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SPECIAL TOPIC
Peripheral Nerve

Ten Myths in Nerve Surgery

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Background: Surgical innovation has provided new options for the management of complex peripheral nerve injuries, generating renewed interest in this field. Historic literature may be misinterpreted or misquoted, or create dogma, which is perpetuated in teaching, research publications, and clinical practice. The management of peripheral nerve injuries is based on complex decision-making, with potential lifelong ramifications for patients incorrectly receiving an expectant or surgical management plan.
Methods: This article includes opinion from expert leaders in the field of peripheral nerve surgery and questions some of the current assumptions and preconceptions around nerve surgery based on clinical evidence. There was extensive debate regarding the contents of the final article, and the different opinions expressed represent the uncertainty in this field and the differing levels of confidence in available published evidence.
Results: Individual practices vary and, therefore, absolute consensus is impossible to achieve. The work is presented as 10 myths which are assessed using both historical and emerging evidence, and areas of uncertainty are discussed.
Conclusions: It is important to learn lessons from the past, and scholars of history bear the task of ensuring references are accurately quoted. Expunging myths will enhance care for patients, focus research efforts, and expand on the surgical possibilities within this specialty. *(Plast Reconstr Surg Glob Open 2024; 12:e6017; doi: 10.1097/GOX.0000000000006017; Published online 1 August 2024.)*

INTRODUCTION

The field of peripheral nerve surgery (PNS) has experienced rapid growth over the last three decades, enabling new treatment options for nerve compression syndromes, motor and sensory nerve deficits, and the management of neuropathic pain. Collaboration between specialists from plastic surgery, orthopaedic surgery, and neurosurgery has enabled PNS to develop as a subspecialty field, bringing new ways of thinking, reviving old procedures, and delivering high-quality research to foster adoption of advanced surgical techniques. Nerve transfers for example, utilized by contemporaneous pioneers, including Otfrid Foerster and Adolf Stoffel at the outbreak of the first World War,[1–3] received renewed interest after the application by Oberlin for elbow flexion restoration after upper brachial plexus injury involving the C5 and C6 roots in 1994.[4] Subsequent authors applied the technique to shoulder reanimation, with redescription of techniques first reported a century prior.[3,5] The Stoffel operation for spastic cavovarus foot was reported in 1913, and later reports by Brunelli defined the role of neurectomy in spasticity.[6,7] Anatomical knowledge of motor innervation patterns and familiarity with these surgical approaches has rekindled interest in hyperselective neurectomy for targeting specific muscle groups to treat spasticity.[8]

Individual surgeon preferences will be based on training and experience. These innovative treatment options are reliable tools when used appropriately. Historical literature may be misquoted, and these errors are perpetuated in teaching, research publications, and practice, creating dogma that continues to direct the nerve surgery conversation. This article assembles a group of experts in the field of PNS, explores the evidence for common assumptions,

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and challenges preconceptions, exposing potential myths therein. This set of 10 myths was compiled after much debate, and inclusion was based on the perceived prevalence in teaching and practice. For each myth, we then reviewed both historical and emerging evidence to inform the debate presented.

Takeaways

Question: Management of peripheral nerve injuries is based on complex decision-making, with potential lifelong ramifications for patients incorrectly receiving an expectant or surgical management plan.

Findings: Historic literature may be misinterpreted or misquoted, or create dogma, which is perpetuated in teaching, research publications, and clinical practice. The work is presented as 10 myths, which are assessed using both historical and emerging evidence, and areas of uncertainty are discussed. It is important to learn lessons from the past, and scholars of history bear the task of ensuring references are accurately quoted.

Meaning: Expunging myths will enhance patient care, focus research efforts, and expand the surgical possibilities within this specialty.

Seddon Classification of Peripheral Nerve Injury

Sir Herbert Seddon described a classification that used the terms neurapraxia, axonotmesis, and neurotmesis to represent increasing levels of severity of peripheral nerve injury (PNI).[9] Neurapraxia defines a nerve with a functional block of conduction, without apparent injury to the axon. Axonotmesis defines axon discontinuity with associated Wallerian degeneration. Neurotmesis implies disruption of the axon and essential supporting connective tissue components of the nerve. Subsequent authors have attempted to build on Seddon's descriptions by redefining his classification.[10] These well-intentioned authors have perhaps complicated the narrative, leading to clinical confusion.[11–14] Revisiting Seddon's landmark article published in 1943 is helpful because details contained therein have been lost in subsequent iterations.[9] Although Seddon described axonotmesis recovery as, "spontaneous and of good quality because the regenerating fibers are guided into their proper paths by their intact sheaths," he described that it is not "easy to make a confident diagnosis of axonotmesis" with a "no man's land" where the behavior of continuity lesions is dependent on the predominance of the classification subtypes. Sunderland later proposed a subclassification with axonotmesis grades 2 and 3, reflecting more internal derangement and potential for worse outcomes; however, this is useful only in a retrospective review rather than in guiding care. Seddon had already concluded that "it is certain that one ought to intervene in any case where there is obvious intraneural fibrosis" or "if recovery fails to take place in the calculated time." Neurotmesis was defined as an injury "in which all essential components have been sundered," "there is not necessarily an anatomical gap," and "the epineural sheath may appear to be in continuity but the rest of the nerve is replaced by fibrous tissue." In the further description, it was defined as an injury "the same as if anatomical continuity was lost" and that neurotmesis is of wider applicability than division. This original description obviates the need for the Sunderland grade 4 classification.[12]

Finally, in the same text, Seddon reported clinical presentations with mixed lesions of nerves, with combinations of neurapraxia, axonotmesis, and neurotmesis, predating the colloquial term Sunderland grade 6 injury. Seddon was therefore accurate from the beginning. Was there, then, a need for further classifications?

Neurapraxic Injuries Never Require Surgery

Neurapraxia is often misused as a general term for any nerve that is not working, providing false reassurance to the clinician and patient. Seddon cautioned the early use of the term to define a PNI "since, at this stage, it was impossible to know whether or not manifestations of peripheral degeneration would ultimately appear."[9] Incorrect early assignation of this grade of injury will create a false impression of inevitable full recovery, may result in inadequate surveillance, and the patient may either be denied appropriate care, or it may be so delayed that an inferior outcome results.[15–19] Repeated clinical examination is recommended to be certain of a diagnosis of neurapraxia. In a mixed motor and sensory nerve trunk, neuropathic pain should be minimal, Tinel sign is either absent or transient, muscle wasting is incomplete, and autonomic function in the cutaneous territory is preserved. Most radial nerve injuries associated with low-energy humeral fractures are indeed neurapraxic and will recover fully.[20] However, with high-energy injuries and extreme fracture displacement, there is a greater potential for a higher grade of injury. Clinicians should be cautious when there is an onset of paralysis after attempting bone reduction, following surgical fixation, or when spontaneous recovery is delayed.[21] Nerve entrapment in a fracture may result in further deterioration beyond neurapraxia, and a Tinel sign may not be clinically detectable. Surgical exploration at the 3-months mark is helpful in cases where clinical recovery is not observed as expected, when there is discrepancy between clinical findings and electrodiagnostic tests and imaging, and when time since injury has reached the point when spontaneous recovery is no longer likely.[11,22–24] In the authors' experience, the rapid recovery of function sometimes seen within a couple of weeks following exploration and decompression of the radial nerve at the lateral intermuscular septum in uncertain cases raises the possibility that recovery from neurapraxia may be accelerated by nerve decompression. Although this is not yet evidenced in the literature, it reframes the discussion and questions the dogma that neurapraxic injuries never require surgery.

Electrodiagnostic Studies Are Essential before Surgical Exploration

Traditional teachings suggest that electrodiagnostic studies (EDx) are essential in diagnosing PNI but must be deferred until conduction block has resolved, delaying the diagnosis of a degenerative nerve lesion when incorrectly assigned a neurapraxic diagnosis. Neurophysiology

studies will demonstrate no distal conduction in complete injuries with axonal degeneration (axonotmesis and neurotmesis) once Wallerian degeneration has completed, after 12–14 days.[25,26] Early EDx within 2 weeks of injury may therefore be falsely reassuring and must be repeated to demonstrate the evolution of denervation, with electromyography (EMG) showing increased insertional activity, muscle fibrillation, and positive sharp waves.[24] Thus, early and repeated EDx can help define an injury as degenerative, questioning an incorrect clinical diagnosis of neurapraxia, perhaps prompting closer surveillance and, if indicated, earlier nerve exploration. When a nerve has an axonotmetic injury, follow-up EMG may detect polyphasia, a sign of muscle reinnervation, thus reassuring the clinician and patient that recovery is progressing. However, quantification of recovery potential through EMG is of limited utility and, therefore, clinical evidence of recovery is more compelling.[22] Nevertheless, exposure of an injured nerve must not be delayed for neurophysiology studies when there are clear indications for exploration, such as a Tinel sign, neuropathic pain, or autonomic changes. There is evidently a cost implication to this practice; however, the benefit and rationale have been illustrated above.

Intraoperative Evaluation of a Continuity PNI Can Always Predict Outcome

In a penetrating wound with disordered nerve function and localizing signs, prompt surgical exposure of the nerve may enable early direct repair without tension, optimizing the potential for functional recovery.[17] Timing of exposure for a closed nerve injury is less clear and is often prompted by management needs for associated injuries, neuropathic pain, diagnostic uncertainty, or absence of nerve recovery progression.[15,16] When a nerve is found to have continuity of the epineural sheath, the surgeon must decide whether spontaneous recovery can be expected. Separation of the internal structural elements may create an "empty sheath" sign, likened to rolling the layers of a shirt sleeve between two digits. With significant separation of the structural elements, fibrous tissue interposition will likely follow, producing a neuroma in continuity. Surgeons may be falsely reassured by motor responses on stimulating distal to the lesion in an acute exploration, but it must be considered that Wallerian degeneration has not completed. Delayed re-exploration and reconstruction may be necessary if no clinical signs of recovery follow. Should the exploration demonstrate a continuity lesion with some preserved function when stimulating proximal to the site of injury, further recovery is likely, and neurolysis may improve recovery potential and restore nerve glide when there is neurostenalgia (a neuropathic pain that results from continuing irritation of a nerve). Recovery may be favorable if the predominant PNI grade is neurapraxia, functional after recovery from axonotmesis, but when there is a mixed grade of injury with partial neurotmesis, intraneural scar will hamper recovery and the outcome cannot be predicted. The role of nerve exploration is helpful in confirming or refuting a clinical diagnosis, optimizing the nerve environment, and informing subsequent surveillance or intervention.

Axon Regeneration is 1 mm per Day

Following axonotmesis or repair of a sensory or mixed nerve trunk, an advancing Tinel sign may be used to reassure both the surgeon and patient that recovery is progressing. The acceptable rate of recovery is often quoted at 1 mm per day. However, this rate is a composite of three variable phases[27]: latency (cellular response to injury with upregulation of protein synthesis, metabolic processes and cellular transport), axon regeneration, and functional end-organ reinnervation.[17,28–30] In vivo studies have shown that following crush of the musculocutaneous nerve, recovery starts after 8 days. This probably reflects a latency period to the beginning of nerve growth and another period to reinnervate endplates after reaching the muscle target. Additionally in a 2-cm-long stretch injury of the median nerve, recovery time is delayed by two-fold.[31,32] Higher grades of axonotmesis, nerve repair, quality of repair, tension at the site of repair, and delayed repair are also factors associated with recovery delays.[33,34] Each factor will exert an effect on the latency period, robustness of axon regeneration, and rate of axonal growth. Even following a low grade, purely axonotmetic injury, various fiber subtypes may regenerate and reach functional maturity at different rates. Experimental methods have shown that small unmyelinated nociceptive and sudomotor fibers achieve functional reinnervation faster than their larger myelinated counterparts.[9,35] Finally, the aging nerve suffers a decline in regenerative capacity. Wallerian degeneration is delayed, trophic factors released by Schwann cells are reduced, and the density of regenerating axons is also reduced, leading to a slower regeneration rate.[36] Therefore, stating to patients that injured nerves regenerate at a 1-mm rate per day is an oversimplification. In the clinic, Tinel sign may be seen to progress at up to 4-mm per day in lower grade and partial axonpathic injuries in sensory and mixed nerves. A strong Tinel sign moving distally in sequential assessments is generally reliable. However, the Tinel sign may be less reliable in deeply placed nerves, obese patients, and after nerve grafting. In a motor nerve injury, Tinel sign is not elicited, and in injury to mixed nerves, advancing Tinel's sign, although predictive of sensory recovery, cannot predict adequacy of motor recovery. Finally, absence of Tinel sign may falsely reassure that there is no axonopathy when there is nerve entrapment within fracture sites.

A Progressing Tinel Sign Does Not Require Further Surgery

Progression of Tinel sign distally along the course of a nerve can be used to monitor recovery after proximal injury. The rate of Tinel progression may be used to predict the timing of functional recovery, but there is no evidence to correlate rate with final function. Similarly, the intensity of the Tinel sign does not correlate with the quality of the final recovery. Static Tinel at the site of injury may raise the suspicion of a neuroma developing and may guide further exploration. In the presence of neuropathic pain with exacerbation on nerve stretch, exploration and neurolysis may still be beneficial, even when there is distal functional recovery. There may be an additional role for distal decompression of the

regenerating nerve at common anatomical compression sites.[23,24] Regenerating nerves are swollen, and axoplasmic transport may be impeded by scar encasement at the injury site and by distal extrinsic compression. The clinical presentation may be slowing of the Tinel progression rate, persistence of Tinel sign at known entrapment points, worsening pain, and dysaesthesia. A typical example is a secondary cubital tunnel compression following medial cord injury or common peroneal nerve entrapment at the fibula neck following sciatic nerve injury. Decompression at such sites often reveals a swollen nerve and may be followed by rapid improvements in pain and sensory and motor function.[37,38]

Nerve Transfer Is the New Gold Standard Method for Paralysis Reconstruction

Autologous nerve grafting has long been the gold standard for anatomical reconstruction of nerve gaps.[5] The results are poorer in mixed nerves when compared with sensory or motor nerves that have fewer fiber subtypes. The results are poorer with delays to reconstruction, unfavorable surgical beds, long gaps, and proximal injuries with long reinnervation distances. Nerve transfers provide a reliable extraanatomical reconstruction alternative when anatomical reconstruction is not feasible, such as in preganglionic root avulsion injuries from the cervical spinal cord.[39,40] The results of nerve transfer for abduction and external rotation at the shoulder and for flexion at the elbow are so good that the technique has superseded a graft reconstruction in otherwise graftable upper trunk ruptures.[3] Nerve transfers performed close to targets, tend to provide better results in comparison with grafting of proximal nerve injuries with long reinnervation distances in adults. However, transfers can be combined with grafts for additional functional gains or for key distal targets where reinnervation distances are so long that useful distal function is not predictable. Isolated peripheral nerve injuries should be considered separately. For ruptures of the axillary, radial, posterior interosseous, and anterior interosseus nerves, the functional results of grafting are generally good, perhaps due to the preponderance of motor function and the relatively simple demands of the reconstruction for function.[41–43] The grafted median and ulnar nerve, while providing important benefits for pain management, sensory recovery, and proximal motor recovery, do not restore useful intrinsic function in the hand. In such cases, targeted distal nerve transfers can enhance the results of grafting; for example, transfer of the opponens motor branch to the deep terminal division of the ulnar nerve for pinch grip restoration.

It is important to remember that for both nerve grafts and nerve transfers in lower motor neuron paralysis, there is a time limit for successful restoration of motor function. Delayed reconstruction will require alternative strategies such as musculotendinous transfer. Critical review of the results of nerve transfers versus tendon transfers is also warranted. For the high radial nerve palsy, the rapid and predictable functional recovery after tendon transfer is often more acceptable to patients than the later recovery after nerve transfers. Where both procedures are possible, a discussion of the benefits and limitations is mandated as part of the informed consent process.

Parsonage–Turner Always Recovers Spontaneously

Classically taught as a neuritis of the brachial plexus, Parsonage–Turner syndrome is thought to have favorable prognosis for spontaneous recovery.[44–47] Although of unknown etiology, this painful nontraumatic disorder has a clinical presentation that is often characterized by a sudden onset of severe arm pain followed by profound motor weakness and atrophy without sensory deficit. The duration of pain varies, from a few hours to 4 weeks. It is theorized to involve an autoimmune process, perhaps triggered by surgery, inflammation, trauma, or viral infection. Parsonage and Turner reported the condition to affect the long thoracic nerve, although the suprascapular nerve, anterior interosseous, axillary nerve, and phrenic nerve may also be involved.[48] The presence of extreme motor weakness (MRC 2 or less), persisting muscle atrophy, or paralysis at 9–12 months may inform the decision for consideration of reconstructive surgery with nerve transfer, although the risk of precipitation of a further neuritic episode is not known. Surgery can involve decompression and micro-neurolysis of the hourglass lesions, as identified on MRI, and nerve transfers for the most severe nonprogressive lesions.[49] Waiting over 12 months before surgical intervention may mean irreversible time-dependent motor atrophy and salvage arthrodesis, functioning free muscle, and tendon transfer may be used late to optimize outcomes. Consideration that Parsonage–Turner syndrome will always recover and will never need surgery is a myth, and longitudinal studies evaluating the natural history of recovery will be helpful to establish prognostic indicators for spontaneous recovery, and to guide patient selection and timing of surgical intervention.

Never Operate on a Patient with Complex Regional Pain Syndrome

Complex regional pain syndrome (CRPS) may manifest in patients following nerve injury.[50] Management is multimodal and should be delivered with a multidisciplinary team that includes pain specialists, therapists, psychologists, and surgeons. Surgery plays a role when a nerve injury is suspected, when there is nerve tether or compression, in type II CRPS.[51] Defining a remediable nerve problem can be challenging, and many such correctable pathologies may be missed.

The myth of surgery in CRPS is based on fear of creating a new pain trigger and exacerbating the underlying syndrome. Any surgical intervention should be carefully planned; diagnostic nerve blocks may be used to localize potential pain drivers and optimize preoperative therapy. Perioperative pain management must be optimized using adjunctive nerve blocks and indwelling nerve catheters to reduce opiate use and provide respite from pain. PNS

may have a role for the treatment of refractory CPRS in patients with focal nerve pain.[52]

TMR is the Solution for Neuroma Pain

Neuropathic pain development is multifactorial, and there has been growing interest in the diagnosis and treatment of symptomatic neuromas with novel surgical techniques in this arena.[53–55] Neuroma resection, capping, or burying proximal nerve stumps to deeper tissues has been used with reasonable efficacy in reducing contact sensitivity or evoked pain responses in symptomatic neuromas.[56] These ablative procedures have no controlled active nerve regeneration or functional interface created. Failures may be due to secondary displacement of the nerves ends, scar tether, and recurrent neuromas. There is interest in creating a functional active interface at the neuroma resection site to modulate the spontaneous activity associated with neuropathic pain from neuromas. Targeted muscle reinnervation (TMR) has been reported for the treatment of neuroma-related pain in the residual limb and for mitigating phantom pain after amputation.[57] TMR is a technique initially designed to optimize myoelectric prostheses but has been successfully adopted for treating and managing neuropathic pain.[58] Both prospective, randomized data and confirmatory cohort studies have demonstrated that TMR is superior.[59–62] Contemporary neuroma solutions often focus on the active management of nerve endings, but no single surgical solution is a panacea for patients with neuroma-related pain. TMR is usually, but not always, successful in treating patients with neuroma pain. When TMR is performed in amputees, it is most often successful in prevention of neuropathic pain, including development of phantom limb pain.[63] Failure of treatment may indicate the presence of other pathology (spine/nerve root pathology, other sites of peripheral nerve compression), centralized pain, recurrent symptomatic neuroma, and/or underlying psychiatric issues.[64] Ultimately, we do not yet know which treatment option is best suited for which patient population.[65,66]

CONCLUSIONS

PNS has evolved tremendously in the past three decades and gained popularity as a subspecialty in plastic-, orthopaedic-, and neurosurgical fields. There is disparity in the educational and fellowship opportunities in the field of PNS for these novel interventions. Existing knowledge is enshrined in dogma, and advances are available through research publications shared at specialty congresses and training workshops. The nuances of clinical decision-making may be unclear in these formats, and individualized training through fellowships in specialist units can help better disseminate the modern practices used to optimize results in this field. These 10 myths in nerve surgery have been selected and presented by experts in the field due to persistent misquoting or misinterpretation in nonspecialist practice that may preclude patients from receiving prompt appropriate care. PNS continues to advance with novel technologies, translating to clinical practice and high-quality clinical research studies, building the evidence base, and identifying future research questions for retro-translation to the laboratory. Expansion of the remit of PNS to all-cause paralysis, disordered muscle tone, and the management of neuropathic pain will continue to benefit patients. Expunging myths will enhance care for patients and will further expand on the reconstructive possibilities for this exciting specialty.

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DISCLOSURE

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