An update on the management of adult traumatic nerve injuries—replacing old paradigms: A review

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ABSTRACT: Acute nerve injuries are routinely encountered in multisystem trauma patients. Advances in surgical treatment of nerve injuries now mean that good outcomes can be achieved. Despite this, old mantras associated with management of nerve injuries, including "wait a year to see if recovery occurs" and "there's nothing we can do", persist. Practicing by these mantras places these patients at a disadvantage. Changes begin to occur in the nerve, neuromuscular junction, and muscle from the moment a nerve injury occurs. These changes can become irreversible approximately 18 to 24 months following denervation. Thus, it is a race to reestablish a functional nerve-muscle connection before these irreversible changes. Good outcomes rely on appropriate acute management and avoiding delays in care. Primary nerve surgery options include direct primary repair, nerve graft repair, and nerve transfer. Acute management of nerve injuries proceeds according to the rule of 3's and requires early cooperation between trauma surgeons who recognize the nerve injury and consultant nerve surgeons. Care of patients with acute traumatic nerve injuries should not be delayed. Awareness of current management paradigms among trauma surgeons will help facilitate optimal upfront management. With the ever-expanding surgical options for management of these injuries and the associated improvement of outcomes, early multidisciplinary approaches to these injuries have never been more important. Old mantras must be replaced with new paradigms to continue to see improvements in outcomes for these patients. The importance of this review is to raise awareness among trauma surgeons of new paradigms for management of traumatic nerve injuries. (*J Trauma Acute Care Surg.* 2019;86: 299–306. Copyright © 2018 Wolters Kluwer Health, Inc. All rights reserved.)

KEY WORDS: Brachial plexus; nerve graft; nerve transfer; nerve injury.

Adult traumatic nerve injuries occur in a multitude of ways in adults, ranging from penetrating trauma to the closed stretch injuries most commonly associated with motor vehicle crashes. These types of injuries are routinely encountered in the trauma setting. In the absence of a penetrating injury, many times patients are told "wait a year to see if recovery occurs" or, worse yet, "there's nothing we can do." The available surgical procedures for nerve injuries continue to expand, and good outcomes rely on timely referral to multidisciplinary specialty centers. The unfortunate patients who do not recover spontaneously but are not referred for a year or more following trauma are at a significant disadvantage, as they are well behind in the race to reinnervate the affected muscles before irreversible changes occur. Many primary nerve surgery options are no longer possible this remote from the injury. With timely referral, there are options that offer significant hope of meaningful recovery of function. The purpose of this review is to update clinicians, particularly trauma surgeons and emergency medicine physicians, who commonly encounter acute traumatic nerve injuries on the management of these injuries and the modern primary nerve surgery armamentarium to replace old mantras with new paradigms.

PATHOGENESIS OF NERVE INJURIES

Nerve injuries secondary to trauma can be thought of in 2 broad categories based on the integrity of the integument: open versus closed.[1,2] Open injuries can be further subdivided into clean, sharp injuries and ragged or contusion injuries. Open, clean, sharp injuries such as glass penetration or knife wounds typically result in complete or partial transection of the nerve. Open, ragged or contusion injuries are different than clean transections, as these types of injuries create significant inflammation within the ragged, contused nerve end, which has important ramifications for management. Closed injuries, with an intact integumentary system overlying the injured nerve, can result either from contusion of the nerve or stretch injury to the nerve. Missile injuries can injure nerves in a variety of ways: transection, heat injury, or concussive injury. For the purposes of most management algorithms based on this classification system, missile injuries are considered closed injuries.[1]

From the time of injury, changes begin to occur in the nerve, neuromuscular junction, and denervated muscle. Ultimately, these changes can become irreversible, such that even with nerve regeneration a functional nerve-muscle unit cannot be reestablished.[3,4] The time course is variable but is on the order of 12 to 24 months following denervation. All surgical strategies are founded on the idea of restoring a functional nerve-muscle unit before the changes become irreversible.

When the tubule created by the perineurium and epineurium is intact following a nerve injury, spontaneous recovery can occur. Axonal regeneration typically occurs at a rate of approximately 1 inch per month, so may take many months to reach the ultimate target. When the tubule is disrupted, this regenerative process cannot occur spontaneously. Thus, the foundational concept behind nerve repair, whether by primary repair, nerve graft repair, or nerve transfer, is to bring sprouting nerve axons into proximity with an intact tubule, such that the sprouting axons can then regenerate back down the tubule. When an intact tubule is not in proximity to sprouting axons, the sprouting axons lack guidance and will form a neuroma.

Nerve injuries can also be classified based on the continuity or discontinuity with the central nervous system and relatedly the location of the nerve injury relative to the dorsal root ganglion. Preganglionic injuries are typically avulsion injuries, wherein the nerve rootlets are pulled from the spinal cord, thus disconnecting the nerve from the central nervous system. In these cases, spontaneous recovery is not possible, as the connection with central nervous system is lost and there are no regenerating axons. For treatment purposes, there is not a viable nerve stump that can be used for repair. Postganglionic injuries can be neuroma-in-continuity injuries or nerve ruptures, but importantly, the proximal portion of the nerve remains in continuity with the central

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TABLE 1. Nerve Injuries Associated With Common Traumatic Injuries

Injury	Associated Nerve Injury	Motor Change	Sensory Loss/Paresthesias
Seat belt	Upper trunk Brachial plexus	Shoulder abduction/forward flexion, external rotation, and elbow flexion	Police badge, lateral arm, lateral hand
Stab to posterior triangle of neck	Spinal accessory nerve	Shoulder shrug, shoulder abduction, and forward flexion	None
Shoulder dislocation	Axillary nerve	Loss of shoulder abduction and flexion	Police badge
Humerus fracture	Radial nerve	Wrist and finger drop	Dorsal lateral hand
Elbow dislocation	Median nerve	Flexion weakness of digits 1–3, "claw hand" while making fist	Lateral palmar hand, digits 1–3, and radial half of 4
Pelvic fracture/hip dislocation	Sciatic nerve	Loss of knee flexion, dorsiflexion, and plantar flexion	Lateral calf, dorsal foot, ventral foot
Knee dislocation or fibula fracture	Peroneal nerve	Foot drop with loss of eversion	Lateral calf, dorsal foot, excluding the medial and lateral edges

In the setting of these common traumatic injuries, the clinician should perform a neurologic assessment to exclude associated nerve injuries.

nervous system. Thus, spontaneous recovery is possible, depending on the extent of injury to the perineurium and epineurium. For treatment purposes, a viable proximal nerve stump will be present.

CLINICAL PRESENTATION

Nerve injuries can occur as part of an extensive collection of injuries in a multisystem trauma or as part of a focal injury. In a major multisystem trauma, nerve injuries can be detected as early as the primary survey when examining for weakness, sensation loss, or the lateralizing signs originally meant to detect brain or spine trauma. Any motor or sensory deficits noted on the trauma survey should be assessed, and the workup of these deficits will be discussed in the diagnosis and management sections. In the setting of a localized trauma, an understanding of the regional anatomy and injuries that put nerves at risk can help lead to recognition of the deficit.

A brachial plexus injury is part of the catalogue of injuries in approximately 1% of all multisystem trauma patients. For motorcycle and snowmobile crashes, however, the rate is much higher (~4%). Traumatic brachial plexus injuries occur overwhelmingly in young males.[5] Injury to any major peripheral nerve occurs in almost 3% of all multisystem trauma patients. The most commonly injured nerves in the upper extremity are the radial and ulnar nerves, while the peroneal nerve is the most commonly injured nerve in the lower extremity.[6–8] Injuries that commonly occur in association with peripheral nerve injuries include closed head injuries/traumatic brain injuries, cervical spine fractures,

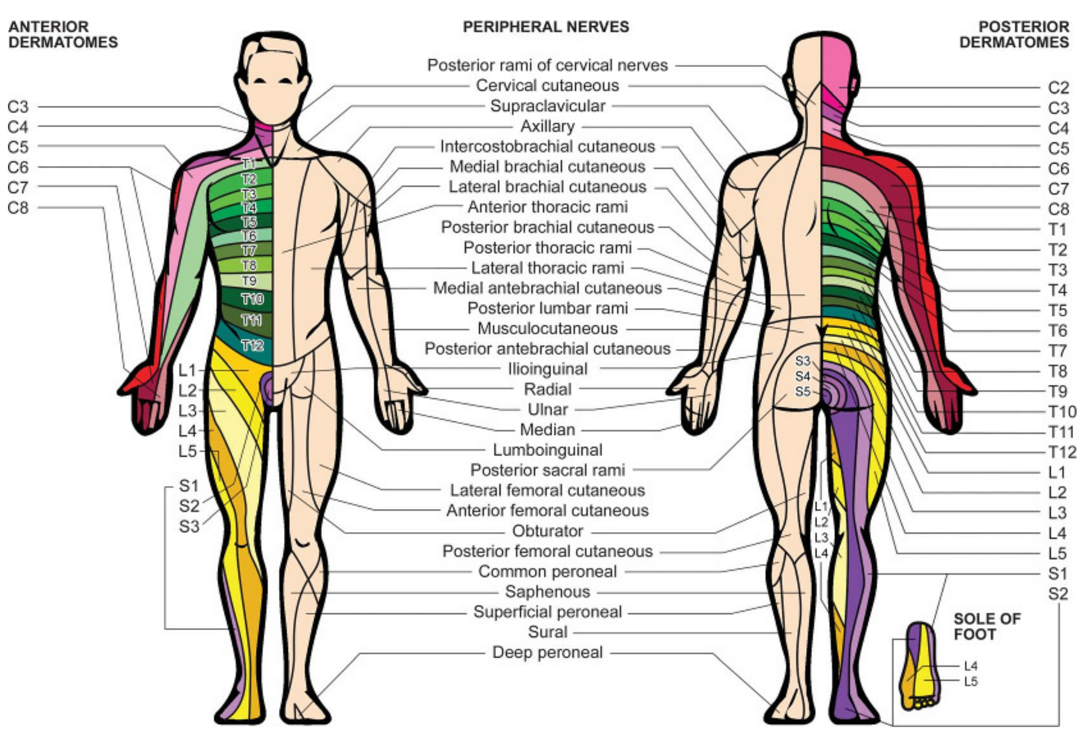

Figure 1. Comparison of peripheral nerve sensory innervation with dermatomal sensation.

clavicle/scapula/humerus fractures, rib fractures, shoulder dislocations, and knee dislocations.[5,6]

The peripheral nerves carry motor, sensory, and autonomic signals to and from the central nervous system, and injuries to these nerves can disrupt these signals resulting in neurologic deficits. The deficits range from mild to severe. The specific presentation and constellation of sensory and motor deficits are based on the nerve or nerves that are injured. There are several common patterns of injury that are associated with specific mechanisms of injury (Table 1).

Traumatic nerve injuries present with maximal deficit immediately following the injury. If a progressive deficit is noted with a nerve injury, one should be alerted to a secondary ongoing process that is contributing to the worsening injury. Potential examples include progressive compression from an expanding hematoma or pseudoaneurysm. With progressive deficits occurring over months following the injury, additional pathologies such as myositis ossificans traumatica should be considered.[9] Regardless, progressive deficits should not be attributed to the trauma and warrant further evaluation.

DIAGNOSIS

Diagnosis begins with the initial trauma survey. Within the primary survey, major neurologic deficits should be identified. Once stabilized and able to participate in the examination, the patient should undergo a detailed neurological examination to identify even minor deficits. The mainstay of diagnosis is the neurological examination. While electrodiagnostic testing and imaging studies can be helpful in specific circumstances, they are not replacements for a comprehensive and skillful neurological examination and rather should be thought of as extensions of the physical examination. The most obvious deficit to both the patient and provider is typically the loss of motor function. Weakness can range from barely perceptible asymmetry to flaccid paralysis. Brain and spine injuries can present similarly, but understanding the motor innervation of peripheral nerves versus the myotomal innervation of nerve roots and the sensory innervation of peripheral nerves versus the dermatomal patterns can help differentiate (Fig. 1). For example, considering a C5 nerve root injury versus an axillary nerve injury, both will present with weakness of the deltoid. However, with a C5 nerve root injury, the supraspinatus and infraspinatus should also be affected, leading to weakness of external rotation and shoulder abduction over the first 15 degrees. With C5 injuries, there may also be mild to moderate weakness of elbow flexion (because of weakness of the biceps and brachioradialis), whereas elbow flexion should not be affected by an axillary nerve injury. The sensory innervation also differs, although can be more difficult to assess. The area of sensory loss for axillary nerve injuries should be limited to the area around the shoulder, whereas with a C5 injury, the sensory loss extends more distal along the anterolateral brachium and even beyond the elbow. Furthermore, nerve injuries most commonly present as monoparesis with loss of function in the muscles supplied by the injured nerve and preserved function in other nerve distributions, whereas brain traumas

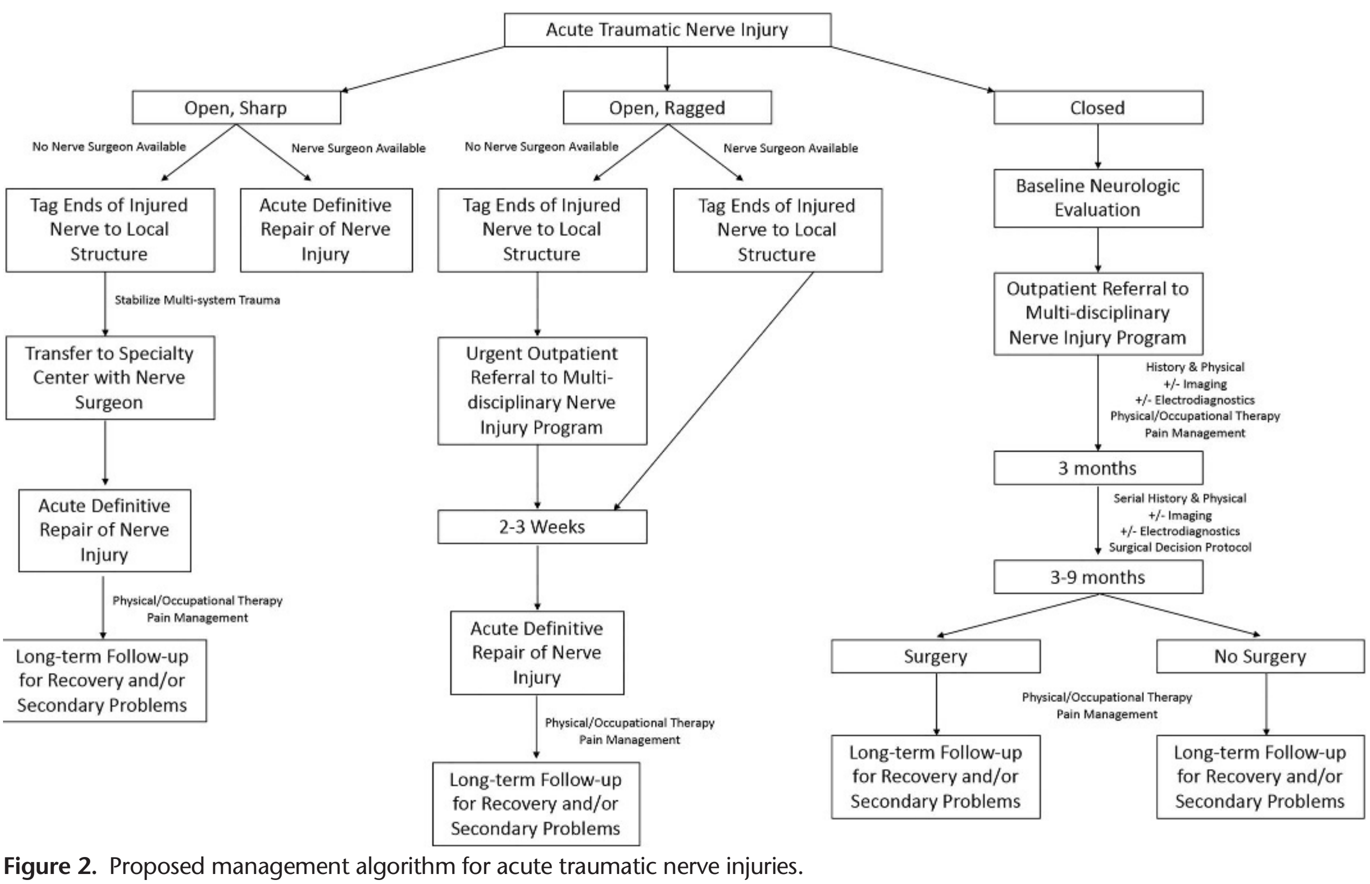

Figure 2. Proposed management algorithm for acute traumatic nerve injuries.

with contusions or hematomas generally cause hemiparesis and spinal cord injuries generally result in bilateral loss of function distal to the level of the injury.

Once the nerve or nerves that are likely to have been injured are identified, the integrity of the integument overlying the injured nerves and any penetrating trauma should be noted. Along with the mechanism of injury, the injury can then be classified as open or closed. This combination of findings will aid in determining the appropriate management strategy.[1] It is also important whenever possible to identify major neurologic deficits before any operative intervention to facilitate the identification of any iatrogenic injuries that may occur, thus allowing appropriate management. Additional workup should include an evaluation for commonly associated musculoskeletal injuries, such as humerus fractures with radial nerve injuries. Consideration should also be given to musculoskeletal mimickers such as a rotator cuff tear mimicking a suprascapular nerve injury. Initial diagnosis and decision-making are based solely on the clinical history and physical examination. Imaging is used for the purpose of evaluating secondary causes of progressive deficits, such as evaluating for an expanding hematoma, and to evaluate for associated injuries and musculoskeletal mimickers.

For closed injuries, the most important component of long-term evaluation continues to be the physical examination. Serial physical examination should be performed to evaluate for spontaneous recovery and to ultimately guide management. It is in the subacute to chronic phase of evaluation and management that additional tests, including electrodiagnostic studies and imaging, can be helpful to the consultant nerve surgeon. Because of the physiology of nerve injury and regeneration, electrical conduction testing can demonstrate relatively normal results for 2 to 3 days. The preservation of normal conduction testing can be seen even in nerves that have been transected, and needle electromyography will not show the full extent of denervation changes until 2 to 3 weeks following injury, although there will be an immediate loss of volitional motor units in the affected muscles. For those reasons, electrodiagnostics are typically not obtained acutely, but rather are most likely to be used by the consultant nerve surgeon in the subacute to chronic period for long-term prognostication and in a serial fashion to evaluate for spontaneous recovery. Dedicated nerve imaging similarly is not typically used in the acute period but may have a role in the subacute to chronic evaluation by the consultant nerve surgeon. A variety of imaging modalities may be used, including ultrasound, magnetic resonance myelography, computed tomographic myelography, and magnetic resonance neurography.[10–13] Imaging can be used primarily to look for indirect or direct evidence of nerve discontinuity or avulsion.

MANAGEMENT

Initial management of traumatic nerve injuries largely depends on the mechanism and type of injury. In general, the *rule of 3's* can be applied.[1] For open, clean, sharp nerve injuries, surgical exploration and repair should be undertaken within 3 days following the injury. For open, ragged, contusion injuries, definitive repair should be performed around 3 weeks following the injury, but the ragged ends of the nerve should be tagged within the first several days following the trauma, when possible. Finally, for closed injuries, the decision for surgery is typically made around 3 months following trauma (Fig. 2).

For nerve transections, the best outcomes are achieved with tension-free primary repair of healthy proximal and distal ends of the nerve. A tension-free repair is important, as tension at the site of coaptation creates a milieu that is not conducive to nerve regeneration by creating tissue ischemia and scar formation.[14] In one large series of brachial plexus lacerations, good outcomes were achieved in 81% of patients with primary suture, 69% with secondary suture (delayed direct repair), and 53% with secondary graft repair.[15] With nerve transections, whether blunt or sharp, the nerve ends retract over time. With significant retraction, tension-free primary repair becomes impossible. Thus, for sharp injuries, the best outcomes are achieved with primary repair, which is easiest to achieve soon after trauma before significant retraction can occur. For ragged transections, the same principles apply, but achieving these goals is slightly different. With ragged transections, the zone of injury is not completely defined at the time of trauma. The zone of injury will declare itself over the ensuing several weeks. Because healthy nerve ends are needed for repair, the recommendation is to allow enough time that the evolution of the zone of injury is complete. To prevent significant retraction, the injured nerve ends are tagged to a local structure such as muscle fascia. After allowing time for the evolution of the zone of injury to be completed, typically 2 to 3 weeks, the surgeon can then return to the operating room and resect the injured, scarred ends of the nerve and, if the ends were tagged preventing retraction, still potentially perform a direct repair without an intervening graft. In most cases, even with tagging the nerve ends, a direct repair cannot be performed and an intervening graft is needed. Nonetheless, tagging the nerve ends facilitates finding them in the second operation and also prevents retraction, shortening the length of the needed graft. Generally, with a gap of up to 3 cm a tension-free repair can still be accomplished, if the injury is in a location where additional length can be gained. Even short gaps may be difficult to bridge with a tension-free repair in some locations (eg, the forearm and lower leg) and will require an intervening graft. With gaps exceeding 3 cm in any location, an intervening graft is typically needed.[15,16]

Use of an intervening graft means that regenerating axons must cross 2 sites of coaptation, as opposed to one with direct repair. At each site of coaptation, axons are lost, thus reducing the number of axons reaching the distal target and decreasing outcomes.[17] This is associated with comparatively worse outcomes. Furthermore, as graft length increases, associated neurologic outcomes decrease.[18] Grafts longer than approximately 6 cm seem to be associated with poor outcomes. As a general principle, the length of the graft should be minimized while still facilitating a tension-free repair.

For patients presenting with open nerve injuries to centers without a peripheral nerve specialist, initial management should consist of management of acute life-threatening injuries and stabilization of injuries to avoid progressive deficits according to typical trauma protocols. The nerve ends should be identified and clipped to a surrounding fixed structure such as the muscle fascia. For clean, sharp injuries, following stabilization, the patient should be transferred to a center with a peripheral nerve specialist for prompt nerve repair, when possible. For blunt,

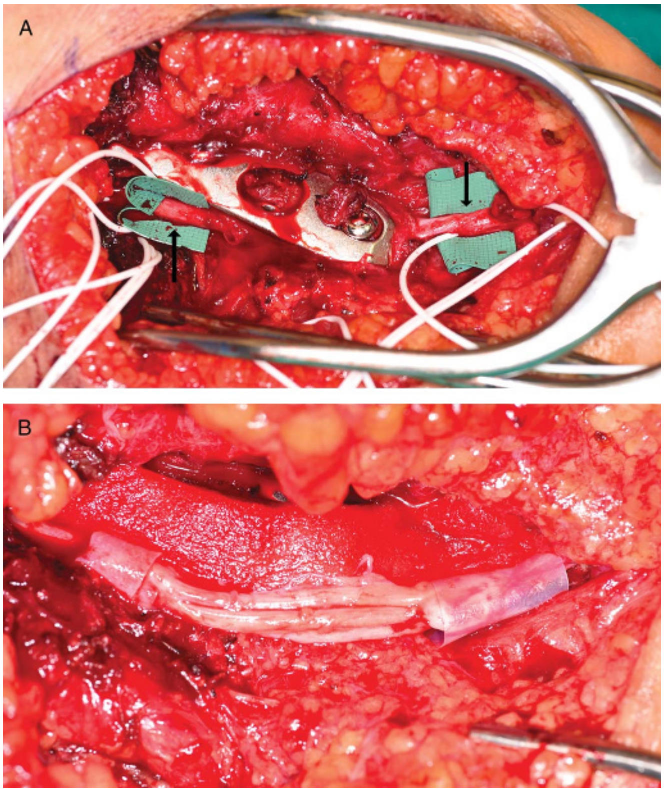

Figure 3. Radial nerve entrapped by fixation hardware. (*A*) The radial nerve (*arrows*) is entrapped by hardware from internal fixation of a humerus fracture. (*B*) The damaged segment of the radial nerve was resected and repaired using a cabled, sural nerve graft.

ragged transections, the nerve ends should be similarly tagged. The patient should then be referred at discharge for urgent outpatient evaluation at a center with a peripheral nerve specialist to facilitate delayed exploration and repair.

For closed injuries, upfront management consists of performing a careful and thorough neurologic examination to serve as a baseline, with referral to a center with a multidisciplinary nerve injury/brachial plexus program for further evaluation and management. Traumatic nerve injuries should be maximal at onset. Progressive neurologic deterioration requires further investigation for a secondary cause such as a compressive hematoma. Secondary causes should be promptly managed.

Closed injuries require serial examination, typically with serial electrodiagnostic studies, to determine appropriate management. Spontaneously recovering nerves should be allowed to recover. Thus, identification of small gains is vital to making an informed management decision. For those patients not displaying sufficient spontaneous recovery by 3 to 6 months postinjury, surgery is typically recommended. Early referral facilitates an appropriate surgical decision-making time frame. With modern primary nerve surgery options, good outcomes can be achieved many times for patients who do not spontaneously recover.

Primary nerve surgery options include neurolysis, nerve graft, and nerve transfer. The surgical strategy depends on the timing of patient presentation, specific nerve(s) injured, type of nerve injury, and intraoperative gross and electrodiagnostic findings. Secondary musculoskeletal options such as tendon transfer, free muscle transfer, and joint fusion are also available but are outside of the scope of this review. The use of intraoperative neurophysiologic monitoring, including nerve action potentials (NAPs), helps facilitate intraoperative decision-making and is an important component of any surgical plan. The use of NAPs is particularly important for lesions that are found to be in continuity, which are the majority of peripheral nerve injuries.[19] In cases where a NAP is obtained across the site of injury, typically neurolysis only should be performed, as the lesion likely to continue recovering.[20] In a large series of brachial plexus injuries, 92% of patients had a good outcome with neurolysis alone when NAPs were present.[15] In another series of penetrating missile injuries, 94% of patients had a good outcome with neurolysis alone when NAPs were present.[21]

An important component of early referral to a multidisciplinary nerve injury program is early initiation of physical and occupational therapy and continued therapy postoperatively. Early and ongoing therapy is important for the following: 1, maintaining supple joints and avoiding contractures while awaiting return of neurologic function; 2, maximizing compensatory mechanisms; 3, implementing braces and orthotics to maximize function; 4, to help in cortical retraining particularly following nerve transfers; 5, to aid with pain control through hyperesthetic desensitization; and 6, to aid in sensory reeducation.[22] Any operative intervention is less likely to have a good outcome if a comprehensive rehabilitation program is not part of the multidisciplinary approach. Early range of motion exercises following nerve injury are particularly important to maintain supple joints that are capable of regaining active movement with reinnervation.

Pain management is another important component of management for nerve injuries. Neuropathic pain can be severe and is best managed with multimodal therapy. In fact, following brachial plexus injuries, pain is the most significant independent predictor of disability.[23] Again, a multidisciplinary approach from a team with expertise in post–nerve injury pain will yield the best results, which is another reason to favor early referral. Pain management strategies often consist of a combination of medications, desensitization therapy, pain psychology, and surgical or procedural options.[24–29] Commonly used medication options include gabapentin, pregabalin, duloxetine, or nortriptyline. Surgical or procedural options that may be considered include nerve graft repair, neurolysis, spinal cord stimulation, dorsal root entry zone lesioning, peripheral nerve stimulation, and pulsed radiofrequency.

Next, we highlight some common traumatic nerve injuries to point out management options and to bring to light the outcomes that can be achieved with modern surgical strategies combined with appropriate initial management. While nerve injuries are devastating, with current techniques, there is hope for meaningful recovery with appropriate initial and definitive management. Upper trunk brachial plexus injuries commonly result from motor vehicle accidents and result in the loss of C5- and C6-innervated muscle function. A common nerve transfer strategy includes spinal accessory to suprascapular nerve transfer, radial nerve triceps branch to axillary nerve transfer, and ulnar nerve fascicle to biceps branch of the musculocutaneous nerve transfer.[30–35] Specifically for elbow flexion, in one systematic review, 83% and 56% of patients achieved at least Medical Research Council grade 4 (i.e., movement against gravity plus moderate resistance) or greater elbow flexion with nerve transfer and nerve graft repair, respectively.[36]

Radial nerve injuries commonly occur in association with humerus fractures. When possible, it is important to evaluate radial nerve function before any operative reduction and fixation to differentiate radial nerve injury associated with the fracture from iatrogenic injury associated with humeral fixation. Iatrogenic injuries should be explored to rule out entrapment by the operative hardware, whereas radial nerve injuries associated with the fracture are treated as closed injuries (Fig. 3). Exceptions to this include open fractures, fractures associated with vascular injury, and fractures requiring internal fixation, in which case the radial nerve should be explored simultaneously.[37] Some centers now favor exploring all radial nerve injuries associated with humerus fractures early to grossly and electrophysiologically characterize the injury.[38] The radial nerve recovers remarkably well. For lesions in continuity, if NAPs are present, more than 95% recover at least antigravity wrist extension. When NAPs are absent, a good recovery can still be expected with more than 90% of direct repairs and more than 85% of graft repairs recovering antigravity wrist extension.[39]

Injury to the ulnar nerve above the proximal forearm is difficult to manage. The long distance from the point of injury to the motor endplates of the hand intrinsic muscles has led to poor outcomes for hand intrinsic function following direct or nerve graft repair.[40–43] New nerve transfer strategies have shown promise and can be considered in addition to or in place of traditional nerve graft repair for high ulnar injuries. The anterior interosseous nerve can be used as the donor and coapted to the distal ulnar nerve in an end-to-end fashion as the definitive repair or in an end-to-side supercharging fashion to supplement a more proximal ulnar nerve repair.[44–46] Early data support improvement in hand intrinsic function in comparison with traditional nerve graft repair alone.[44,46] In fact, in the small comparative series by Baltzer et al,[44] 84% of the patients who had a supercharge end-to-side nerve transfer had some recovery of ulnar-innervated hand intrinsic muscle function.

CONCLUSIONS

Traumatic nerve injuries are a common part of the catalogue of injuries encountered in patients with multisystem trauma. Care continues to evolve, but with modern techniques, we can offer hope of meaningful functional recovery in many cases. Care begins with astute recognition of the injury. It cannot be overemphasized that there is no replacement for a skillful neurological examination in identifying these injuries. Optimizing long-term outcomes starts with appropriate initial management at the time of trauma. Thus, it is important for trauma physicians to be aware of the appropriate initial management for nerve injuries. The old mantras of "there is nothing we can do" or "wait a year to see if recovery occurs" put the patient at a disadvantage. These mantras should be replaced with a paradigm of appropriate initial management and early referral or consultation with a peripheral nerve specialist for definitive care. There are successful interventions, and waiting for a year is far too long and excludes the patient from many potential management options. The importance of multidisciplinary specialty care cannot be overstated to maximize functional recovery and minimize pain in these patients. Ultimately, the best outcomes will result from trauma physicians partnering with peripheral nerve surgeons to provide high-quality care.

AUTHORSHIP

B.W.S. contributed to the concept of the study, literature search, synthesis of the literature, drafting and critically revising the article, and approved the final version. S.S., D.A.S., J.R.J., and L.J.-S.Y. contributed to synthesis of the literature, drafting and critically revising the article, and approved the final version. T.J.W. contributed to the concept of the study, literature search, synthesis of the literature, drafting and critically revising the article, approved the final version, and supervised the study.

DISCLOSURE

The authors declare no conflicts of interest.

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