prevent any regenerating motor nerve fibers from being misdirected to cutaneous reinnervation. The SRN separates from the radial nerve just distal to the elbow in the front of the lateral epicondyle, then descends behind the brachioradialis along the lateral side of the upper forearm. It branches into a major palmar and dorsal branch. The SRN can be identified through a dorsolateral incision approximately 7 cm from the wrist, where it winds around the tendon of the brachioradialis to pierce the deep fascia. The area of hypoesthesia corresponds to the dorsum of the thumb and adjacent sides of the first and second web space. It can provide a nerve graft of 15 to 20 cm.



Fig. 1. Isolation of the LABCN while harvesting a radial forearm flap.

Dorsal cutaneous branch of the ulnar nerve

The dorsal cutaneous branch of the ulnar nerve (DCBUN) is an uncommon source of nerve graft that has been employed with clinical success. It is an appropriate size and length for use as a digital nerve graft. It can be identified at its takeoff from the main ulnar nerve, 5 cm proximal to the wrist. It passes distally under cover of the flexor carpi ulnaris (FCU), then perforates the deep fascia. It runs along the dorsomedial aspect of the wrist and hand before dividing into two to three dorsal digital branches. The area of sensory loss corresponds to the dorsal ulnar aspect of the carpus and proximal parts of the ring and small fingers. Painful neuroma formation or loss of hand function related to the use of this nerve is not typical [46]. The nerve can be approached through a dorsomedial incision centered over the distal radioulnar joint. The DCBUN provides a graft of 4 to 6 cm (see Fig. 2).

Posterior interosseous nerve

The terminal portion of the posterior interosseous nerve (PIN) provides proprioception to the joint capsule. Harvesting the nerve leaves no apparent motor or sensory deficit. The PIN lies adjacent to the posterior interosseous artery on the dorsal surface of the interosseous membrane, deep to the fourth extensor compartment. It ranges from 1 to 5 mm and contains one to five fascicles. It is a good match for grafting digital nerve defects at the distal interphalangeal joint (DIP) [47]. The nerve can be located through a dorsal wrist incision just proximal to Lister's tubercle, developing the plane between the third and fourth extensor compartments. The mean length of the PIN from its terminal expansion at the wrist to its most distal muscular branch (to the extensor pollicis longus) is 6 cm [48].

Anterior interosseous nerve

The terminal portion of the anterior interosseous nerve (AIN) also provides proprioception to the joint capsule. Harvesting the nerve similarly leaves no apparent motor or sensory deficit. The nerve is located adjacent to the anterior interosseous artery on the anterior surface of the interosseous membrane, deep to the pronator quadratus. It also can be approached through a dorsal incision as for the PIN, after excising a window in the interosseous membrane (Fig. 3). The primarily motor fibers of the AIN provide an expendable donor of adequate size and fascicle number suitable for grafting the recurrent motor branch of the median nerve [41] or the deep motor branch of the ulnar nerve at the wrist [49].

Lower extremity grafts

Sural nerve

The sural nerve is a common source of nerve graft material. It is formed from the medial cutaneous sural nerve that originates from the tibial nerve. It descends between the two heads of the gastrocnemius piercing the deep fascia in the upper part of the leg, where it is joined by the

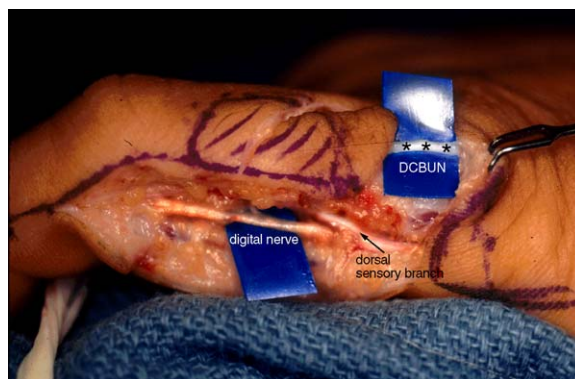


Fig. 2. Dorsal sensory branch arising from the proper digital nerve of the small finger. Abbreviation: *(DCBUN), dorsal cutaneous branch of the ulnar nerve.

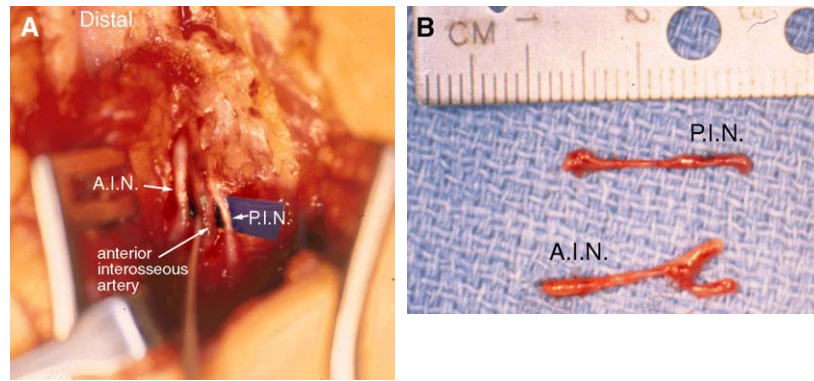


Fig. 3. AIN and PIN grafts. (A) Intraoperative photo of PIN. A window in the interosseous membrane allowed isolation of the AIN. (B) Typical size of harvested grafts.

lateral sural cutaneous branch off the peroneal nerve. It then passes downward near the lateral margin of the Achilles tendon to the interval between the lateral malleolus and the calcaneus. After giving off a medial calcaneal branch, it runs forward, below the lateral malleolus, and is continued along the lateral side of the foot. It supplies the skin of the lateral and posterior part of the lower one third of the leg. To harvest the nerve, the patient is positioned supine on the operating table, with a sandbag placed at midcalf level. The leg is flexed with the foot on the sandbag to maintain the flexed knee position. The nerve is located via a longitudinal incision that is 1 cm posterior and superior to the lateral malleolus, where it often is accompanied by the lesser saphenous vein. Traction is placed on the nerve until it can be palpated 3 cm proximally, then a second transverse incision is made. In this manner, the nerve is followed as high as the popliteal fossa by dividing all of the sural communicating branches. The sural nerve provides graft lengths of 30 to 40 cm (Fig. 4).

Superficial peroneal nerve

The superficial peroneal nerve generally has been overlooked as a potential donor nerve graft. It is the major lateral branch of the common peroneal nerve that innervates the peroneus longus and brevis muscles and provides sensation to the lateral aspect of the lower leg and dorsal foot. It begins at the bifurcation of the common peroneal nerve between the fibula and the proximal peroneus longus. It then descends on the interosseous membrane with the anterior tibial artery to the front of the ankle joint, where it divides into a lateral and medial terminal branch. It can be located through an anterolateral ankle incision, then followed proximally. It provides a consistently long graft, comparable to the sural nerve. It has been used successfully for grafting of the median, radial, and ulnar nerves, including digital nerve defects. It is of particular use when multiple or long nerve grafts are required [50].

Lateral femoral cutaneous nerve

The lateral femoral cutaneous nerve is an independent branch off the lumbosacral plexus that provides sensation to the anterolateral aspect of the thigh. It pierces the fascia lata 2 cm below and medial to the anterior superior iliac spine. It is approached through an incision medial and inferior to the anterior superior spine. The nerve is identified where it becomes subcutaneous, just distal to the sartorius. It provides a graft 10 to 20 cm long.

Saphenous nerve

The saphenous nerve is the largest cutaneous branch of the femoral nerve. It descends on the lateral side of the femoral artery and enters the adductor canal. It descends along the medial side of the knee, then becomes subcutaneous between the tendons of the sartorius and gracilis. It passes down the medial side of the leg next to the saphenous vein. It divides into a medial and lateral branch in the lower one third of the leg, continuing as far as the great toe. The nerve can be identified through a posteromedial incision adjacent to the long saphenous vein, midway between

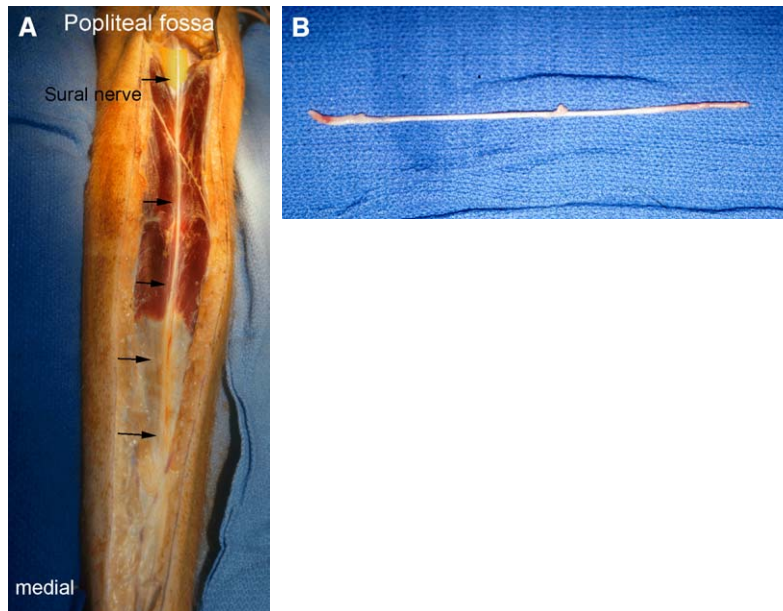


Fig. 4. (A) The sural nerve anatomy looking from the posterior aspect of a prone right leg (arrows). (B) Harvested sural nerve graft.

the medial malleolus and Achilles tendon. It provides a graft of 40 cm in length. It should not be harvested if the sural nerve also is being used because of the large combined donor site defects.

Nerve graft preparation

Millessi [24,51] has written extensively on nerve graft preparation. If the recipient nerve is the approximate diameter of the graft, the two stumps are transected until normal-appearing tissue without fibrosis is seen. The graft is inserted by an epineurial repair. If the recipient nerve is larger than the graft, the fascicular pattern determines the type of preparation. If the nerve contains one to four fascicles, the stump is resected until healthy tissue is encountered. Multiple nerve grafts are used to cover completely the cross-sectional area of each fascicle (ie, 1:2 or 1:3 ratio).

When there are 5 to 12 fascicles that are the size of the nerve graft, each fascicle is grafted individually. When there is a polyfascicular pattern with a group fascicular arrangement, interfascicular dissection is performed to isolate the fascicle groups, which are grafted individually. Millessi recommended sectioning each group of fascicles at different levels to prevent an overlap of the suture lines. If there is no group fascicular arrangement, interfascicular dissection is not performed. Graft insertion is guided by the intraneural topography of the nerve for that specific level of injury.

Motor sensory differentiation

The use of intraoperative motor and sensory nerve differentiation can diminish the risk of fascicular mismatch when grafting a nerve. Available methods are the anatomic method, based on separate identification of groups of fascicles [52–55]; the electrophysiologic method, using awake stimulation [56]; and histochemical methods, which rely on staining for enzymes specific to motor or sensory nerves [57].

Electrical fascicle identification

Awake stimulation requires the cooperation of the anesthesiologist and the patient. It is based on the observation that motor and sensory fascicles can be differentiated by direct

stimulation [58]. The median and ulnar nerves in the distal forearm are most amenable to this technique [56]. It is especially useful when there is a nerve defect, owing to the dissimilar fascicular pattern between the proximal and distal nerve ends. The initial nerve dissection is performed under a regional block with tourniquet control. The wound is infiltrated with local anesthetic before release of the tourniquet. After 20 minutes, the patient is awakened. A low-amperage stimulator is applied to the major fascicles of the proximal nerve end in a systematic manner, starting at 0.2 to 0.5 mA. Sensory fascicles elicit pain and may be localized to a specific digit. Motor fascicles elicit no response at lower intensities and poorly localized pain at higher intensities. A cross-sectional sketch of the proximal stump is made (Fig. 5). The sensory fascicles are tagged with 10–0 nylon, and the patient is placed under general anesthesia. The distal stump is stimulated in a similar fashion. The reverse picture is seen, with motor fascicles eliciting a muscle twitch and sensory fascicles being silent. A cross-sectional map is made again and used to match the proximal and distal motor and sensory fascicles.

Use of nerve action potentials

Neuromuscular function in humans, as in other mammals, disappears 3 to 5 days after nerve section [59]. The preservation of nerve action potentials for 10 days after nerve transection can be used in place of the muscle twitch to map the distal stump (unpublished data); this prevents the need to dissect the nerve to its distal motor branch. Nerve action potential recordings after acute nerve transection are characterized by diminishing amplitudes with preserved latencies until the action potential is no longer present. The compound motor action potential (CMAP) disappears at 7 to 9 days versus the sensory nerve action potential (SNAP), which disappears at 10 to 11 days [60].

The initial dissection is performed with nitrous oxide because fentanyl can abolish the response. The nerve stimulation is performed after the tourniquet has been deflated for 20 minutes using a pulse width duration of 0.05 ms and a repeat rate of 1 to 2 per second. Averaging is used for small-amplitude nerve action potentials. CMAPs are recorded from the thenar/hypothenar muscles, and SNAPs are recorded from either the index or small finger using ring electrodes (Fig. 6). A grouped fascicular repair is performed as described previously.

In chronic injuries, the awake stimulation of the proximal stump is unchanged. Because the nerve action potentials are no longer present, it is necessary to dissect the distal motor branch, then follow the motor fascicles proximally to the nerve stump (Fig. 7).

Nerve lesions in continuity

Electrical stimulation is useful to determine if there are any intact fascicles in a neuroma in continuity [61]. Bipolar hook electrodes are used with the stimulating and recording electrodes separated by at least 4 cm. The stimulus frequency is two to three times per second with a pulse duration of less than 0.1 ms. The intensity is slowly increased to the range where a response is expected (3–15 V). The recorder sensitivity is increased to a maximum of 20 $\mu\text{V}/\text{cm}$. The nerve is stimulated proximal to, across, and below the lesion. It is estimated that there must be at least 4000 myelinated axons for a recordable nerve action potential to conduct through a neuroma

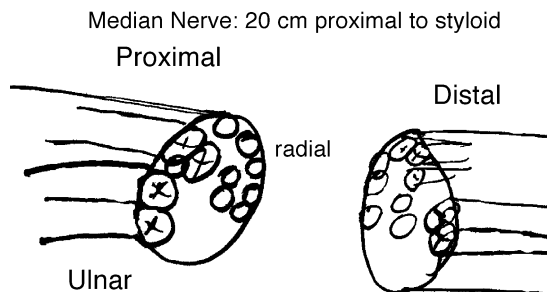


Fig. 5. Intraoperative drawing of fascicular mapping.

(Fig. 8) [62]. A neurolysis is performed to single out any normal-appearing fascicles; this is confirmed electrically. Nonconducting fascicles are excised and grafted.

Grafting specific nerves

Median nerve

Anatomy

The median nerve arises from the medial and lateral cords of the brachial plexus. It contains the nerve root fibers from C6-T1. It provides the motor supply to the pronator teres, the flexor digitorum sublimus, the palmaris longus, the flexor carpi radialis, the thenar muscles, and the radial two lumbricals. Its anterior interosseous branch supplies the flexor pollicis longus, the pronator quadratus, and the flexor digitorum profundus to the index and middle fingers. Its sensory distribution includes the palmar surface of the thumb, index, middle, and radial half of the ring finger. It lies lateral to the axillary artery, but then crosses medial to it at the level of the coracobrachialis. At the elbow, the median nerve travels behind the bicipital aponeurosis but in front of the brachialis. It enters the forearm between the two heads of the pronator teres and is adherent to the undersurface of the flexor digitorum sublimus muscle until it becomes superficial, 5 cm proximal to the wrist. It then passes underneath the carpal transverse ligament, giving off the recurrent motor branch and sensory branches to the thumb and fingers.

Injury at the elbow

The median nerve is located through an S-shaped anteromedial incision at the cubital fossa. The lacertus fibrosus is divided taking care to preserve the LABCN. The median nerve and brachial vein lie medial to the artery. At this level, the motor branches of the median nerve consistently collect into three fascicular groups. There is an anterior group (to the pronator teres and flexor carpi radialis), a middle group (to the flexor digitorum sublimus and hand intrinsics), and a posterior group (to the AIN branch) [63]. These branch groups can be traced proximally without harm, within the main trunk of the median nerve for 2.5 to 10 cm [64].

Injury in the forearm

The median nerve is approached through an S-shaped incision over the volar forearm. The nerve is identified on the undersurface of the sublimus muscle. In the upper third of the forearm, the motor branches usually lie peripherally, typically on the radial and ulnar sides. The motor fascicles from the recurrent motor branch are in a slightly radial position at 100 mm proximal to the radial styloid. The central core of the proximal stump should be connected distally with the motor and sensory components of the hand. Any large identifiable forearm motor branches should be attached about the periphery (Fig. 9).

Injury at the wrist

The median nerve at the wrist has approximately 30 fascicles. The motor recurrent branch often consists of two fascicles, which are situated in a volar position, with the various sensory groups in the radial, ulnar, and dorsal positions. The motor branch can be separated from the main trunk without harm for 100 mm proximal to the thenar muscles [55]. The motor fascicles in the recurrent motor branch are identified where they leave the median nerve trunk, then are followed proximally to the distal nerve end. To maintain motor continuity when there is a median nerve gap at the wrist level, a sural nerve graft should be sutured to the large bifascicular group of fascicles along the volar aspect of the distal stump and connected to a matching radial group of fascicles in the proximal stump (Fig. 10).

Injury in the hand

The median nerve is approached through an extensile carpal tunnel approach, with division of the transverse carpal ligament. The recurrent motor branch most commonly is found distal to the transverse carpal ligament as it enters the thenar muscles (Fig. 11) [65]. The terminal portion of the AIN provides a good-caliber match at this level.

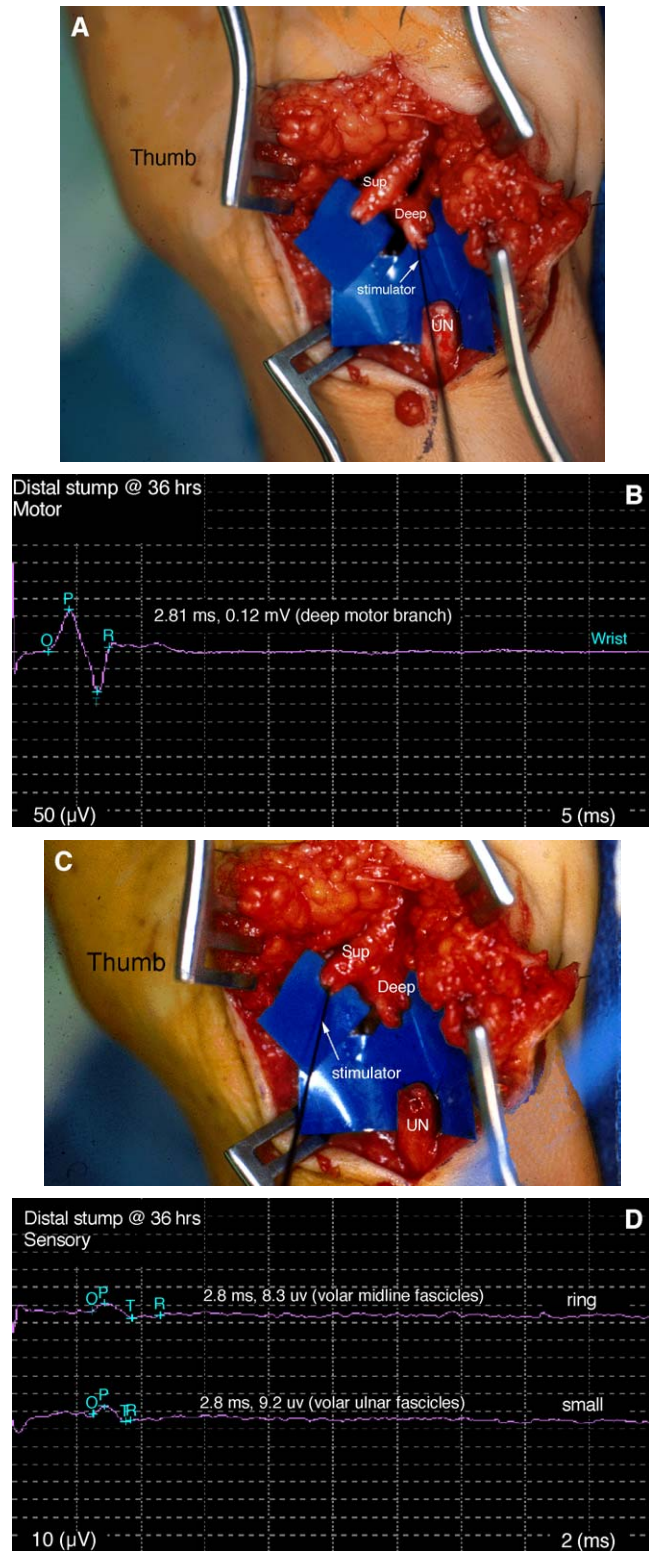


Fig. 6. Intraoperative stimulation of ulnar nerve (UN) at wrist. (A) Stimulation of deep motor branch. (B) CMAP with normal latency but low amplitude [recorded from abductor digiti minimi (ADM)]. (C) Stimulation of superficial (Sup) sensory fascicles. (D) SNAPs with normal latencies but low amplitudes (recorded from small and ring fingers).

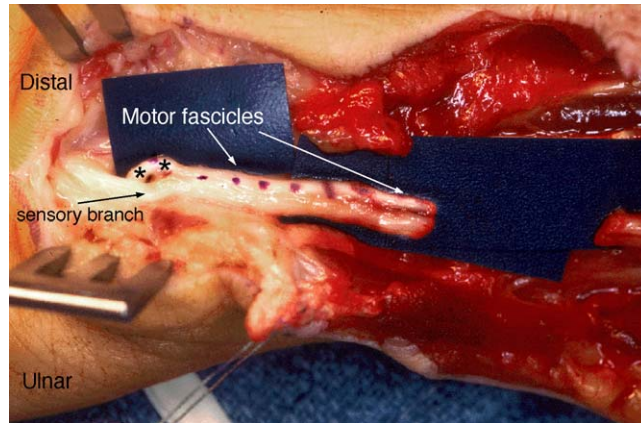


Fig. 7. Ulnar nerve motor fascicles (arrows) traced from the distal stump to the deep motor branch in the palm.

The sensory fibers travel within the common digital nerves to the thumb, index finger, and middle finger and the communicating branch to the third web space. The LACBN and MABCN are suitable grafts for nerve gaps at this level (Fig. 12). When the median nerve defect is greater than 5 cm and extends from the wrist to the common digital nerve bifurcation, sural grafts are more appropriate (Fig. 2).

Digits

Many authors recommend nerve grafting when the gap exceeds 1 cm with the wrist and all three finger joints extended [43]. The digital nerves are approached through a midlateral or a volar Brunner incision. The LACBN is a good-caliber match at this level. The dorsal sensory branch that arises from the proper digital nerve also can be used as graft material. This branch most commonly arises proximal to the PIP flexion crease, then crosses superficial or deep to the digital artery to lie just above the extensor mechanism, innervating the dorsum of the middle phalanx [66]. This branch can provide a 1- to 2-cm nerve graft (see Fig. 2). Distal to the DIP joint, the nerve trifurcates. The terminal PIN is a suitable graft at this level.

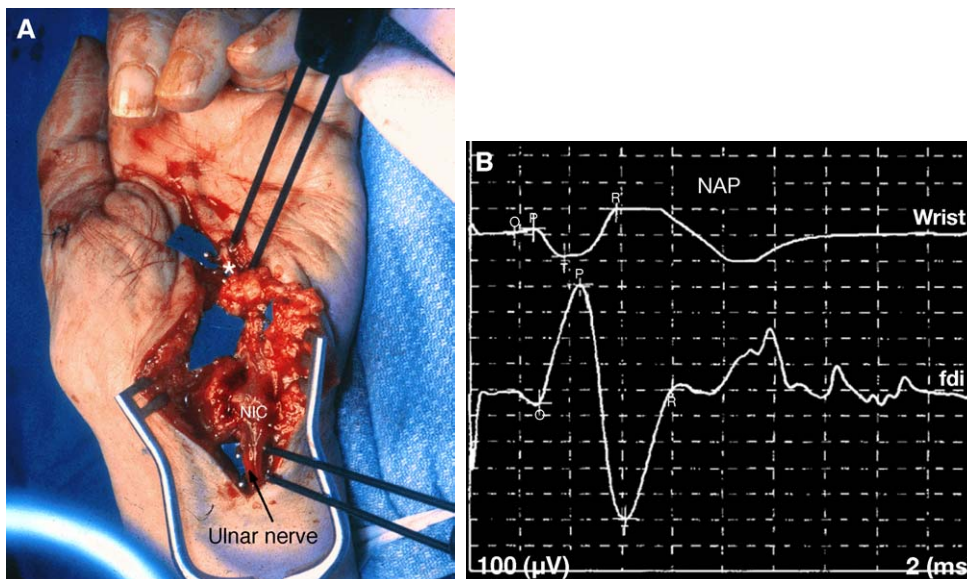


Fig. 8. Neuroma in continuity of ulnar nerve. (A) Nerve stimulation with bipolar electrodes proximal to a neuroma-incontinuity (NIC), with recording over a common digital nerve (*). (B) Nerve action potential (nerve action potentials) recorded from the common digital nerve (top tracing). Nerve stimulation also elicited a CMAP from the first dorsal interosseus (fdi).



Fig. 9. Proximal median and radial nerve grafts. (A) Laceration through antecubital fossa. (B) Note median nerve laceration and radial nerve laceration at bifurcation of SRN and PIN. (C) Multiple fascicular grafts to median nerve, SRN, and PIN.

Ulnar nerve

Anatomy

The ulnar nerve arises from the medial cord of the brachial plexus. It contains the nerve root fibers from C8-T1. It provides the motor supply to the hypothenar muscles, the ulnar two lumbricals, the interosseous muscles, the adductor pollicis, the FCU, and the profundus to the ring and small fingers. Its sensory distribution includes the palmar surface of the small finger, the ulnar half of the ring finger, and the dorsoulnar carpus. It lies medial to the axillary artery and continues distally to the midarm, where it pierces the medial intermuscular septum. The nerve often is accompanied by the superior ulnar collateral artery. At the elbow, it lies between the medial epicondyle and the olecranon, where it is covered by Osborne's ligament. It enters the forearm between the two heads of the FCU covered by a fibrous aponeurosis (the cubital tunnel). It runs deep to the FCU until the distal forearm. At the wrist, it passes over the transverse carpal ligament, medial to the ulnar artery through Guyon's canal. The deep motor branch is given off at the pisiform and passes underneath a fibrous arch to lie on the palmar surface of the interossei. It crosses the palm deep to the flexor tendons, to terminate in the adductor pollicis and ulnar head of the flexor pollicis brevis.

Injury at the elbow

The ulnar nerve is located through a curved posteromedial incision behind the medial epicondyle. At the elbow, the ulnar nerve contains about 20 fascicles, including the motor branches to the forearm muscles. The motor fascicles to the FCU and the intrinsics are centrally located, whereas the sensory fibers are superficially located. The proximal motor branches to the FCU and flexor digitorum profundus often can be traced for 6 cm before interfascicular connections [54]. It is possible to distinguish between sensory and motor fascicles in the distal nerve end using low-intensity electrical stimulation, if performed within a few days of the injury.

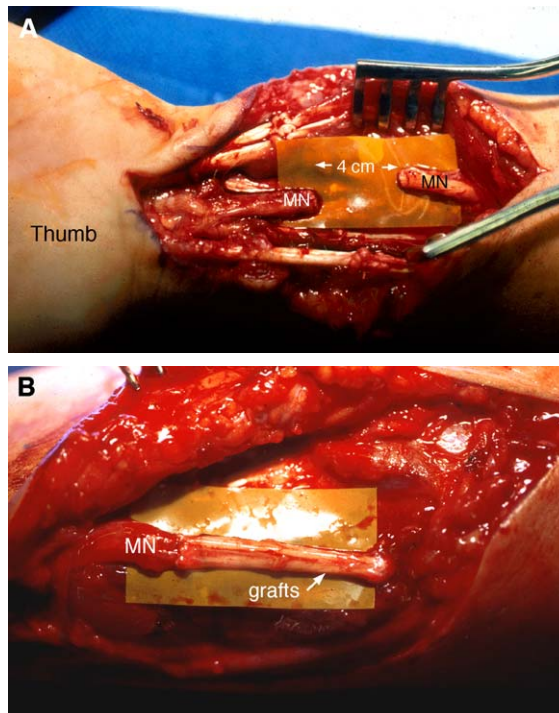


Fig. 10. Median nerve (MN) laceration near wrist. (A) A 4-cm defect between MN ends. (B) Sural nerve grafts with matching of volar radial fascicle groups.

Occasionally, fascicles innervating the flexor muscles can be separated from fascicles supplying the intrinsic muscles in the hand [67]. The sural nerve commonly is used as graft material at this level (Fig. 13).

Injury in the forearm

The motor fascicles lie dorsal and slightly ulnarly to the sensory fascicles at the wrist level and usually maintain a dorsal relationship as one moves proximally. The motor component remains as a distinct entity 90 mm proximal to the styloid [52]. At 50 to 85 mm proximal to the radial

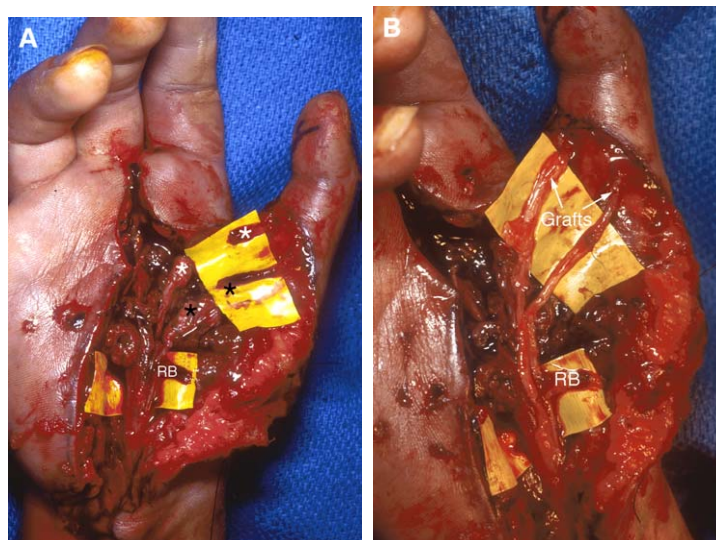


Fig. 11. Median nerve laceration. (A) Laceration of median nerve at junction of motor recurrent branch (RB) and digital sensory nerves to the thumb (*). (B) Repair of recurrent branch, LABCN grafts to digital nerves.

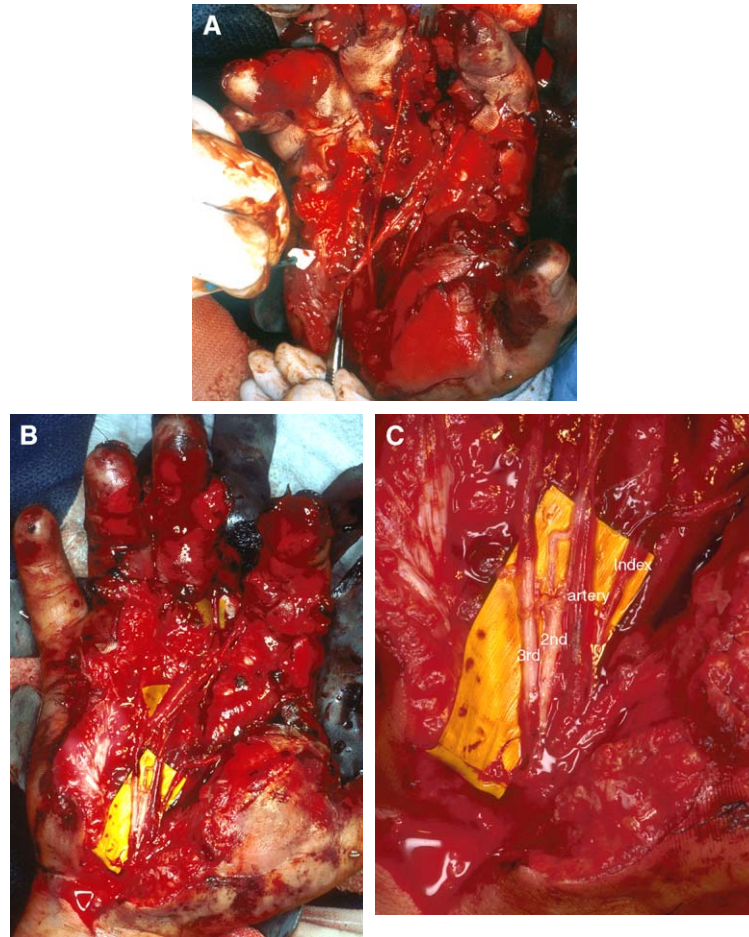


Fig. 12. Blast injury. (A) Disrupted common digital nerves and artery (forceps). (B) Repair of nerve to index, graft of second and third common digital nerves. (C) Close-up view.

styloid, the dorsal sensory branch joins the other groups. At the level of the midforearm, 50 mm from the ulnar styloid, the motor fascicles lie dorsal to the sensory fascicles [55]. A sural nerve graft should be placed in the dorsal quadrant of the proximal nerve end and the dorsoulnar quadrant of the distal nerve end to restore motor continuity.

Injury at the wrist

The ulnar nerve has 15 to 25 fascicles at the wrist. It can be divided into a volar sensory component and a dorsal motor component. The ulnar nerve is approached through an S-shaped incision over the volar ulnar forearm. The nerve is identified medial to the ulnar artery underneath the FCU muscle. If a muscle twitch is no longer present, the motor branch can be traced from the takeoff of the deep motor branch to the distal nerve end (see Fig. 7).

Hand

The nerve is approached through a volar ulnar incision in line with the ring finger. The deep motor and more superficial sensory fascicles are separated easily at this level and allow separate grafting (Fig. 14). The sural nerve, LABCN, or MABCN provides suitable sized grafts. The DCBUN usually is not grafted because neuromas of this nerve are uncommon.

Digits

Grafting in the digits is similar to grafting in the median nerve.

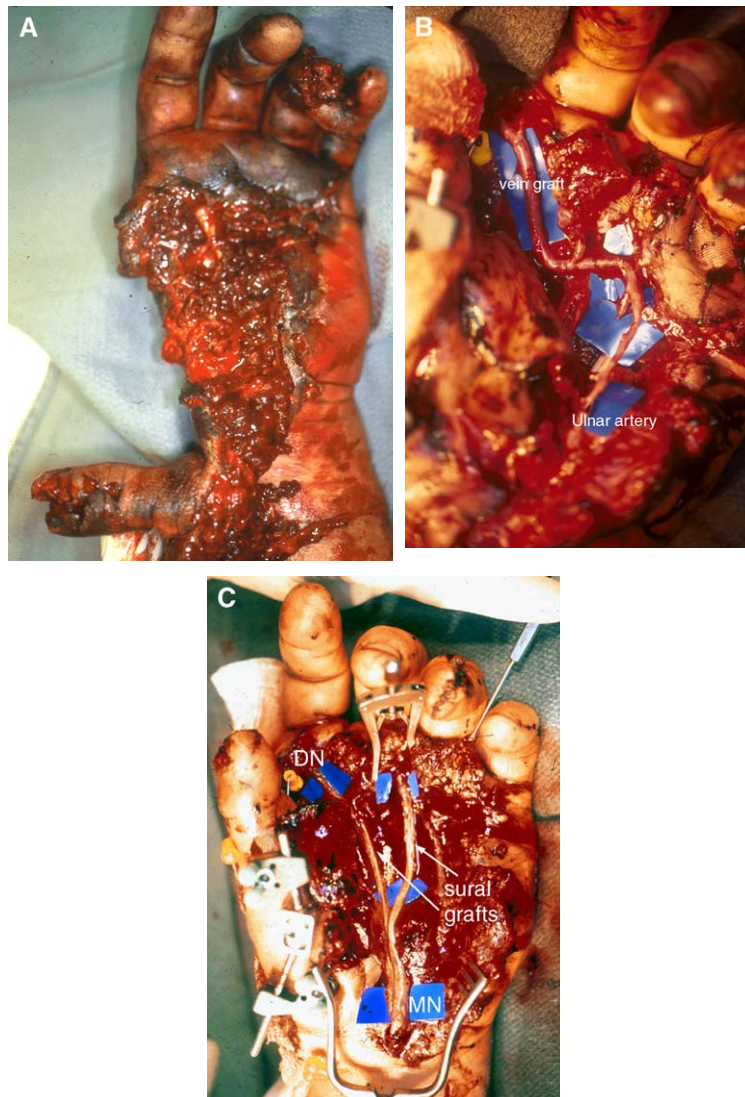


Fig. 13. Avulsion injury. (A) Thumb amputation associated with avulsion of the palmar arch and median nerve branches in the palm. (B) Thumb replant plus reconstruction of palmar arch with vein graft. (C) 12-cm sural nerve grafts from proximal median nerve to digital nerves (DN).

Guidelines for digital nerve graft selection

Higgins et al [68] investigated the fascicular cross-sectional area and number of fascicles of five nerve graft sites to specific digital nerve segments. In the fingertip distal to the DIP, the AIN, PIN, and MABCN all were appropriate choices for caliber-matched grafts. The LABCN was the only similar donor nerve, however, when number of fascicles was assessed. The LABCN also is the best match in caliber and fascicle number for digital nerve deficits from the metacarpophalangeal joint to the DIP joint and from the common digital nerve bifurcation to the metacarpophalangeal joint. The sural nerve was the most appropriate choice when grafting defects between the wrist and the common digital nerve bifurcation, even though there were considerably fewer fascicles and a smaller cross-sectional area than the common digital nerve.

Radial nerve

Anatomy

The radial nerve arises from the posterior cord of the brachial plexus. It receives contributions from C5-8 spinal roots. It runs medial to the axillary artery. At the level of the

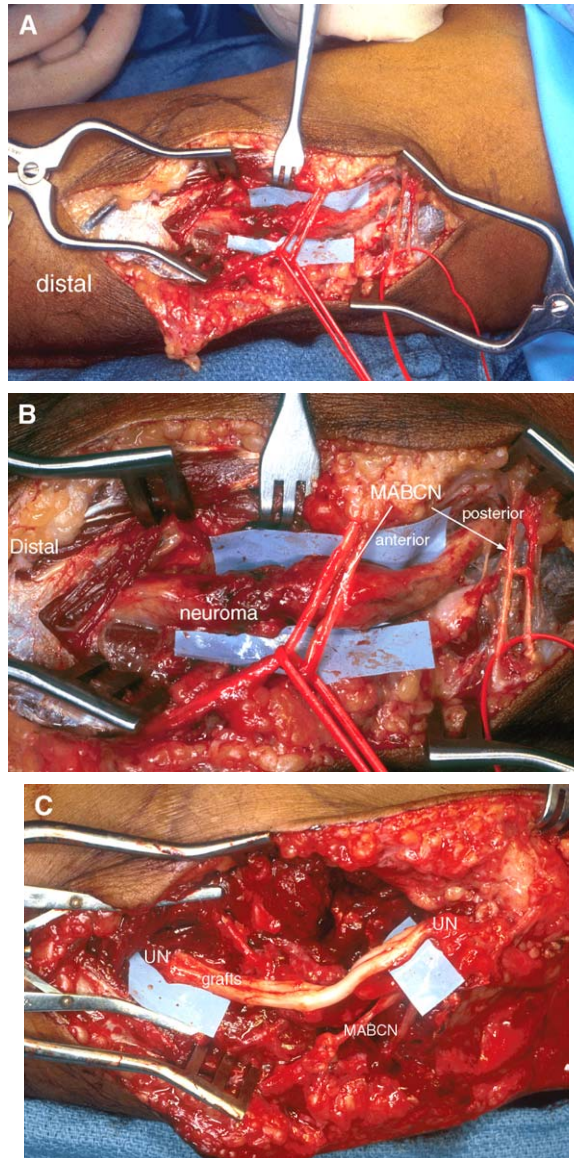


Fig. 14. Neuroma of ulnar nerve at elbow. (A) Medial aspect of the right elbow showing an ulnar nerve neuroma. (B) Close-up view of neuroma. Note the anterior and posterior branches of the MABCN. (C) Sural nerve grafts to ulnar nerve (UN).

coracobrachialis, it courses posteriorly to lie in the spiral groove of the humerus. In the lower arm, it pierces the lateral intermuscular septum to run between the brachialis and the brachioradialis. It divides 2 cm distal to the elbow into a superficial sensory branch and a deep motor branch, the PIN.

The radial nerve gives off branches to the extensor carpi radialis longus and brevis, brachioradialis, and anconeus before giving off the PIN branch. The PIN continues on between the superficial and deep head of the supinator muscle, to exit on the dorsal forearm. After it emerges from the distal border of the supinator, the PIN sends branches to the extensor digitorum communis, extensor carpi ulnaris, extensor digiti quinti, extensor pollicis longus and brevis, and extensor indicis proprius in descending order, although there may be considerable variation [69].

Injury at the elbow

The volar approach to the radial nerve is through an anterolateral incision, developing the intermuscular interval between the brachialis and the brachioradialis. Recurrent branches from

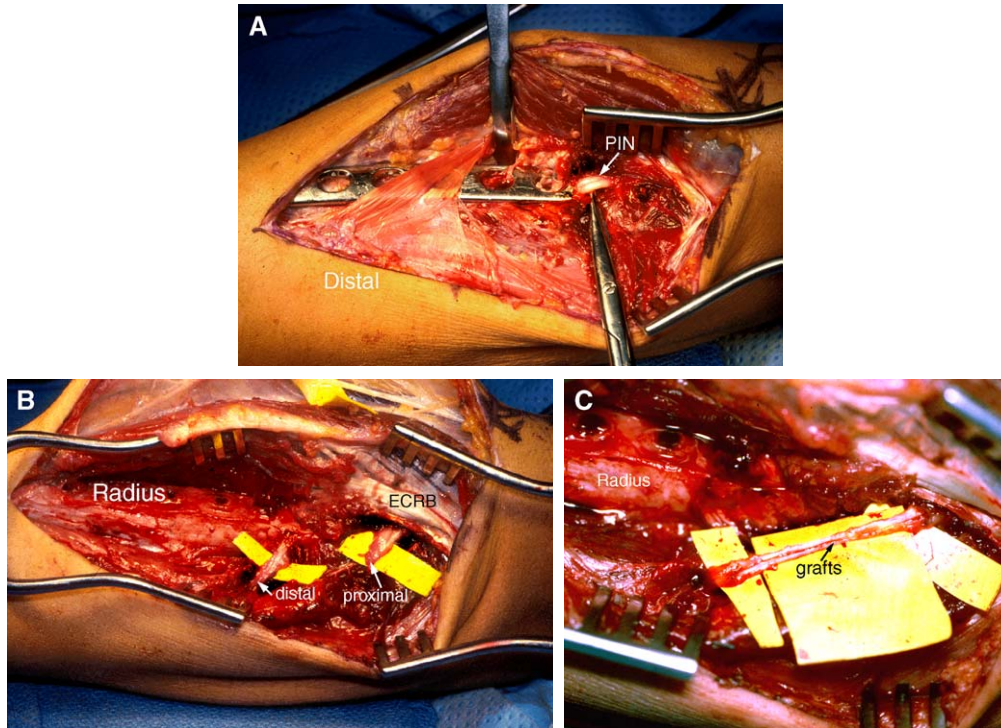


Fig. 15. Posterior Interosseous Nerve (PIN) injury. (A) Dorsal approach to left forearm showing a PIN injury after plating of a proximal radius fracture. (B) Proximal and distal nerve ends isolated. (C) Interposed nerve grafts. ECRL, extensor carpi radialis longus.

the radial artery must be divided to gain access to both nerve branches. Separate grafting of the superficial and deep branch are relatively straightforward (see Fig. 9).

Injury in the forearm and wrist

The PIN nerve is approached through a dorsolateral approach, developing the plane between the extensor carpi radialis brevis and the extensor digitorum communis. At this level, the PIN contains motor fibers only; separate fascicle identification is unnecessary (Fig. 15). The PIN also has a short distance to travel to reinnervate the motor end plates, which accounts for the generally favorable results [70]. Lacerations of the superficial branch in the forearm are not usually grafted, which allows harvest of the SRN for grafting adjacent nerve injuries. Some authors advocate grafting the SRN at the wrist, mostly to prevent symptomatic neuroma formation [71].

Summary

Nerve grafting is a century-old art [72] that is honed by experience and limited only by the imagination. Myriad factors may influence the type of graft and manner in which it is used. A sound knowledge of the intrafascicular topography combined with intraoperative aids for motor and sensory differentiation can lead to superior clinical results, especially with large nerve deficits. The basic tenets of managing the nerve gap will undoubtedly remain in vogue until the results of reinnervation through the use of synthetic conduits can reliably match the time-tested standards of the autogenous nerve graft.

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