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Adult Peripheral Nerve Disorders—Nerve Entrapment, Repair, Transfer and Brachial Plexus Disorders

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Abstract

Learning Objectives—After reviewing this article the reader should be able to: 1. Describe the pathophysiologic bases for nerve injury and how it applies to patient evaluation and management. 2. Realize the wide variety of injury patterns and associated patient complaint and physical findings associated with peripheral nerve pathology. 3. Evaluate and recommend further tests to aid in defining the diagnosis. 4. Specify treatment options and potential risks and benefits.

Summary—Peripheral nerve disorders comprise a gamut of problems ranging from entrapment neuropathy, to direct open traumatic injury and closed brachial plexus injury. The pathophysiology of injury defines the patient symptoms, exam findings and treatment options and is critical to accurate diagnosis and treatment. Goals of treatment include management of often associated pain and improvement of sensory and motor function. Understanding peripheral nerve anatomy is critical to adopting novel nerve transfer procedures, which may provide superior options for a variety of injury patterns.

Introduction

Peripheral nerve disorders comprise a gamut of problems that significantly affect patient function and quality of life. These disorders include entrapment neuropathy, such as carpal tunnel syndrome; brachial plexus injury, such as that seen in a motorcycle upper extremity traction injury; and direct open traumatic injury. An understanding of the anatomy and pathophysiology combined with the goals of maximizing function and treating the frequently associated pain will help unravel and simplify the mystery of these complex disorders.

Anatomy, from the cervical or lumbar roots extending to the muscle and sensory end organs, is vital to understanding loss of function and determining treatment options. Newer therapies for proximal nerve injuries such as nerve transfer procedures, in fact demand an intricate knowledge of the anatomy not only within the extremity but within the nerve itself.

Pathophysiology of nerve injury is the second critical component of diagnosis and treatment. Seddon and Sunderland classified nerve injury into five degrees and Mackinnon added a sixth. The underlying pathophysiology defines the presenting pathology and directs subsequent management. First through fourth degree nerve injuries may occur with closed or open injuries with varying effects on the microanatomy surrounding and within the nerve. Fifth degree injuries occur only with open nerve transection injury. Sixth degree injuries represent a combination of the first through fifth degree injuries. Fourth, fifth and sometimes sixth degree injuries benefit from surgical intervention. The type of intervention is determined by the nerve(s) injuries as well as the age and level of injury.

First degree injury is a neurapraxia or conduction block often due to demyelination. There is no advancing Tinel's sign with time because there is no Wallerian degeneration and no regeneration. At most there is a segmental area of demyelination and recovery can occur within minutes to about three months after injury depending on severity. Second degree injury is an axonotmesis or injury such that the axons undergo Wallerian degeneration but the endo and perineurial layers of connective tissue or endoneurial tubules around the axons remain intact. As the nerve regenerates, the Tinel's sign will progress along the course of the nerve; this represents the advancing front of regenerating nerve fibers. Recovery will be complete. This occurs because there is no damage within the nerve so the appropriate axon will reach the appropriate end organ without getting lost down the incorrect path and without the barrier of scar tissue. A third degree injury adds scarring within the nerve—recovery can occur, with an advancing Tinel's sign but the degree of recovery will be limited by the amount of scar tissue. First through third degree injuries associated with closed injuries are typically managed expectantly without surgical intervention.

In contrast, fourth and fifth degree injuries require surgery for optimal recovery. Fourth degree injury is essentially the extreme of a third degree injury. The nerve is in continuity but filled with scar. There is no progressive Tinel's sign on exam over time because regenerating axons cannot penetrate scar. Surgery consisting of excision of scar and repair, nerve transfer, etc. is necessary to achieve return of function. Fourth degree injury may be seen in trauma with a high mechanism of energy such as a motorcycle accident where traction or crush injury cause through and through scarring of the nerve. They can also be seen in gunshot wounds that don't actually directly penetrate the nerve but cause such a significant local blast effect that the end result is the same—complete distal loss of function. Fifth degree, neurotmesis, injuries also require surgical intervention but this is usually more obvious because there is an open injury with direct nerve transaction. Nevertheless, the bottom line is the same; these injury patterns have no advancing Tinel's with time and will not recover distal function without some type of intervention.

Sixth degree or mixed injury is a neuroma-in-continuity and may contain different components of all these types of injuries. Depending both on what function is preserved and what recovers over time, surgical exploration and repair may or may not be warranted. For example, a sixth degree median nerve injury in the arm with preserved motor function, complete loss of sensation in the appropriate distribution and no pain, will be better served with distal sensory nerve transfer from the fourth to first web space alone than with proximal grafting. This avoids loss of the more critical motor function that might occur with the very tedious and exacting dissection in the zone of injury at the site of the neuroma in continuity(1, 2).

Essentials of Preoperative Assessment and Management

A careful history includes a clear description of the specific chief complaint and the mechanism of injury. Especially in nerve compression, however, patients may have vague symptoms that are difficult to describe. The onset of symptoms (including a delineation of associated pain related symptoms), duration, attempted previous treatment (both operative and non-operative), and what ameliorates or exacerbates symptoms should be elicited. Specific questions regarding associated medical disorders (such as atherosclerotic disease, diabetes, renal failure) and previous trauma and surgeries are also important.

The patient's age, gender, occupation and hobbies affect their needs and the resulting care plan. Other information such as underlying patient stressors including worker's compensation issues or legal action associated with the complaint help round out a complete picture of the issue at hand. The attached Pain Questionnaire, see Figure 1, further discussed

elsewhere(3), is a useful adjunct for eliciting and more precisely defining pain symptoms, the impact of the problem on the patient's quality of life, and adjunctive information.

Timing is especially important when it comes to nerve injuries for two main reasons. First, it is critical to restore motor innervation in a timely fashion (*time is muscle*). If reinnervation does not occur within a timely fashion (in most adults, this is within one year of denervation), it is unlikely that any muscle recovery will occur. This is because muscle tissue is time sensitive. Second, performing serial physical exams over time allows correct diagnosis of the degree of nerve injury. This is vitally important in closed injury such as a brachial plexus traction injury. When multiple nerves are injured, treatment options can be almost prohibitively limited. Fortunately, many of these injuries are of mixed pattern and spontaneous recovery of neurapraxic and axonotmetic injuries occurs over time improving treatment options and outcomes.

The physical exam can be more limited or quite extensive depending on the type of disorder at hand. An acute open laceration at the elbow level just over the cubital tunnel quickly guides the examiner to confirm the loss of distal ulnar nerve sensation and motor function. A brachial plexus closed injury demands careful examination of the affected extremity as well as shoulder and back musculature to determine the level of injury and help assess for signs of root level avulsion. This will also provide information about surrounding intact muscle function whose corresponding nerves may be available for use as donors for a nerve transfer procedure. Evidence of Horner's syndrome as well as loss of serratus, rhomboid or diaphragm function also point to a root level avulsion.

More chronic symptoms of compressive neuropathy demand assessment of distal nerve function as well as adjunctive exam techniques. This includes percussion of the nerves to elicit Tinel's sign at putative compression points and various provocative maneuvers to exacerbate symptomatology, such as the Phalen's test(3).

Table 1 highlights elements of the motor examination as organized by specific joint and muscle function.

The sensory exam is used to corroborate the motor exam except in cases of isolated sensory nerve injury where it becomes more critical. We use both two point discrimination as well as ten/ten testing (4, 5) for documentation of sensation. Having the patients draw the areas of decreased sensation (using the pain diagram) can also be helpful in expeditiously assessing areas of diminished sensation.

Associated vascular, direct tendon/muscle and underlying bony issues should also be assessed. Passive and active range of motion of all of the joints of the affected extremity is important. For example, preserved motion at the shoulder and elbow can compensate for significantly decreased wrist level loss of motion. Also, if passive motion is not maintained or cannot be restored with vigorous therapy, there is little sense in restoring active range of motion. Assessment of other deficits, such as hemiparesis and the need to use latissimus for transfers may be vitally important, because sacrifice of the thoracodorsal nerve would clearly be contraindicated in this patient.

Diagnostic tests, such as electrodiagnostic and radiologic assessment are helpful adjuncts; the need for them should be determined on a case by case basis. For example, suspicion of median nerve compression at the wrist can be confirmed by nerve conduction studies. Degree of distal thenar denervation can be evaluated by adjunctive electromyography. Electrodiagnostic tests can be very helpful in eliminating more central or non-surgical etiologies of disease such diabetic polyneuropathy.

More complex closed brachial plexus injuries often benefit from serial electrodiagnostic testing to assess for recovery. Initial denervation patterns at two months followed by evidence of reinnervation over time, such as motor unit potentials on electromyography, is promising. Importantly, fibrillations on electromyography imply axonal injury. Motor unit potentials and nascent units imply recovery. Motor unit potentials occur with collateral sprouting from adjacent uninjured axons at the motor end plates and occur at about 8 to 12 weeks. Nascent units occur with reinnervation of actual injured axons. Both imply spontaneous recovery will occur and are relative contraindications for surgery. These findings may precede clinical evidence of recovery and allow decision making to proceed in a timely fashion.

For these complex injuries, imaging work-up with MRI or CT myelogram may show root level avulsion injury, which is important for prognosis and determining treatment options. A chest x-ray that reveals rib fractures eliminates use of intercostal nerves as potential donors for nerve transfer or free functioning muscle transfer. Additionally, inspiration and expiration views allow assessment of diaphragmatic paralysis.

Preoperative management does not end with these investigative studies. It also includes active treatment through pain management and physical therapy. Pain management of peripheral nerve disorders is complex.(6–8) Suffice it to say that there are a number of medications (including sympatholytics such as clonidine, anti-inflammatory agents, antiepileptics such as gabapentin and pregabalin, and antidepressants such as amitriptyline) that may help in treating the difficult to treat and often debilitating pain associated with both open and closed acute injuries as well as subacute and chronic compressive neuropathies. Other adjuncts such as sympathetic blocks (9), nerve stimulators (10, 11) and spinal cord stimulators (12, 13) can also be helpful in chronic neuropathic pain. Acute neuropathic pain due to a traumatic or iatrogenic nerve injury may be amenable to surgical treatment with neuroma resection and burying the nerve; diagnostic blocks are often useful to determine if the patient has more isolated pain that might be amenable to this treatment prior to doing surgery. Physical therapy can assist in pain management and specific techniques, such as stress loading (14) are particularly helpful in management of incipient or established chronic regional pain syndrome. Therapy is also instrumental in maintaining passive motion in the setting of loss of motor function as restoring function in the setting of joint contractures would be obviously frustrating and futile. In summary, treatment of the complex pain that is often associated with nerve injuries is to diagnose early, treat early and support the patient long term in the management of this often intractable, always challenging, chronic disease process

Goals of Treatment

The goals of treatment vary by patient factors as well as type of pathology. They include full restoration of sensory and motor function whenever possible, alleviation of pain, and reduction of the symptoms of nerve compression.

Advantages/Disadvantages of Treatment Alternatives

Treatment alternatives vary widely depending on the clinical situation at hand. In general, acute open injuries (except gun shot wounds) should be treated with timely surgical exploration and management. Acute closed injury, gun shot associated nerve dysfunction, and compression neuropathy should be examined and managed in a more deliberate fashion.

Acute open injuries of sensory, motor or mixed peripheral nerves should be treated with surgical exploration. Significant open proximal injuries benefit from emergent exploration as soon as possible after injury. Within 72 hours, the distal nerve ends still contain

neurotransmitters that allow intraoperative stimulation and clear identification of the distal end. For sharp injuries, the repair can be performed immediately. For less clean injuries, the endings can be clearly identified and tagged for later repair. Delaying repair for a few days or up to three weeks allows any crush component of injury to declare itself and allows appropriate trimming and grafting if necessary. Occasionally, for example, during simultaneous vascular repairs, when it is clear that later surgical intervention would be potentially fraught with danger, simultaneous nerve injury graft repair is warranted. Under these specific circumstances, the advantages of immediate nerve repair outweigh the disadvantages with the proviso that aggressive debridement should be performed to get out of the zone of injury and nerve grafts are often necessary.

For brachial plexus and other peripheral nerve injuries, there are multiple options for treatment including direct injury-level exploration with nerve repair or grafting, distal nerve or tendon transfers, free muscle transfer and fusion procedures. Determining the appropriate treatment demands consideration of patient factors (age, health, type of function desired, speed of recovery desired), injury factors (number of roots or nerves injured, type of injury) and, most importantly, time since injury. Complete brachial plexus injuries are among the most devastating of nerve injuries; there is no one ideal method of reconstruction. Use of motor fibers from non-plexus sources including intercostal, phrenic, spinal accessory and contralateral seventh cervical root(15–17) is described, however varying clinical outcomes are reported(18). This is a difficult problem with no clear definitive treatment available.

Direct or interposed graft nerve repair is clearly indicated for acute or subacute distal injuries. These repairs work well if the motor end organ is reinnervated in a timely fashion and the appropriate orientation is maintained (matching motor to motor and sensory to sensory in mixed nerves) or precisely performing an epineurial repair (in single fiber type and single function nerves such as a single proper digital nerve). Even if significant time has elapsed since injury, it may also be reasonable to perform direct or graft repair if the nerve carries sensory fibers only as this end organ is not time sensitive--however, the risks of surgery are generally justified only to restore areas of critical sensation (such as the sole of the foot or the first web space).

Direct anatomical nerve repair or graft is less attractive if the injury is distant from the appropriate end organ because of the length of time required for regeneration. For example, no matter the technical quality of repair, a very proximal ulnar nerve repair will not result in good intrinsic muscle function in an adult. This is because by the time reinnervation reaches the end organ the muscle will have become unresponsive. If the nerve endings are not trimmed back outside the longitudinal zone of injury or approximated appropriately, the results will also be disappointing.

Nerve repair with interposed graft is done in clinical scenarios similar to those that are appropriate for direct repair. A graft should be used when the ends cannot be approximated without tension. Graft repair may be one of the few remaining options in a case of multi-nerve injury where there are no donors for nerve or tendon transfers. Grafts are commonly used to repair single function nerves such as sensory nerve or in other injuries that occur close to end organ but have sufficiently long enough zone of injury (open laceration with a crush component) that interposed material is required for repair. Unfortunately, autologous expendable nerve graft is limited and harvesting it leaves an anesthetic area with risk of painful neuroma formation. Other non-nerve autologous tissue such as vein graft(19–21) and manufactured conduits are available and may be reasonable choices for non-critical sensory nerve repair.

Nerve transfers are advantageous because they deliver regenerating nerve fibers to the target end organ more quickly. This effectively ‘converts’ a proximal level injury to a more distal injury. This approach also allows avoidance of the area involved in the initial traumatic injury—dissection is carried out distally in a relatively unscarred area and is much more technically straightforward and in sixth degree or mixed injuries with some function present, distal nerve transfers allow for reconstruction of the lost function without fear of downgrading useful function. Nerve transfers, unlike tendon transfers, require no immobilization and are useful in patients with significant stiffness. They can also restore function for which no good tendon transfers exist such as pronation(22). Unlike tendon transfers, reinnervation of the muscle does not disrupt the muscle-tendon unit biomechanical structure. The excursion, origin/insertion and length tension relationship are left undisturbed.

On the other hand, recovery from nerve transfers does take time. Reinnervation, though quicker than that seen in proximal level nerve repair or graft procedure, can take several months. The intraneural dissection required is technically demanding and requires knowledge of functional fascicular anatomy within the nerves. Finally, it can be challenging to help patients with retraining as many therapists are unfamiliar with these transfers.

Tendon transfers are time-tested, well accepted and more commonly taught. Therapists also are more familiar with the retraining/therapy required post surgically. After initial immobilization, patients can rehabilitate and use these in a relatively shorter period of time—weeks versus the months required in nerve transfer procedure. However, tendon transfers clearly have many limitations. Sensation and certain motor functions cannot be restored with tendon transfers. Surgery requires an extensive zone of dissection that can lead to significant scarring, stiffness and adhesions. Disruption of the length tension relationship and normal excursion of the muscle tendon unit limits outcomes. Postoperative immobilization to protect the tendon transfers will compromise a stiff hand and are contraindicated in very stiff hands. Complications such as rupture, inadequate tensioning and stretch are problematic. Overall, these are effective but, in concept and execution, more crude than nerve transfer procedures.

The advantages and disadvantages of surgical management of compressive neuropathy are more nuanced than those for nerve injury. In the absence of motor wasting, observation and conservative management such as splinting and adaptive mechanisms are reasonable. When motor wasting or evidence of denervation on EMG is present, timely decompression and the need for surgical treatment is clear. For other symptoms, including sensory dysfunction, surgical treatment may be undertaken when the severity of subjective symptoms outweigh the associated risks, potential complications and downtime required by the surgical procedure. For relatively straightforward surgery, such as carpal tunnel release, risks are relatively low and surgery may be done with relatively minimal downtime. For thoracic outlet decompression, on the other hand, potential complications such as neurovascular injury and pneumothorax, are more significant, and relatively minor symptoms should initially be managed non-surgically.

Key Elements of Surgery

Peripheral nerve surgery demands meticulous attention to detail, a gentle touch and patience. The information included below will outline tips for successful nerve surgery. The exact anatomic details and steps of specific surgeries are available elsewhere. What follows are principles that define the basics of nerve surgery from decompression and exploration to complex nerve transfer procedure.

Careful communication with anesthesiology is required as long-acting paralytics will obviously prevent successful intraoperative nerve stimulation. Also, when trimming the

damaged proximal nerve ending, it is often useful to lighten the anesthetic to allow for close assessment of hemodynamic changes; abrupt tachycardia with more proximal bread loafing of the cut nerve end provides evidence that the zone of injury has been resected and functional nerve fibers are exposed and ready for repair.

Although a bloodless field allows faster and easier dissection, use of a tourniquet is not always possible. Caution should also be used when doing nerve transfers, as after about one hour of tourniquet time, temporary palsy may develop, which interferes with the specific nerve branch stimulation required to determine appropriate donor nerve fascicles.

In most cases of trauma, the zone of injury is much larger than first anticipated. Significant proximal and distal extension of existing scars and lacerations, zigzagging across joints to prevent contracture, is often necessary. It is vital to get out of the zone of injury and find normal nerve proximally and distally. Then the cut or crushed nerve can be identified, appropriately trimmed back, and repaired. The nerve should be cut carefully without crushing it. Any bulging fascicles can be trimmed back prior to repair. The nerve ends should be aligned using clues such as the visible fascicular pattern as well as by matching the pattern of small vessels on the surface of the epineurium. An epineurial repair is generally adequate and the ends should be gently apposed. Grouped or fascicular repairs(23, 24) are appropriate where the proximal and distal anatomy are clear (such as matching the deep motor branch fascicles the ulnar nerve when performing a wrist-level laceration). Sutures should be tied down loosely to avoid kinking the individual fascicles. Repairs should be done under no tension; any tension demands use of interposed graft, and the adjoining joints may be ranged with the wound still open to make sure that even in extremes of extension the nerve repair remains tension-free.

When nerve grafts are used, the graft proximal end should be marked so that the graft can be reversed prior to inlay. This is so no regenerating nerve fibers are 'lost' by regenerating down side branches of the nerve graft. Cable grafts may be tacked together ex vivo using fibrin glue or epineurial sutures. They should be kept in alignment so that the appropriate fascicular anatomy of the nerve is maintained as it regenerates through the cables to the distal cut end. In these cases, it may be prudent to do a grouped fascicular repair. For example, a median nerve laceration at the wrist level that requires cable grafting, might benefit from fascicular repair of the sensory portion via three cables to the distal sensory portion. The motor fascicles to the thenar musculature could be repaired using an additional cable separately to optimize regeneration down the appropriate path.

Use of autologous graft provides superior regeneration and is preferred for restoration of motor and key sensory function. One example of this would be use of a segment of lateral antebrachial cutaneous nerve for repair of the radial digital nerve to the index finger. There may even be a role for preferential use of a motor graft for critical restoration of motor function.(25) For example, use of the obturator nerve branch to gracilis muscle may be indicated for repair of an iatrogenic spinal accessory nerve injury sustained during lymph node biopsy. Conduits are easy to use, diminish operative time and eliminate graft donor site deficits. However, at present the outcomes with autologous graft remain superior.(26) Therefore conduit use is only clearly indicated for sensory function such as repair of the non-critical sensory zones of the hand; we recommend use of autologous nerve graft for the first web space critical sensory area. Nerve allotransplantation carries risks of immunosuppression, however temporary, and should be reserved for special cases where no other options exist(27).

Although there may be a role for direct exploration of brachial plexus injury with resection and interposition grafting in babies and children; the distance required for regeneration to

the motor endplate is prohibitive in adults. In fact, in many cases we do not perform direct plexus exploration at all and treat with distal transfers alone. More distal nerve transfers that take functioning nerve fibers from muscles with redundant function and reroute them into the non-functioning nerve to the denervated muscle provide an attractive alternative. The same principles of nerve repair hold true when performing nerve transfer, however, there are a few additional caveats. In these cases, intraoperative nerve stimulation is crucial to determine what donor fascicles are expendable and confirm that the recipient nerve fiber is non-functional. Internal neurolysis proximally in the recipient nerve and distally in the donor nerve is key to providing adequate length, in most cases, to allow for direct approximation of the transfer without use of interposed graft. At the level of the nerve transfer, the donor nerve branch should be cut as far distal ('donor distal') and the recipient as far proximally as possible. The recipient side can then be trimmed if there is excess length as this will shorten the time for recovery by bringing viable fascicles closer to the end organ.

Nerve transfers commonly used in plexus or other proximal nerve injuries include both motor and sensory transfers.(28, 29) For example, a motor transfer used for patients with upper brachial plexus injury, includes the nerve transfer to biceps and brachialis muscles from expendable median and ulnar nerve fascicles at the level of the arm.(30) The fascicular anatomy at this level allows intraneural dissection of branches that contribute to the flexor carpi radialis and flexor digitorum superficialis muscles (median nerve) and to the flexor carpi ulnaris (ulnar nerve). These small branches are cut distally and transposed towards the individual branches of the musculocutaneous nerve that go to the biceps and brachial muscles. The repair is done mere centimeters from the motor end organ allowing for recovery of function in a few months. By specific dissection and identification of the branches to the individual motor fascicles, wasteful direction of motor fascicles into the terminal sensory lateral antebrachial cutaneous nerve is avoided.

Other useful motor transfers are shown in Figures 2, 3 and 4a and b.

An example of a sensory nerve transfer is one that is performed at the wrist level for patients with a high median nerve injury. In this transfer, the ulnar nerve non-critical sensory component to the fourth web space or the dorsal cutaneous branch is transferred to the median nerve critical sensory territory to the first webspace. Again, the donor nerve is carefully dissected distally, stimulation of the ulnar intrinsic motor fascicles will confirm their location so that they may be preserved and the sensory component is cut. The median nerve sensory component may be cut proximally allowing tension-free repair at the wrist level. This particular transfer could be combined with other proximal transfers from radial nerve branches (extensor carpi radialis brevis) to restore median innervated pronation and anterior interosseous nerve function. A tendon transfer such as an extensor indicis opponensplasty could restore opposition and that combination of nerve and tendon transfers is a very reasonable option for this of injury pattern.

Another useful sensory transfer is shown in Figure 4c and d.

Nerve decompression procedures may seem initially straightforward but also demand an attention to detail and patience. (Insert Video Graphic 1). See Video 1, which demonstrates a carpal tunnel release surgery being performed by decompressing the median nerve in the wrist through the carpal tunnel. This procedure involves transecting the transverse carpal ligament. Available in the "Related Videos" section of the Full-Text article on PRSJournals.com or, for Ovid users, available at [INSERT HYPERLINK HERE](#). This common procedure, especially in certain patient populations (end-stage renal disease and diabetics) may require incisions that go proximal to the wrist to allow release of thickened forearm fascia. Keeping incisions ulnar to and not directly on top of the median nerve is also

helpful. Inserting a finger proximal and distal to the area of direct release can reveal any constricting bands or points of compression that should encourage more extensive incisions. Thorough release is important in all nerve decompression procedures and sometimes demands additional adjuncts such as step-lengthening the pronator teres (for median nerve compression in the forearm) or transposing the nerve (for ulnar nerve compression at the elbow). If the ulnar nerve is transposed, it is critical that the nerve rests in a gentle curve, not compressed by a fascial sling or kinked at the distal and proximal extent of dissection.

Perioperative management

Pain control is critical (see the preoperative management section). Intraoperative use of a lidocaine Bier block supplemented with dexmedetomidine (31) may be helpful in patients at risk for or with complex regional pain syndrome. We include 25–30 mcg of dexmedetomidine, an alpha-2 adrenergic receptor agonist(31), in the lidocaine solution used for the regional block. Injection of local into the incision and the use of bupivacaine pumps can be helpful adjuncts postoperatively. For all direct nerve repairs, nerve grafts and nerve transfers, repairs are tension-free and allow early motion to promote nerve gliding. Generally, a bulky dressing and splint is applied for 48 hours for comfort, and then full active and gentle passive range of motion is started with further more vigorous therapy only limited by skin wound healing and patient comfort. Tendon transfers, however, do require immobilization to allow healing of tendon repair prior to therapy. Hand therapy to help with retraining, scar management, edema and pain control is vital to recovery.

Complication Management

Complications in nerve surgery are not dramatically different from those of any standard surgery. Delayed wound healing, especially of lower extremity incisions and in higher risk populations (diabetics and renal failure patients) can occur. Seroma in the axilla and in areas of motion such as the elbow can be minimized by judicious use of drains.

Complications more specific to nerve surgery are best managed by avoidance. These include failure to completely excise the neuroma or scarred nerve and damage to neighboring structures (for example, the medial antebrachial cutaneous nerve during ulnar nerve surgery). Early recognition and treatment with consultation with pain management and medical and procedural intervention (stellate ganglion blocks, peripheral nerve stimulator and dorsal column stimulator) as well as aggressive therapy including stress loading and desensitization will minimize fallout.

Expected Outcomes

Nerve compression that is diagnosed correctly and treated properly produces positive patient outcomes with complete symptom relief and are rewarding indeed. Nerve repairs and transfers, done in a timely fashion and given time, can also produce excellent outcomes with restoration of 4+/5 motor function and useful sensation. Even in late injuries, nerve repair can lead to restoration of critical protective sensation. For certain injuries, such as brachial plexus injury with loss of shoulder function, and complete brachial plexus injury, work is still being done to achieve optimal outcomes.(32) Finally advances in nerve surgery, such as use of end-to-side transfers may further diminish donor site deficits and improve outcomes. (33, 34) (Insert Video Graphic 2) See Video 2, which demonstrates an end-to-side spinal accessory to suprascapular nerve transfer procedure, available in the “Related Videos” section of the Full-Text article on PRSJournals.com or, for Ovid users, available at [INSERT HYPERLINK HERE](#).

Coding

Refer to Table 3.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Pain Questionnaire

Name: _____ Date: _____

Age: _____ Gender: Male _____ Female _____ Dominant Hand: Right _____ Left _____

1. Pain is difficult to describe. Circle the words that best describe your symptoms:

Burning	Throbbing	Aching	Stabbing	Tingling	Twisting	Squeezing
Cramping	Cutting	Shooting	Numbing	Vague	Stinging	Indescribable
Pulling	Smarting	Pressure	Coldness	Dull	Other: _____	

Level of symptoms: place a mark through the line to indicate the level of your pain, if zero is no pain and the end of the line is the most severe pain you can imagine having.

2. Mark your average level of pain in the last month

_____

No Pain Most Severe Pain

3. Mark your worst level of pain in the last week

Right _____

No Pain Most Severe Pain

Left _____

No Pain Most Severe Pain

4. Where is your pain? (Draw on diagram)

Mark on this scale how your pain has affected your quality of life:

_____

0% 100%

Very little A large amount

Mackinnon, S.E. and Novak C.B., 2001

Figure 1. Pain Questionnaire. We find this diagram quite useful for localizing and describing the symptoms related to nerve injury particularly in nerve entrapment syndromes.

Figure 2. Spinal Accessory to Suprascapular Motor Nerve Transfer

In this transfer, spinal accessory (Cranial Nerve XI) motor fibers are re-routed and repaired to the non-functional suprascapular nerve. This is particularly useful in patients with brachial plexus injuries with dysfunction due to nerve root level avulsions rendering the musculature innervated by the suprascapular nerve non-functional. A posterior transverse incision is made just cephalad to the spine of the scapula and the nerves are isolated on the underside of the trapezius (spinal accessory donor nerve) and at the suprascapular notch (suprascapular recipient nerve). The donor nerve is cut as far distally as possible and the recipient is cut proximally after release at the notch to allow for easy, tension-free repair. (Reproduced with permission, Mackinnon SE and Colbert, SH, *Nerve Transfers in the Hand and Upper Extremity Surgery, Techniques in Hand and Upper Extremity Surgery*, 12: 20–33, 2008.)

Figure 3. Radial to Axillary Motor Nerve Transfer

In this transfer, radial nerve branch to triceps medial head muscle motor fibers are rerouted and repaired to the non-functional axillary nerve branch to the deltoid muscle. This is particularly useful in patients with brachial plexus injuries with dysfunction due to nerve root level avulsions rendering the musculature innervated by the deltoid nerve nonfunctional. A curvilinear incision is made over the posterior shoulder and the nerves are isolated at the posterior arm between the triceps heads (medial triceps nerve branch of radial nerve donor nerve) and in the quadrangular space (axillary recipient nerve). The donor nerve is cut as far distally as possible and the recipient is cut proximally to allow for easy, tension-free repair. The donor nerve fibers can be repaired to preferentially reinnervate the recipient motor fibers by neurolysing out and excluding the sensory component of the axillary nerve. (Reproduced with permission, Mackinnon SE and Colbert, SH, Nerve Transfers in the Hand and Upper Extremity Surgery, *Techniques in Hand and Upper Extremity Surgery*, 12: 20–33, 2008.)

Figure 4. Median to Ulnar Motor and Sensory Nerve Transfers

In this transfer, anterior interosseous (median) nerve branch to pronator quadratus muscle motor fibers are re-routed and repaired to the non-functional ulnar nerve deep motor branch. This is particularly useful in adult patients with very proximal ulnar nerve injuries. Although direct exploration and repair may allow restoration of ulnar innervated extrinsic musculature, intrinsic function will not be restored due to the length of time required. By the time regenerating fibers reach the hand level intrinsic muscle fibers, that muscle will be non-functional. By use of more distal transfers, ant Claw procedures can be avoided. In addition, critical areas of sensation can be restored in a more timely fashion. In figures a and b, the motor branches are isolated, transected and repaired to effect the motor transfer. In figures c and d, the sensory branches are likewise dissected out and repaired to restore sensation to the ulnar border of the hand--in this case sensation to the non-critical third web space is sacrificed. (Reproduced with permission, Mackinnon SE and Colbert, SH, *Nerve Transfers in the Hand and Upper Extremity Surgery, Techniques in Hand and Upper Extremity Surgery*, 12: 20–33, 2008.)

Table 1

Motor exam of the upper and lower extremity with specific tips that will aid the diagnosis and treatment of pathology associated with traumatic injuries of the brachial plexus and peripheral nerves as well as compressive neuropathy(1, 2).

Upper Extremity Exam**Shoulder:** This is a complex joint to assess with multiple muscles providing multiple movements. Overall, the movements to assess include internal and external rotation, abduction, adduction, flexion and extension.

- Specifically assess the function of the following muscles: deltoid (resisted shoulder abduction to 90 degrees—palpate muscle), supra(resist shoulder abduction—palpate muscle)and infraspinatus (resisted external rotation of the arm at the shoulder—palpate muscle), serratus anterior(shoulder forward flexion past 90 degrees and have patient do push up against wall and assess for scapular winging), latissimus dorsi (ask patient to cough and palpate muscle or assess resisted shoulder adduction), pectoralis (resist shoulder adduction and palpate muscle) and trapezius(shoulder abduction past 90 degrees and assess ability to shrug shoulder upward).

Elbow: Assess flexion and extension.

- Specifically assess if biceps/brachialis(resisted elbow flexion in forearm supination—palpate muscle)or brachioradialis(resisted elbow flexion with the forearm in neutralor the thumb in a 'hitchhiker' position—palpate muscle) alone is contributing to elbow flexion. Assess resisted elbow extension and palpate the triceps muscle bellies.

Forearm/Wrist: Assess flexion, extension, pronation, supination, and ulnar and radial deviation.

- For extension, be sure to individually palpate extensor carpi radialis brevis/longus(resisted wrist extension with wrist in radial deviation)and extensor carpi ulnaris (resisted wrist extension with wrist in ulnar deviation).
- For flexion, palpate flexor carpi ulnaris(resisted wrist flexion with wrist in ulnar deviation), flexor carpi radialis(resisted wrist flexion in radial deviation)and palmaris longus(oppose thumb to small finger and flex wrist, palpate palmaris as separate tendon just ulnar to the flexor carpi radialis tendon).
- For supination, assess forearm supination with the elbow in extension (this will eliminate biceps muscle mediated supination).
- Pronation of the forearm due to pronator teres and quadratus muscle function is difficult to differentiate by motor exam alone but with resisted forearm pronation, the pronator teres can be visualized/palpated at the proximal forearm ulnar border.

Hand: Assess extrinsic (muscle bellyproximal to the wrist) as well as intrinsic muscle (muscle belly in the hand) function for each finger and the thumb.

- Extrinsic muscle function includes extension and flexion of the digits and abduction of the thumb.
  - Be sure to assess flexion at the proximal and distal interphalangeal joints of the fingers with careful assessment of flexor digitorum profundus function that is ulnar innervated (to the small and ring fingers) and median innervated (to the index and long fingers).
  - Also, carefully assess the extensor pollicis longus separately from the extensor pollicis brevis by resisting thumb extension at the distal and proximal phalanx respectively and palpating the tendon proximally.
  - Note that abduction of the thumb is provided by both the radial nerve innervated extrinsic abductor pollicis longus muscle as well as the median nerve innervated intrinsic abductor pollicis brevis muscle.
- Intrinsic muscles include the muscles at the hypothenar and thenar eminences as well as the interosseous muscles and lumbricals.
  - Be sure to assess palmar abduction of the thumb (median innervated abductor pollicis brevis muscle function)—resist and palpate muscle belly.
  - Also assess first dorsal interosseus muscle function (distal most ulnar innervated intrinsic musculature—palpate at radial aspect of index finger with pinch).

Lower Extremity Exam

Hip: This is a complex joint to assess with multiple muscles providing multiple movements. Overall, the movements to assess include internal and external rotation, abduction, adduction, flexion and extension.

- Specifically assess the function of the following muscles: iliopsoas (resisted hip flexion with knee flexed), adductors (resisted hip adduction with knee extended, palpate muscles at medial thigh), gluteus maximus (assess hip extension with the patient in the supine position) gluteus medius and minimus (assess internal rotation with hip and knee flexed).

Knee: Assess flexion and extension.

- Assess quadriceps function by checking extension against resistance and assess hamstring flexion by checking flexion against resistance—easiest when the patient is lying supine.

Ankle and Foot: Assess inversion, eversion, plantar and dorsiflexion at the ankle and palpate and assess toe function.

- Assess tibialis posterior muscle ankle inversion and peroneus longus and brevis muscle ankle eversion by resisting these ankle motions and palpating and/or visualizing the muscle action.
- Assess the gastrocnemius and soleus muscles at the posterior calf by resisted plantar flexion and direct palpation.
- Assess the tibialis anterior muscle at the anterior lower leg by resisted ankle dorsiflexion.
- Assess resisted toe flexion provided by the flexor digitorum and hallucis longus muscles. Assess resisted toe extension provided by the extensor digitorum longus and extensor hallucis longus. Palpate the extensor digitorum brevis muscle (usually innervated by a deep peroneal nerve branch) over the dorsolateral aspect of the foot during resisted toe extension.

Other musculature to examine:

The examination of other muscle groups is critical to both diagnosis and treatment as the presence or absence of their function will help determine level of injury as well as potential nerve transfer donors.

Proximal Musculature: Testing muscles that receive innervation at a very proximal level from the cervical roots provides valuable information on the level of injury, especially in closed brachial plexus patients. Loss of function of these proximally innervated muscles, hints at a very proximal level of injury such as root avulsion off the spinal cord.

- Assess the serratus anterior muscle (long thoracic nerve innervation originating from cervical roots five, six and seven) by checking for scapular winging as the patient does a 'push-up' against the wall; also assess forward flexion of the shoulder past 90 degrees. Occasionally these muscles can be visualized just anterior to the lateral border of the latissimus muscle and lateral to the lateral border of the pectoralis major muscle.
- Assess the rhomboid muscles (dorsal scapular nerve innervation originating from cervical roots four and five) by having the patient put their hands behind their back and push backwards, the rhomboid muscles on either side of the spine just medial to the border of the scapula can often be palpated.

Potential Donors: Testing muscles that receive via the cranial nerves or very proximally to see if they are spared is also useful in determining what may be available as proximal donor motor nerves especially in cases of brachial plexus injury.

- Assess the trapezius muscle (spinal accessory nerve innervation) by having the patient shrug their shoulders against resistance—this allows assessment of the upper trapezius.
- Assess the pectoralis muscle clavicular (have patient raise arm above shoulder level and resist forward pushing) and sternocostal (have patient adduct arm at the shoulder against resistance) heads. Loss of function of these not only eliminates a potential proximal donor nerve, it suggests that there is an injury at the level of the lateral or both lateral and medial cords of the brachial plexus, respectively.

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¹ Russell, S. M. *Examination of Peripheral Nerve Injuries: An Anatomical Approach*. New York: Thieme, 2006.

² Brain. *Aids to the Examination of the Peripheral Nervous System*, Fourth Ed. Philadelphia: Elsevier 2000.

Table 2

Examples of nerve transfer techniques that can be used instead of the more traditional equivalent reconstructive method in cases of specific nerve injury patterns.

Injury Pattern/Deficit	Nerve Transfer (donor to recipient nerve branch)	Traditional Reconstructive Method
Upper plexus injury—loss of elbow flexion	Double fascicular transfer (from median and ulnar nerves to biceps/brachialis branches)	Transfer of triceps, latissimus or pectoralis muscle; Steindler flexorplasty, long nerve grafts
Upper plexus injury—loss of shoulder function	CN XI to suprascapular nerve and triceps to deltoid branch	Shoulder fusion, Saha procedure, long nerve grafts
Lower plexus injury—loss of pronation	Brachialis or ECRB (if C7 is spared) to pronator branch	Biceps, BR or brachialis muscle rerouting
Lower plexus injury—loss of thumb and index finger flexion	Supinator to AIN or Brachialis to AIN	Tendon transfers (BR to FPL and ECRL to index FDP)
Axillary nerve injury	Triceps, medial pectoral or thoracodorsal nerve to axillary nerve	Shoulder fusion, long nerve grafts
Radial nerve injury	Median (FCR, FDS branches) to radial (ECRB and PIN branches)	Tendon transfers (PT to ECRB, PL to EPL, and FCU, FCR or FDS to EDC)
Loss of median innervated pronation	ECRB to pronator teres branch	Biceps, BR or brachialis muscle rerouting
Loss of median innervated thumb and finger flexion	Supinator or brachialis to AIN branch (combine w/tenodesis of long to ring/small flexors)	Tendon transfers (BR or ECRL to FPL and side to side tenodesis with ulnar FDP's or ECRL to index/long FDP)
Isolated AIN injury	FDS to AIN branch	BR to FPL tendon transfer and FDP tenodesis, fusion of IPJ of thumb
Distal median nerve injury	AIN to median motor branch	Opponensplasty
Distal ulnar nerve injury	AIN to ulnar nerve deep motor branch	Static and dynamic claw hand correction procedures

CN XI - cranial nerve XI/spinal accessory nerve, ECRB - extensor carpi radialis brevis, BR -brachioradialis, AIN - anterior interosseous nerve, FPL - flexor pollicis longus, ECRL - extensor carpi radialis longus, FDP - flexor digitorum profundus, FCR - flexor carpi radialis, PL -palmaris longus, FDS - flexor digitorum superficialis, PIN - posterior interosseous nerve, PT -pronator teres, FCU - flexor carpi ulnaris, EDC - extensor digitorum communis, IPJ - interphalangeal joint

Table 3**Common CPT Codes in Peripheral Nerve Surgery**

Nerve decompression:

- Most nerve decompression procedures fall in the 64702–64727 Nervous System CPT codes section
- The tendon lengthening code (24305) is added to ulnar nerve decompression and transposition (64718) at the elbow, if the pronator-flexor tendon origin is step-lengthened. However, if no transposition is done, only 24305 should be included because it includes the decompression of the ulnar nerve at the cubital tunnel.
- For the lower extremity, tarsal tunnel release (28035) and Morton's neuroma excision (28080) are found in the Musculoskeletal System CPT codes section. Note, however, that decompression of a plantar digital nerve (64726) is in the Nervous System section

Nerve repair, grafts and transfers:

- These codes are found in the 64831–64911 Nervous System CPT codes section
  - Attention should be paid to the number of cables used and length of each cable as there are different codes for single versus multiple strand graft repairs and repairs that are up to 4 cm versus greater than 4 cm in length. The codes also differ by site of nerve graft--where the graft is placed not harvested--for example, head and neck versus hand versus arm, etc.
  - For nerve transfer procedures, the code for nerve pedicle transfer, first stage (64905) is used, even though the second stage is rarely performed. The second state is not required in order to bill the first stage of a nerve pedicle transfer.
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Current Procedural Terminology (CPT) 2009, American Medical Association, Chicago, IL.