Peripheral Nerve Repair and Grafting Techniques: 
A Review

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Abstract

In this review, various conventional nerve repair techniques including direct epineurial repair, grouped fascicular repair, fascicular repair, and nerve grafting are described. The indications for use, as well as the relative advantage and disadvantage, of each technique are discussed. The experimental and clinical evidence from a review of the pertinent literature does not demonstrate a significant difference in outcome of one method over the others. Surgical decisions should be made by a thorough evaluation of all aspects of the nerve injury and surgical methods. All nerve injuries cannot be repaired using only one type of nerve repair method. The surgeon should be familiar with all the techniques described and be prepared to use them under appropriate circumstances.

Key words: epineurial repair, fascicular repair, nerve graft, nerve injury

Introduction

Nerve injuries and brachial plexus injuries are relatively frequent, affecting 5% and 1% of trauma patients, respectively.18,26 Following peripheral nerve injury and division of the nerve fiber, Wallerian degeneration occurs in the distal axon.43 Degeneration of the axon also occurs for a variable distance proximal to the site of nerve division.26,27 After this period of degeneration, myelinated and unmyelinated fibers from the proximal stump will sprout, forming regenerating units, and attempt to reinnervate the distal stump.26,27 However, in some instances, spontaneous reinnervation fails to occur due to the size of the nerve gap, neuroma formation, and scar tissues. In the absence of spontaneous reinnervation, surgical intervention with nerve repair becomes necessary.

The aim of nerve repair is to direct the regenerating fibers successfully into the environment of the distal nerve with minimal loss of fibers at the suture line. The success of a nerve repair is dependent on sensory, motor, and autonomic axons making appropriate connections with their distal end organs.41

The results following nerve repairs are influenced by many parameters, such as the nature, location, and extent of the injury, the level and timing of the repair, the fascicular anatomy, appropriateness of re-alignment of the injured nerve, and the surgical technique, as well as patient factors.

Note that a peripheral nerve repair is not a type of cellular repair, but is actually a repair done at the level of the connective tissue to coapt a healthy proximal nerve to a healthy distal nerve stump.29 This then provides the appropriate anatomical environment, so that axons from the proximal stump can regenerate into endoneurial tubes within the distal nerve stump and hence be lead to end organs to restore function. Since a nerve graft functions as a conduit, whose axons are destined to undergo degeneration as soon as it is removed from its harvest site, the graft essentially provides an endoneurial tube network available to be exploited by regenerating axons from the proximal host nerve stump. It also provides viable Schwann cells, as long as the caliber of the nerve graft is not too large. For this reason, small caliber cutaneous nerves are most commonly used as graft material. The small caliber

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nerves, when sutured in a series of parallel segments, are in close proximity to tissue fluid, and are therefore nourished. They also undergo rapid revascularization, and thus remain viable.  

**Anatomy of Peripheral Nerve**

In order to discuss repair of injured nerves, it is important to appreciate the normal anatomy of peripheral nerves. Each peripheral nerve is encircled by an external epineurium. The epineurium is a loose outer sheath, composed of aerolar connective tissue and a longitudinal plexus of blood vessels. The blood supply of a peripheral nerve is relatively rich, with a well-developed collateral pathway, yet disturbance of this blood flow may lead to various types of nerve injuries.\(^{45}\) Nerve fibers occupy 25% to 75% of the cross-sectional area of a nerve, depending on the examined nerve and its location. Nerve fibers may be myelinated or unmyelinated. The diameter of myelinated nerve fibers ranges from 2 to 25 µm,\(^{39}\) while the diameter of unmyelinated fibers ranges from 0.2 to 3.0 µm.\(^{45}\)

Groups of nerve fibers form bundles, called fascicles. Each fascicle is composed of many nerve fibers and is encircled by perineurium. From a surgical perspective, the perineurium is the smallest structure capable of accepting sutures in peripheral nerves. Fascicular diameter ranges from 0.04 to 3 mm.\(^{39}\) Fascicles are arranged individually or within groups as they course along the nerve. They are grounded in epineurial connective tissue and epifascicular interfascicular epineurium.

Peripheral nerves are subdivided into monofascicular, oligofascicular, and polyfascicular types (Fig. 1). Monofascicular nerves, such as the terminal branches of the digital nerves, are composed of one large fascicle containing many nerve fibers. These nerves normally have either pure sensory or pure motor function. Oligofascicular nerves are composed of a few fascicles and may be either pure or mixed nerves with both sensory and motor elements. Polyfascicular nerves are composed of many small fascicles. For example, the radial nerve in the upper arm is a polyfascicular nerve, which contains fibers that serve a variety of distal specific functions. From the proximal limb plexus to the fingers or toes, the internal anatomy can change in the same nerve. For example, the ulnar nerve is classified as polyfascicular in the axilla, oligofascicular in the elbow, while its motor branch is monofascicular in the palm.\(^{45}\)

![Fascicular Patterns in Peripheral Nerve](image)

**Fig. 1** Schematic diagram of peripheral nerve architecture and composition. The patterns of fascicular structure of peripheral nerve are illustrated: monofascicular, oligofascicular, and polyfascicular (diffuse and grouped). The anatomical composition, with emphasis on the connective tissue layers of the nerve, namely epineurium (external and internal), perineurium, and endoneurium are also illustrated.

**Selection of Method of Nerve Repair**

Nerve repair methods are divided into direct repair (neurorrhaphy) and graft repair techniques. Direct repairs can be further subclassified into epineurial repair, grouped fascicular repair, and fascicular repair techniques. Graft repairs are typically performed by using harvested autogenous sensory nerve (for example, the sural nerve) segments. The surgical method selected depends on the nerve type and the tension at the repair site. Tension, in turn, is influenced by the size of the gap between the proximal and the distal stump, the longitudinal excision required, the timing of the nerve repair, and the nature of the injury (location and mechanism).\(^{14,25,45}\)

The type of direct nerve repair should be selected on the basis of both nerve type and location. In the proximal portion of the extremities, nerves show polyfascicular patterns, with fascicles often segregated as groups.\(^{45}\) By examining the proximal and distal ends of the transected nerves at this level under proper magnification, the surgeon may be

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able to coapt these fascicular groups. In these instances, it is suitable to carry out group fascicular or epineurial repairs. In the very distal portion of the extremities, the fascicular pattern is often mono- or oligofascicular, and fascicular repairs may be more appropriate.

When repairing nerve injuries, the longitudinal excursion of the nerve at the site of injury should be considered. As the extremity moves, the nerve undergoes gliding movements and the length of the nerve changes. In the upper extremity, notable neural excursion is produced when the wrist and fingers are extended and the elbow is flexed. In the median nerve, a mean of 7.4 mm excursion is caused by extension of the wrist and fingers, whereas a mean of 4.3 mm excursion results from flexion of the elbow. A mean of 9.8 mm excursion is produced in the ulnar nerve by flexion of the elbow. The greatest excursion of peripheral nerves is found at the wrist, close to the carpal tunnel, whereas in the palm and fingers, excursion is relatively short. When the nerve repair of a transected nerve is planned, the surgeon must consider not only the nerve gap, but also the demand for longitudinal excursion during extremity movement, to avoid disruption of the repair site. For example, when considering the repair of a 2 cm gap in the median nerve at the level of the elbow, the graft length should be 3.5 cm, taking into account the 1.5 cm of longitudinal excursion produced during full elbow movement. In other words, the surgeon must be aware of dynamic factors.

The nature of injury is another important factor for the surgeon to be aware of. In cases of acute injuries, when the type of injury is a sharp and clean laceration, a direct repair is usually possible. In most instances, an epineurial repair would suffice. If the surgeon has identified a distinctive fascicle carrying a specific function such as pure motor or pure sensory in the proximal and distal stumps, fascicular repair is appropriate. The remaining portion of the nerve repair would be performed using epineurial repair. Blunt mechanisms of injury generally produce considerable scarring; the resection of which leaves a significant gap, often requiring a graft repair.

**General Principles of Nerve Repair**

In any nerve repair, several principles should be followed. The surgeon must have a mastery of the regional and nerve anatomy as well as facility with microsurgical procedures. Dissection should always be performed from the normal nerve toward the region of injured nerve to ensure correct anatomical identification. Sharp dissection is imperative to dissect nerve stumps from contiguous and scarred soft tissues. Nerve repair is carried out under magnification, using either an operating microscope or loupes. As excessive numbers of sutures can lead to additional scar formation, the number of sutures should be minimized.

During direct suture repairs, nerve stumps are trimmed proximal and distal from the injury site until normal fascicular structures can be identified. The degree of resection required is easily determined, as the fresh fascicles sprout out under the trimmed epineurium and the epineurium retracts back slightly. Nerve stumps may be encircled and enmeshed strongly or loosely by a variable amount of scar tissue. The scarred nerve is resected back until a normal fascicular pattern can be seen (Fig. 2). The above debridement step is critical, as the leading cause for failure of repair is inadequate resection of injured nerve back to healthy tissue. Blood from the sectioned surface of the stumps should be irrigated away with isotonic saline. Such bleeding, caused by oozing from many small vessels, can be
stopped by pressure utilizing a piece of muscle or Gelfoam. When bleeding is from arteries, the bleeding point in the stump should be explored and coagulated by using fine-tipped bipolar forceps under magnification. After bleeding is controlled, the stumps should be kept as fresh as possible until the suturing is carried out.

The stumps must be sufficiently mobilized usually both proximally and distally, in order to perform repair without tension. This mobilization can be supported by anterior transposition of the ulnar nerve at the elbow for ulnar nerve repair (Fig. 3), partial resections of fibula for peroneal nerve repair, mild flexion of the elbow for most nerve repair of the arm, and mild flexion of the knee for repairs of the peroneal and tibial nerves. It is arguable whether mild tension at the repair site of a direct repair is wrong or disastrous, but tension leading to distraction of the nerve is to be avoided. Hence, if a direct repair is to be performed, slight movement of the extremity, in spite of the mobilization of the nerve stumps and some joint flexion, repairing the nerve with grafts is favored to avoid distraction of the repaired nerve postoperatively.

**Epineurial Repair**

Epineurial suture repair has been the traditional and commonly used method of repair. It is usually applied to the actually transected nerve injury. Sutures are passed through the epineurial sheath. The overriding principle of epineurial repair is to obtain continuity of the nerve stumps without tension and with proper anatomical alignment. Surface features such as longitudinal blood vessels in the epineurium can confirm the rotational alignment of the nerve. This helps the surgeon to coapt fascicles correctly. The fascicular arrangement is reoriented and matched with care before the placement of the first suture.

Suture repair is performed using 8-0 nylon or 9-0 nylon non-absorbable sutures under magnification. The nerve repair is accomplished by first placing two orienting lateral sutures through the epineurium, 180 degrees apart, to avoid rotational displacement during mobilization (Fig. 4). The suture is placed on the normal area of the epineurium, proximally and distally, and tied. After the lateral sutures are tied, their suture tails may be held with an instrument, such as a fine hemostat, so that the rotation of the nerve is facilitated for coaptation of the posterior wall. The lateral edges of the stumps are widened slightly, so that the proximal and distal epineurial edges coapt clearly. Additional interrupted sutures to adjust the two stumps approximate these more strongly. As the suture needle passes through the epineurial sheath, a small amount of the deeper structure (internal epineurium) is usually contained within the stitch, so that fascicular coaptation is maintained appropriately. The epineurium should not be connected so tightly that it leads to
mismatching, malalignment, or protrusion of the fascicles. This can be avoided by leaving a small gap between the epineurium retained together by a suture. Minimal numbers of epineurial sutures are placed (usually 4 to 8) to ensure accurate coaptation of the nerve stumps.

Most polyfascicular nerves can be repaired by direct epineurial repair. If the nerve repair cannot be performed with 8–0 sutures because of the distraction of the repair site, it suggests that tension at the suture line is too great for direct repair. Distraction of the repair site postoperatively can be a major contributor to failure, and must be avoided. Therefore, if a gap is large and cannot be reduced by i) mobilization of the nerve, or ii) provision of mild extremity movement, without producing significant tension on the repair site, nerve grafting is required and the results should be better than direct repair with tension.56 If a gap is small (a few cm or less), direct suture repairs work very well and may yield better results than grafts.5,28,65

**Grouped Fascicular Repair**

Grouped fascicular repair is potentially a more accurate and more practical technique relative to the simple epineurial repair.5,26,41 In practice, grouped fascicular repairs are best applied where fascicles representing special function are well formed and recognized within the main nerve. The following are examples when grouped fascicular repair is especially appropriate: matching groups of fascicles in mixed motor and sensory nerves that can be identified (e.g. the ulnar nerve at wrist); partially injured major nerves; and nerves consisting of two major fascicular groups that can be easily recognized (e.g. the radial nerve just proximal to the elbow where posterior interosseous and superficial sensory radial nerves form two discrete branches).

Connection of matching groups of fascicles is performed by placement of sutures in the interfascicular epineurium. The external epineurium is dissected back and adjacent groups of fascicles are isolated gently. Identification and separation of groups of fascicles can be difficult in damaged tissue. Therefore, the damaged nerve ends should be debrided until normal groups of fascicles can be seen. The groups of fascicles are then dissected, and the proximal and distal ends aligned and then coapted together by placement of 8–0 to 10–0 sutures through the interfascicular epineurium (Fig. 5). Usually two to three sutures are used for each group of fascicles. Again, the number of sutures should be minimized to avoid scar formation and the suture line must be free of tension. It is critical to avoid tension at the repair site as the interfascicular epineurium is not as strong as the external epineurium. If significant tension is present, nerve grafting is indicated.

Grouped fascicular repair has several advantages over fascicular suture repair. The interfascicular anatomical arrangement of the nerve is more likely to be preserved as there is no manipulation within the interfascicular epineurium. The physiological environment (blood-nerve barrier) is less likely to be disturbed, due to less direct injury to the perineurium.61 Scar formation is reduced and the procedure requires less time.

**Fascicular Repair**

Fascicular repair involves the suturing of corresponding fascicles in proximal and distal nerve stumps, to gain optimal alignment. Reconnection of isolated fascicles is performed by placement of sutures in the perineurium. The external epineurium is stripped for lengths approximately double the diameter of the cross-sectional area of the nerve. The adjacent paraneurial connective tissue should be preserved as a layer because it contains the blood vessels and it can be used to cover the repair site. The loose connective tissue and vessels between the fascicles are carefully dissected so as to not injure fascicles. Fascicular dissection is achieved by removing a small amount of interfascicular epineurium proximally and distally to the site of the lesion and separating the fascicles as they approach the injured area. Each fascicle can be recognized by the spiral bands of Fontana, found in the perineur-
um.42) Protrusion of the intrafascicular material is identified from the perineurial edge on the end of a fascicle. This is trimmed meticulously to obtain excellent coaptation before suture placement.

Proximal and distal stumps are matched with corresponding fascicles. Two or three 10–0 or 11–0 sutures placed through the perineurium, 120 to 180 degrees from each other, are usually sufficient for each fascicle to be coapted. Placement of sutures is accomplished under high magnification, taking care to include only perineurium and to avoid endoneurial contents. The knot should not be tied tightly since this produces lateral protrusion of the interfascicular contents. If excessive tension is loaded on the perineurium, the spiral bands of Fontana disappear. It has been suggested that these nerve branches maintain the proper fascicular structure and provide the elasticity of the perineurium, allowing tolerable stretching deformation.39 If this band disappears, the surgeon should re-examine the nerve stumps to eliminate the tension at the repair site.

With the fascicular repair technique, individual fascicles can be re-approximated. Moreover, the interfascicular arrangement within the nerve fascicle can, at least theoretically, be properly aligned. In oligofascicular and monofascicular nerves, fascicular repair is achieved more easily and appropriately. Thus, it is especially beneficial for some distal median and ulnar nerve repairs, in which the motor and sensory fascicles can be well recognized.42 A fascicular repair may be suitable in this situation, especially if individual fascicles can be appropriately matched and aligned. However, the indications for actual fascicular repair are less clear than for grouped fascicular repair. The most frequent indication remains repairing partially damaged nerves. The disadvantage is that the repair is time consuming and that it promotes intrafascicular scar formation from increased dissection.

**Postoperative Care**

Postoperative care following nerve repairs (and nerve grafting) is similar to that for other extremity soft tissue operations with a few exceptions. Prior to wound closure, blood or fluid collection in and around the repair site should be avoided by careful and meticulous intraoperative hemostasis. Sizeable postoperative collections should be aspirated or surgically evacuated to avoid severe scarring adjacent to the repair site. The strength of the nerve repair reaches a plateau by 3 weeks postoperatively. Some attention on the part of the patient is required to avoid overstretching, abducting, or extending the extremity in the early weeks following surgery. A bulky extremity dressing and shoulder immobilizer slings serve as useful reminders to the patient to exercise caution. Movement of the extremity, even after 3 weeks postoperatively, should be done gradually. Nerves do not recover by being at rest, nor does joint mobility recover back without motion. Therefore, it is important to mobilize the extremity gradually and progressively, aided by a therapist, following approximately 3 weeks of immobilization. Dressing is usually changed at discharge (usually the 2nd or 3rd postoperative day) and applied to provide gentle compression on the operative site.13

**Epineurial Versus Grouped Fascicular Repair and Fascicular Repair**

Both clinical and experimental studies have been done to establish the superiority of one or the other of these repair methods.32,43 However, no definitive consensus has been reached. The specificity of muscle reinnervation after epineurial and fascicular repair was studied in the rat sciatic nerve.35 In a retrograde tracing study using horseradish peroxidase introduced into the peroneal nerve, the number and location of motoneurons in the spinal cord were analyzed. Fascicular repair, in contrast to epineurial repair, minimized improper central reconnection of peripheral units.35 These data suggest that fascicular repairs provide better anatomical reinnervation than epineurial repairs. However, other experimental studies, while showing some histological differences in the pattern and disposition of regenerated nerve fibers8 (Fig. 6), have not shown significant differences in functional outcome.3,11,12

Epineurial repair is easier and faster, and demands less manipulation of the fine internal structure including vascular supply, minimizing both the internal disruption of the nerve as well as the disturbance of the blood supply. However, this technique has been criticized because a significant percentage of patients treated by this method do not obtain satisfactory postoperative results. Even in the most meticulous manipulation, epineurial repairs cannot provide true fascicular alignment and a large amount of disorganization occurs at the site of coaptation. Fascicular malalignment is especially augmented in situations where there is a large amount of connective tissue within the nerve structures to be sutured together.41

In theory, grouped fascicular and fascicular repairs provide greater potential of regenerating fibers to enter appropriate endoneurial tubes in the distal stumps compared to epineurial repair. Direct alignment of fascicles is possible and damaged fas-
Peripheral Nerve Repair

Fig. 6 Schematic histologic sections following epineurial repair (upper row), grouped interfascicular repair (middle row), and graft repairs (lower row) are illustrated (based on primate experiments by Hudson et al., 1979). The nerve fascicular pattern and axonal disposition (intra- and extrafascicular) proximal (left column) and distal (right column) to the repairs are similar under the three types of repairs. Following epineurial repair, loss of fascicular structure is evident at the suture site (center column), but the majority of axons are re-captured within fascicles in the distal stump (right column). While grouped fascicular (interfascicular) repair preserves a better fascicular pattern at the suture line (center column), the distal stump (right column) is indistinguishable from epineurial repair. As expected, the middle of the interfascicular graft segment (center column) exhibits the fascicular profile inherent to the graft origin.

cicles can be selectively repaired. The disadvantages of these methods include the following: i) scar formation if there is any tension at the repair site, ii) more time-consuming procedures, iii) potential damage to the interfascicular crossing fibers, and iv) disruption of blood supply. Therefore, the outcomes of these methods depend on the balance of excellent fascicular alignment, degree of internal trauma, and amount of scar formation. The actual benefits of fascicular repair have probably not been obtained clinically because of the potential for mismatching of repaired fascicles and increased surgical manipulation, which disturbs the fine structure of the nerve ends. If it was possible to adjust the fascicles completely, appropriately, and with minimum surgical trauma, grouped fascicular and fascicular repair may result in improved clinical results compared with epineurial repair.

Nerve Grafting

When a direct repair produces considerable tension at the nerve repair site, grafting is recommended, as undue tension at the nerve repair site will reduce final functional recovery. While use of bioartificial substitutes for nerve gap repair, various non-nerve tissue conduits, and nerve allografts have all had experimental and limited clinical success, the gold standard for nerve gap repair remains a nerve autograft as a first principle, the surgeon must obtain healthy proximal and distal stumps of the nerve by evaluating and removing the damaged area of divided nerves and nonfunctioning portions of the tissue. The epineurium is cut in a longitudinal fashion, and a circular band of the epineurium resected. The major fascicles or groups of minor fascicles are dissected free from one another in normal tissue under magnification. As the ends of the nerve are approached, there are more fibrotic components between the fascicles and tissue. At this point, the fascicles are cut and trimmed individually using fine, sharp scissors. The proximal and distal repair sites to be grafted must be completely tension-free. The surgeon must move the extremity within a range of movement to confirm that there is no tension on the graft repair sites when the extremity is moved. The number and length of the nerve graft segments, which are required to cover the cross-sectional area of the nerve stumps, are then defined. In general, graft length should be about 10% longer than the repaired gap to consider retraction and shrinkage.

In accomplishing nerve grafting, it is important to try to match the sensory and motor components of the individual fascicles at the proximal and distal repair sites as accurately as possible. This can be difficult when grafting in the proximal extremities, as the interfascicular pattern at the proximal stump will frequently be mixed motor and sensory and, therefore, cannot be specific. At the distal nerve stump, the arrangement can theoretically be more specific. Using topographic cues, the surgeon can at least attempt to reconstitute the fascicular alignment. In the more distal extremity, more precise fascicular matching is possible. Given the segregation of motor and sensory fascicles and fascicular
groups from each other, such matching also ensures the best possibility of more specific reinnervation.

After the nerve graft is harvested, it is manipulated delicately to avoid causing injuries, kept moist, and then placed at the repair sites. The graft(s) is cut into segments of the required length. To avoid aligning a graft to non-fascicular tissue, interfascicular tissue is resected back and fascicles are exposed as groups or “fingers.” Graft segments are adjusted in place to proximal and distal fascicular groups of the stumps by two lateral sutures. The lateral sutures are placed to widen the edge of the graft segment like a fish-mouth so they cover as much of the fascicular arrangements as possible, since the cross-sectional area of the nerve graft is usually smaller than the recipient stumps to which it is sewn (Fig. 7). The sutures are passed through the epineurium of the graft to the interfascicular epineurium and perineurium remaining on the surface of the isolated fascicular group. When there is no tension at the suture site, this type of repair is adequately strong. According to the size of the nerves and fascicles, additional sutures may be needed to approximate the stumps. Usually, all of the grafts can be sutured first proximally and then distally to complete the repair more easily. It is imperative to re-examine all the graft repair sites after the surgery because graft ends can be easily distracted when other grafts are being sewn in place. Similar to the direct repair, it is important to place the grafts into a healthy, well-vascularized tissue bed to allow for nourishment of the grafts and to minimize scar formation.

The general postoperative care for graft repair is identical to direct nerve repair as outlined above. Immobilization of the extremities undergoing graft repair for more than 3 weeks is not needed, as there should be little or no tension at the repair sites and therefore, less possibility of disruption of the repair sites. Longer duration of immobilization may result in needless scar formation along the length of the graft.

Although it has been suggested that functional results of longer nerve grafts will be poor, this perhaps depends not on the length of the graft, but the fact that longer grafts are usually associated with other factors that correspond to poorer functional results. For instance, longer nerve grafts are required to repair long nerve gaps, which are often associated with more extensive and more proximal nerve injuries. These injuries increase the distance and time to reinnervation of motor end organs, and are more severe nerve injuries in nature. These factors, accompanied with a greater loss of neurons in spinal cord or dorsal ganglion, may contribute to the poor outcome observed with long graft repairs.14

**Donor Nerves for Grafts**

The donor nerves used for nerve grafting are commonly expendable sensory nerves whose harvest results in no significant complications. Donor nerves include the sural nerve, lateral antebrachial cutaneous nerve (LACN), anterior division of the medial antebrachial cutaneous nerve (MACN), dorsal cutaneous branch of the ulnar nerve, and superficial sensory branch of the radial nerve (SSR). In selecting a donor graft, the surgeon must consider the cross-sectional area of the nerve to be repaired, the length of the nerve gap, and donor site morbidity.
Table 1  Donor nerve grafts

<table>
<thead>
<tr>
<th>Nerve graft</th>
<th>Length (cm)</th>
<th>Morbidity</th>
<th>Dissection difficulty</th>
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<tbody>
<tr>
<td>Sural</td>
<td>30–50</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>MACN (above elbow)</td>
<td>10–12</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td>MACN (below elbow)</td>
<td>8–10</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>LACN (below elbow)</td>
<td>10–12</td>
<td>++</td>
<td>+</td>
</tr>
<tr>
<td>SSR</td>
<td>20–30</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>DCBUN</td>
<td>4–6</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>LFCN thigh</td>
<td>15–20</td>
<td>III</td>
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Relative donor site morbidity and ease of dissection (compared to the sural nerve as a standard) are outlined, along with the approximate length of graft material that can be obtained. DCBUN: dorsal cutaneous branch of the ulnar nerve, LACN: lateral antebrachial cutaneous nerve, LFCN: lateral femoral cutaneous nerve, MACN: medial antebrachial cutaneous nerve, SSR: superficial sensory branch of the radial nerve.

ity (Table 1). In small nerves such as the digital nerves, the total length of a graft required is the length of the actual nerve gap, as they require just one graft segment for repair. In larger nerves, such as the median nerve and the ulnar nerve in the forearm, the total length of the obtained donor graft must take into consideration the actual length of nerve gap, the need for nerve and graft excursion with extremity movements, and the number of segments necessary to cover the cross-sectional area.

It is believed that when a large caliber nerve is used as a graft, the central portion of the graft is not likely to be vascularized, and therefore, undergoes necrosis, resulting in poor axonal regeneration, which leads to the failure of the repair. Small diameter nerve grafts are nourished directly from the surface and revascularized by inosculation at relatively short-time points. Therefore, the diameter of the graft is the most important determining factor in survival. For this reason, multiple small diameter nerve grafts are used as a standard method for the repair of major nerves. In each graft segment, there is a single strand of the nerve (usually oligofascicular) with a definable number of axons and neural tissue.

Ideally, the donor nerve graft would be obtained from the same extremity as the nerve defect, so that regional anesthesia could be considered and the graft can be obtained without need for a second incision. However, this is only possible in select circumstances, as for example in repair of an accessory nerve injury, using a graft from the adjacent greater auricular nerve. In the majority of situations, the nerve graft needs to be obtained from another area, as the considerable length of donor tissue is not locally available or the sensory loss created by harvesting an adjacent nerve is not clinically acceptable (see below).

When selecting a donor nerve, the surgeon should consider the resulting loss of sensory function. The area of permanent anesthesia created after harvesting the donor nerve must be minimized, and a critical area for sensation should be avoided, since this loss can lead to serious postoperative complications. Also, the area of sensory loss resulting from harvesting should not be adjacent to an area of anesthesia from the primary nerve injury, thereby minimizing the loss of function in that area. For example, if the digital nerve of the thumb was receiving a graft, the LACN would not be an acceptable nerve to harvest, because it innervates the sensation of the volar and dorsal radial aspect of the thumb.

An anatomical survey of commonly utilized donor nerves follows.

MACN (Figs. 8 and 9): The proximal MACN, as it comes off the medial cord, is large in caliber. It can be used as a single trunk graft for repair of axillary and other infraclavicular nerve injuries, where the nerve is easily exposed. The MACN then closely follows the brachial vein entering into the subcutaneous space about midway in the upper arm, where it also divides into an anterior and a posterior division. The more distal MACN is found with the elbow extended, by measuring two fingerbreadths below the medial epicondyle in line with flexor carpi ulnaris and then moving up two fingerbreadths toward the middle of the forearm. Approximately 12 cm of nerve can be obtained through a longitudinal medial forearm incision. The distal MACN is smaller in caliber and can be used as multiple cables for grouped interfascicular repairs for distal nerve injury. However, this nerve should not be used in cases of ulnar nerve injury, because of potential sensory overlap.

LACN (Figs. 8 and 9): The LACN is the terminal sensory branch of the musculocutaneous nerve. This nerve is located in the arm at the lateral border of the biceps tendon, where it lies in the subcutaneous tissue, superficial to the brachialis muscle. It is easily harvested between the cephalic and accessory cephalic veins, above, at, and below the elbow (Fig. 9). Both the anterior and posterior divisions can be obtained, which yields approximately 12 cm of graft tissue. Occasional loss of sensation and hypesthesia in the thenar area can result following resection of this nerve, so it should not be used in case of median nerve injury.

SSR (Fig. 8): The SSR is the terminal sensory di-
take-off of the posterior interosseous nerve. This nerve is an especially desirable nerve graft for repair of proximal radial nerve injury because it supplies a relatively unimportant sensory zone on the dorsal surface of the hand, where sensation can be sacrificed without significant clinical consequences. It is important to recognize this nerve in the distal portion of the radial nerve in order to exclude it from the nerve repair of the motor radial nerve (posterior interosseous).11

**Dorsal cutaneous branch of the ulnar nerve** (Fig. 8): The main ulnar nerve branches to form the dorsal cutaneous nerve branch approximately 4 cm proximal to the wrist crease, which runs from palmar to dorsal and becomes superficial at the ulnar styloid. This branch of the nerve is usually obtained 1 to 2 cm distal to the ulnar styloid and, because of its limited length and small caliber, is often used to repair small gaps in digital nerves.29

**Sural nerve** (Fig. 10): The sural nerve is the most common choice as a donor nerve for peripheral nerve grafting. It supplies the cutaneous sensation in the lateral and posterior lower third of the leg and the lateral aspect of the foot and heel. The sural nerve complex usually consists of three components: the medial sural cutaneous nerve, the lateral sural nerve (also called the peroneal communicating branch), and the sural nerve proper (Fig. 10). In most instances, the sural nerve proper is formed in the distal portion of the lower leg by union of the medial sural cutaneous nerve and the peroneal communicating branch. In 20% of cases, the peroneal communicating branch is absent.30 Up to 20 cm of the sural nerve proper can be obtained from the posterior lateral lower leg.31 With a diameter ranges from 2.5 to 4.0 mm proximally and from 2.0 to 3.0 mm distally, the sural nerve is ideal for relatively fast revascularization, ensuring its dominant use for interfascicular nerve grafting. Histological studies have confirmed that there are 9 to 14 fascicles with a nutrient artery and veins in the sural nerve.32 The sural nerve originates as a monofascicular nerve at the lateral foot area. Fascicles increase in number along the nerve as it courses up the leg, and at its most proximal segment (behind the knee), it carries many fascicles as a polyfascicular nerve.

Usually the sural nerve and the medial sural cutaneous nerve are harvested as long sural nerve grafts for repair of extensive injuries such as a brachial plexus injury. If the segment from the sural nerve proper to the medial sural cutaneous nerve is harvested, it will provide a generous (30 to 50 cm) length of nerve graft material. The peroneal communicating branch lies superficial to the fascia of

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**Fig. 8** Schematic diagram of the anatomy and sensory deficits produced by harvesting of upper extremity cutaneous nerves (lateral antebrachial cutaneous nerve: LACN, medial antebrachial cutaneous nerve: MACN, superficial sensory branch of the radial nerve: SSR, and dorsal cutaneous branch of the ulnar nerve: DCBUN). The anterior view shows LACN and MACN, while the posterior view shows SSR and DCBUN. Note that as a variation, branches of the LACN can supply innervation to areas supplied by the SSR.

**Fig. 9** Schematic of gross anatomical dissection of the superficial antebrachial fossa, emphasizing the location of the lateral and medial antebrachial cutaneous nerves.
the triceps surae muscles, and thus is easily harvested surgically. When the length of nerve graft need is limited, the peroneal communicating branch can be harvested alone and the medial sural cutaneous nerve can be saved. Using this technique, sensation in the distribution of the sural nerve may be retained and the incidence of symptomatic neuroma and bothersome anesthesia at the harvesting site of the sural nerve or in its component branches is likely to be decreased.\textsuperscript{33}

Harvest of the sural nerve is relatively easy with the patient in a supine position, with the lower extremity flexed and internally rotated at the hip, flexed about 40 degrees at the knee, and the ankle dorsiflexed. A longitudinal incision extending from the lateral aspect of the ankle to the popliteal fossa will ensure that all sural communicating branches can be identified, that no damage is done to the donor nerve, and that the maximum amount of nerve graft material is obtained. Alternatively, multiple step incisions can be applied for harvesting the sural nerve from the ankle region to the popliteal fossa (Fig. 11).

Some long-term morbidity results following harvesting a sural nerve. In the most liberal report regarding morbidity, 44% of patients complained of the sensory deficit around the lateral aspect of the foot, 42% of calf tenderness, while symptoms caused by neuroma formation and intolerable pain was found in 16% of patients.\textsuperscript{30} Ortiguela et al.\textsuperscript{33} reported that 6.1% of their patients had neuroma producing symptoms in donor legs, and 9.1% of patients were dissatisfied with the altered sensibility in the foot. However, in general, these symptoms are minor and relatively well tolerated by patients.

**Direct Repair Versus Graft Repair**

It is obvious that direct repairs should be done when a tension-free repair is possible. There is considerable evidence that excessive tension is highly deleterious to axon regeneration and that nerve grafting should be applied in the repair of large gaps.\textsuperscript{22,25,30} Direct repair under tension carries a high rate of failure, especially if the defect is large.\textsuperscript{23,44} However, there is debate about how to repair nerve injuries when there is a small- to moderate-sized gap...
between the injured nerve stumps. Should extensive mobilization and stretching of the nerve be done to allow for direct repair with single anastomosis even under mild tension? Alternatively, should the tension be eliminated by nerve graft repair, in which situation the regenerating axons have to go through two coaptation sites? These problems are addressed on the balance of the following situations. First, tension across a direct suture repair decreases blood flow and promotes proliferation of connective tissue within the nerve, which may block effective axon regeneration. Acute, excessive stretch may cause intraneural hemorrhage, resulting in scar formation and axoplasmic degeneration. Further damage is produced by maturation of scar tissue, which may shrink and constrict nerve fibers. In short, excessive tension may result in a neuroma in continuity. Second, in nerve grafting, the regenerating axon sprouts must cross two suture sites of coaptation. Scar tissue at the distal site of coaptation may block the crossing of axons from the graft to the distal stump. Axons may be wasted at both the proximal and distal suture lines by being misdirected into the perifascicular and epineurial connective tissue.

Many experimental studies comparing epineurial repair under tension versus interfascicular graft repair have been carried out. Some state that regeneration through mildly stretched direct nerve repair is of equal value to meticulously executed graft repair and encourage direct repair. Moreover, functional recovery may not be impaired when direct repair is carried out for the repair of moderate gaps under tension, and the recovery attained may be similar to that following grafting. When the gap, and therefore the tension created, is relatively small, the effect of two suture lines would be more deleterious for axonal regeneration than tension at the suture line, although there is a minor decrease in regeneration due to the degree of tension.

Therefore, if a nerve gap can be overcome with mild tension, a direct repair technique is preferred. It is technically easier to perform, less time consuming and, under the stated conditions, allows for return of function at least equal to that obtainable with nerve grafting. Also, the morbidity associated with harvesting a graft is avoided. Other authors advocate no tension at the suture site and state that an ideal nerve repair occurs only when the repair site is tension-free. They hold that nerve grafting for nerve repair is selected in such conditions and that nerve regeneration after grafting without tension is much better than after direct suture under moderate tension, even though the regenerating axons must cross two suture lines.

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