Review Article

Adult Traumatic Brachial Plexus Injuries

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Abstract

Adult traumatic brachial plexus injuries are devastating life-altering injuries occurring with increasing frequency. Evaluation includes a detailed physical examination and radiologic and electrodiagnostic studies. Critical concepts in surgical management include knowledge of injury patterns, timing of surgery, prioritization in restoration of function, and management of patient expectations. Options for treatment include neurolysis, nerve grafting, or nerve transfers and should be generally performed within 6 months of injury. The use of free functioning muscle transfers can improve function both in the acute and late setting. Modern patient-specific management can often permit consistent restoration of elbow flexion and shoulder stability with the potential of prehension of the hand. Understanding the basic concepts of management of this injury is essential for all orthopaedic surgeons who treat trauma patients.

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Dr. Noland or an immediate family member serves as a paid consultant to ExoToe LLC, Foot and Ankle Orthopedics, and Husband's company. Dr. Spinner or an immediate family member serves as a paid consultant to Mayo Medical Ventures. Dr. Shin or an immediate family member has received IP royalties from Mayo Medical Ventures and Trimed. Neither Dr. Bishop nor any immediate family member has received anything of value from or has stock or stock options held in a commercial company or institution related directly or indirectly to the subject of this article.

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Adult traumatic brachial plexus injuries (AT-BPIs) are devastating life-altering injuries that result in notable physical disability, psychological distress, and socioeconomic hardship. These injuries can result from a variety of etiologies, including penetrating injuries, falls, and motor vehicle trauma. Most are closed injuries involving the supraclavicular region. High-velocity injuries that torque the head violently away from the shoulder can result in injury to the upper brachial plexus roots and with varying degrees of injury to the lower roots (Figure 1A). Violent overhead abduction and traction can result in lower AT-BPI with varying degrees of upper root injury (Figure 1B).

Although the exact number of adult traumatic AT-BPIs occurring each year is difficult to ascertain, the popularity of extreme activities and sports, as well as the increasing number of survivors of motor vehicle accidents, has increased the number of AT-BPIs.[1-3] Most of these injuries occur in men aged 15 to 25 years.[2] An understanding of nerve injury physiology[4] and advances in brachial plexus reconstruction[5-10] have resulted in improved outcomes.

Anatomy

The brachial plexus is formed by five cervical nerve roots: C5, C6, C7, C8, and T1 (Figure 2). Anatomic variations with contributions from C4 (prefixed) to T2 (postfixed) have been described.[11] Injuries are classified based on their location with respect to the dorsal root ganglion (Figure 3A): a *preganglionic* injury occurs proximal to the dorsal root ganglion (Figure 3B) and a *postganglionic* injury, distal to the dorsal root ganglion (Figure 3, C and D).

Figure 1

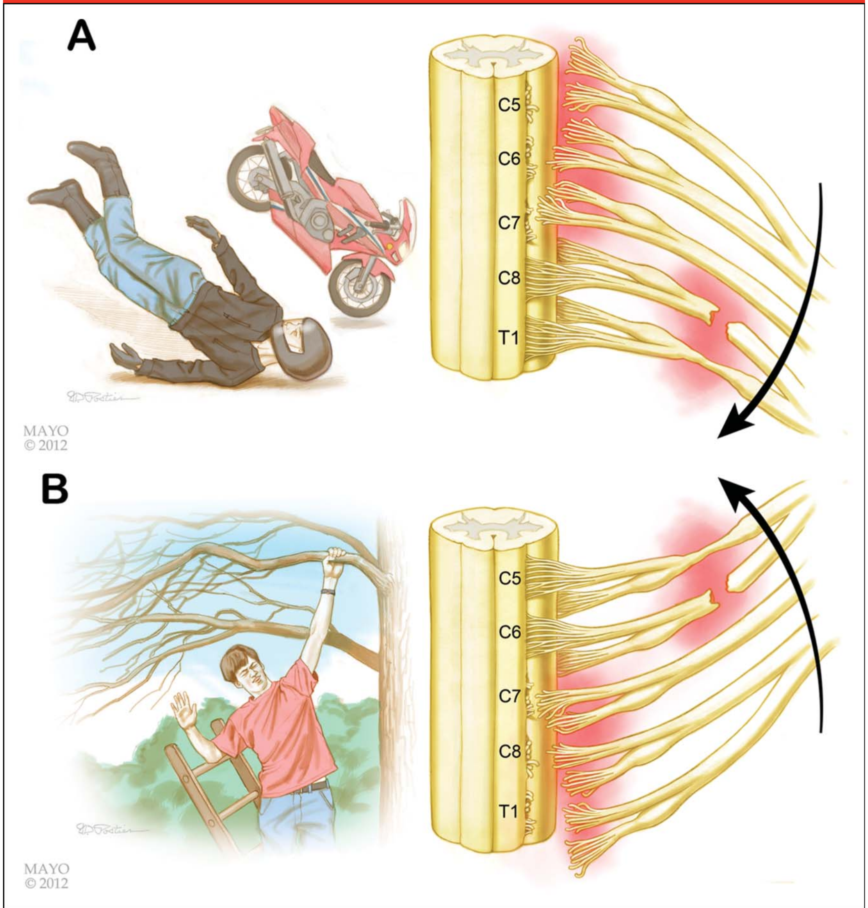


Diagram showing the mechanisms of adult traumatic brachial plexus injury. **A**, High-velocity injuries that torque the head violently away from the shoulder can result in injury to the upper brachial plexus roots and with varying degrees of injury to the lower roots. **B**, When the arm is violently abducted over the head, injury can occur starting with lower elements of the brachial plexus and then extend to the upper elements (Reproduced with permission from the Mayo Foundation for Medical Education and Research, Rochester, MN.).

Patient Evaluation

History and Physical Examination

Information regarding the mechanism and timing of injury as well as associated injuries and their treatment should be obtained. A detailed physical examination is imperative. Initial and subsequent examination findings are serially recorded to determine whether there is improvement of function. Examination can be used to ascertain if the injury is preganglionic or postganglionic. Weakness of proximal innervated muscles (ie, rhomboids) suggests preganglionic injury. Examination can also identify concomitant spinal cord and/or vascular injuries. Coexistent spinal cord injuries (including complete spinal cord injury, Brown-Sequard syndrome, and anterior cord syndrome) can occur in up to 12% of preganglionic AT-BPIs[12] and coexistent vascular injuries (including injury to subclavian, axillary, and brachial vessels) can occur in up to 28% of AT-BPIs.[13]

Observation

Observation can reveal muscle atrophy. Inspection of the ipsilateral eye, pupil, and eyelid can identify a Horner syndrome (triad of pupil miosis, eyelid ptosis, and anhidrosis), pathognomonic of a T1 root avulsion. Pulmonary compromise is unusual but can be associated with phrenic nerve injury. Abnormal gait patterns may distinguish the presence of an upper motor neuron lesion, from an underlying spinal cord injury.

Manual Motor Testing

The British Medical Research Council muscle grading system and its many variations have been used for decades in the evaluation of muscle strength (Figure 4, bottom). To make the British Medical Research Council grading more precise, a greater grade cannot be obtained unless the criteria of the lesser grade is obtained (Table 1). For example, to be a grade 3, grade 2 must first be obtained (partial movement of part with gravity eliminated). To be a grade 3, the muscle must move through full range of motion against gravity; full range of motion will vary by patient and thus active motion must equal passive motion (ie, the patient's available full range). Manual muscle testing of all muscles of the upper extremity can be performed systematically (Figure 4).

Range of Motion

Active and passive range of motion of shoulder flexion/abduction/external rotation, elbow flexion/extension, forearm pronation/supination, and wrist and finger flexion/extension occurs at each visit.

Sensation

Sensory examination should include testing of different modalities (especially light touch) in various nerve distributions (especially the independent sensory areas for each nerve root (autonomous zones), Figure 4, lower left). Although sensation of spinal or peripheral nerve dermatomes can be unreliable, general areas of viable and insensate sensation are recorded.

Tinel Sign

The presence (or absence) of percussion tenderness in the supraclavicular or infraclavicular fossa is evaluated. Radiating electric-like shock to a dermatome may represent a nerve root rupture. Lack of percussion tenderness over the brachial plexus indicates an avulsion. An advancing Tinel sign distal to the spinal nerve(s) may suggest a recovering lesion.

Vascular Evaluation

Vascular injuries can occur with brachial plexus lesions or with more severe injuries, such as scapulothoracic dissociations; their incidence is reported as 13% to 28% with brachial plexus injuries.[12,13] A vascular examination of the upper extremity is imperative for preoperative planning in the event that a free functioning muscle transfer (FFMT) will be necessary. Brachial, radial, and ulnar arteries are palpated. If they are not readily palpated, Doppler ultrasonography can be used in the clinic and noninvasive vascular studies as well as a vascular surgery consult to determine if vascular reconstruction will be necessary.

Reflexes

Lower extremity reflexes are evaluated to rule out concomitant spinal cord injury.[12] Patients with lower extremity hyperreflexia should be properly referred for evaluation by a neurologist to rule out upper motor neuron injuries.

Radiographic Evaluation

Chest Radiograph

Inspiration/expiration chest radiographs evaluate the function of the phrenic nerve (innervation from C3-C5). Diaphragm paralysis may be present with C5 root avulsions. Chest radiographs may reveal rib fractures, which are important as displaced rib fractures may injure the intercostal nerves (ICNs) often used in reconstruction. Transverse process fractures are frequently seen in the setting of preganglionic injury and may be treated nonoperatively.

Figure 2

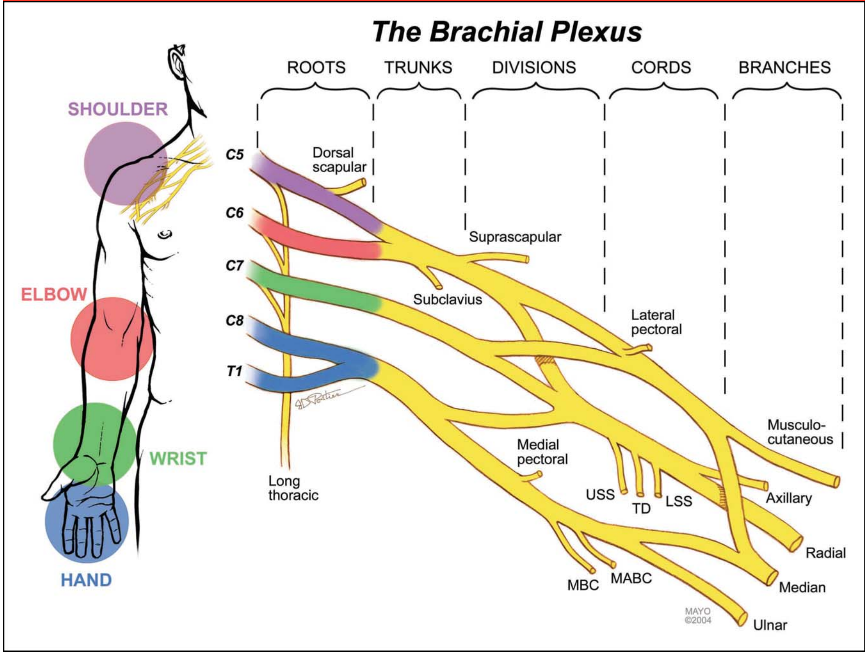


Diagram showing the classic anatomy of the brachial plexus demonstrating the nerves, trunks, divisions, cords, and terminal branches. Color coding demonstrates the common roots that innervate the different anatomic areas (C5 shoulder, C6 elbow, C7 wrist, C8/T1 hand) (Reproduced with permission from the Mayo Foundation for Medical Education and Research, Rochester, MN.).

Table 1

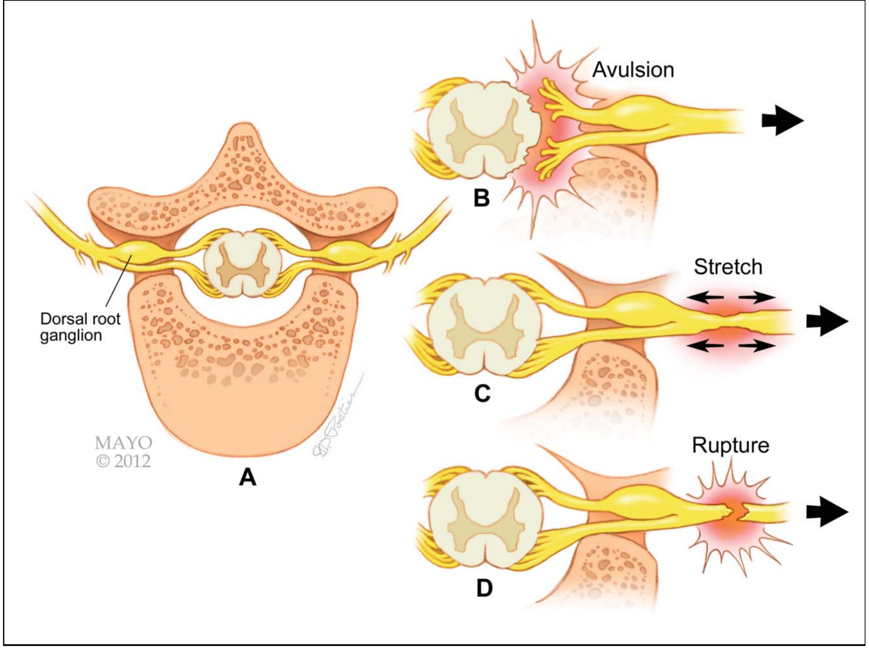
Modified British Medical Research Council Scale

Grade	Degree of Muscle Strength	Descriptive Term
0 = Zero	No palpable contraction	Nothing
1 = Trace	Muscle contracts but part does not move	Trace
2 = Poor	Partial movement of part with gravity eliminated	With gravity eliminated
3 = Fair	Muscle moves the part through the full arc of passive motion against gravity	Against gravity
4 = Good	Full range of motion against gravity plus added resistance	Near normal
5 = Excellent	Normal strength	Normal

Myelography

CT combined with myelography is instrumental in visualizing nerve root injury.[14] A CT myelogram may reveal asymmetric or absent nerve rootlets or a pseudomeningocele, which are highly suggestive of a nerve root avulsion (Figure 5, A and B). MRI is also useful (Figure 5C) and has the

Figure 3



A, Diagram showing a cross-sectional view of the spinal cord depicting the location of the dorsal root ganglion. Root-level injuries are classified based on the injury location with respect to the dorsal root ganglion. **B**, An avulsion injury occurs when the roots of the brachial plexus are ripped out of the spinal cord (ie, uprooted). This is a *preganglionic* injury because the injury occurs proximal to the dorsal root ganglion. **C**, A stretch injury distal to the dorsal root ganglion is a *postganglionic* injury. **D**, Another type of *postganglionic* injury with complete rupture of the root (Reproduced with permission from the Mayo Foundation for Medical Education and Research, Rochester, MN.).

advantage of being noninvasive.[15,16] Specialized MRI sequences (eg, fast imaging employing steady-state acquisition [FIESTA] or CUBE) can clearly demonstrate nerve rootlet anatomy.[17] A retrospective review comparing CT myelography with MRI in evaluating brachial plexus injuries found that the sensitivity of root avulsion was equivalent (92.9%).[15] However, many patients have had previous orthopaedic procedures about the shoulder/neck and imaging artifacts occur on MRI. In our practice, CT myelography is the benchmark of radiologic evaluation for nerve root avulsion.

Ultrasonography

Recently, interest in the use of ultrasonography in the evaluation of traumatic adult brachial plexus injuries has been noticed.[18] A recent systematic review of the use of ultrasonography in the diagnosis of traumatic adult brachial plexus injuries identified an overall sensitivity of 87%, with higher accuracy in the higher root levels (C5-C7).[18] Its application in specific settings may be beneficial. However, it is user dependent and often difficult to visualize some neural anatomy (especially distal nerve roots) secondary to depth and the tremendous amount of scar tissue that develops after injury.

Vascular Evaluation

When vascular injury is suspected, angiography (traditional magnetic resonance angiography or CT angiography) may be indicated to confirm the patency of a previous vascular repair or reconstruction. In acute situations, arteriography may be required to diagnose vascular discontinuity. In later settings, a CT angiography, magnetic resonance angiography, or traditional arteriography can be helpful to evaluate the patency of the subclavian artery. Revascularization of the extremity may be necessary if there is insufficient collateral circulation. Finally, patency of the thoracoacromial trunk is important in preoperative decision making, especially when considering restoration of hand or elbow function with FFMT.

Electrodiagnostic Studies

Electrodiagnostic studies are integral in the preoperative, intraoperative, and postoperative setting.[14] Preoperatively, they corroborate the diagnosis, localize the site of the injury as preganglionic or postganglionic, define the severity of axon loss and completeness of a lesion, eliminate other conditions from the differential diagnosis, and reveal subclinical recovery or unrecognized disorders. Baseline electromyography (EMG) and nerve conduction velocity studies are obtained 3 to 4 weeks after injury following Wallerian degeneration. Earlier testing may yield false-positive results as not enough time has elapsed. Serial physical examinations and electrodiagnostic studies performed over several months (if time permits) allow for the assessment of spontaneous recovery or failure of muscle reinnervation.[11] The EMG findings of fibrillation potentials in proximal muscles, such as the rhomboids, combined with a preserved sensory nerve action potential (NAP) are seen in preganglionic injury.

A combination of techniques can be used intraoperatively to gather information as part of the surgical decision. These techniques include NAPs, somatosensory and motor-evoked

Figure 4

Brachial Plexus Nerve Muscle Record

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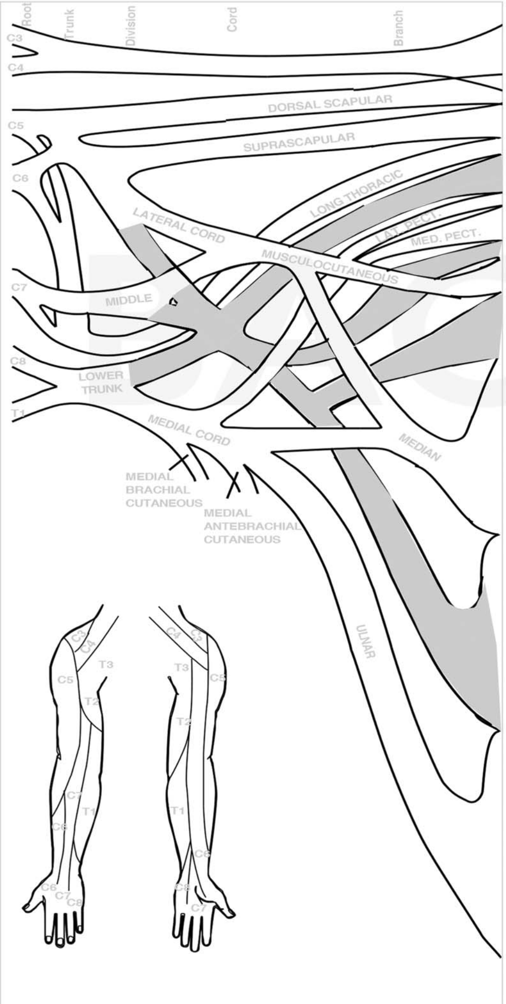
Provider: Pager:

Brachial Plexus — Currently involved ☐ Left (L) ☐ Right (R) ☐ Both (B)

Tinel's in Neck	
Horner's Sign	
Diaphragm	
EMG	
Pain	



	DATE
	Side Involved
	Examiner
C3, C4, XI	Upper trapezius
C3, C4, XI	Middle trapezius
C3, C4, XI	Lower trapezius
C(3), C(4), C5	Levator scapulae
C4, C(5)	Rhomboids
C(5), C6	Supraspinatus
C(5), C6	Infrapinatus
C(5), C(6), C(7)	Serratus anterior
C5, C6	Teres major
C5, C6	Subscapularis
C5, C(6), C7	Clav. pect. major
C6, C(7), C(8), T1	Stern. pect. major
C6, C7, C8, T1	Pect. minor
C6, C(7), C8	Latissimus dorsi
C(5), C6	Biceps & Brachialis
C5, C6, C7	Coracobrachialis
C(5), C6	Deltoid anterior
C(5), C6	Deltoid middle
C(5), C6	Deltoid posterior
C5, C6	Teres minor
C7, C(8), T1	Pronator quadratus
C(6), C(7)	Pronator teres
C(6), C(7)	Flex. carpi rad.
C7, C(8), T1	Flex. dig. prof. II, III
C7, C(8), T1	Flex. dig. sup.
C7, C(8), T1	Palmaris longus
C7, C(8), T1	Flex. pol. long
C6, C7, C(8), T1	Flex. pol. brev. (long)
C6, C7, C(8), T1	Abd. pol. brev.
C(8), T(1)	Opponens pollicis
C8, T1	Lumbricales, 1, 2
C6, C(7), C8	Triceps
C(5), C6	Supinator
C(5), C6	Brachioradialis
C(6), C(7)	Ext. carpi rad. long.
C6, C7, C8	Ext. carpi rad. brev.
C(7), C8	Ext. carpi ulnaris
C(7), C8	Ext. dig. com.
C(7), C8	Ext. dig. minimi
C(7), C8	Ext. ind. prop.
C(7), C8	Ext. pol. longus
C6, C(7)	Ext. pol. brev
C6, C(7)	Abd. pol. long.
C7, C(8), T1	Flex. carpi uln.
C7, C(8), T1	Flex. dig. prof. IV, V
C8, T(1)	Abd. dig. minimi
C(8), T(1)	Add. pol.
C8, T(1)	Opp. dig. minimi
C(8), T(1)	1 Dorsal interosseous
C(8), T(1)	2 Dorsal interosseous
C(8), T(1)	3 Dorsal interosseous
C(8), T(1)	4 Dorsal interosseous
C8, T1	1 Palmar interosseous
C8, T1	2 Palmar interosseous
C8, T1	3 Palmar interosseous
C8, T1	Lumbricales 3,4
C8, T(1)	Flex. pol. brev. (short)
Others	

Grade	Degree of Muscle Strength	Descriptive Term
0 = Zero	No palpable contraction	Nothing
1 = Trace	Muscle contracts, but part does not move	Trace
2 = Poor	Partial movement of part with gravity eliminated	With gravity eliminated
3 = Fair	Muscle moves the part through full range of motion against gravity	Against gravity
4 = Good	Full range of motion against gravity plus added resistance	Near normal
5 = Excellent	Normal strength	Normal

Key Note on Legend bar for draw tool	
Roots	X = Avulsion O = Rupture == = Stretch

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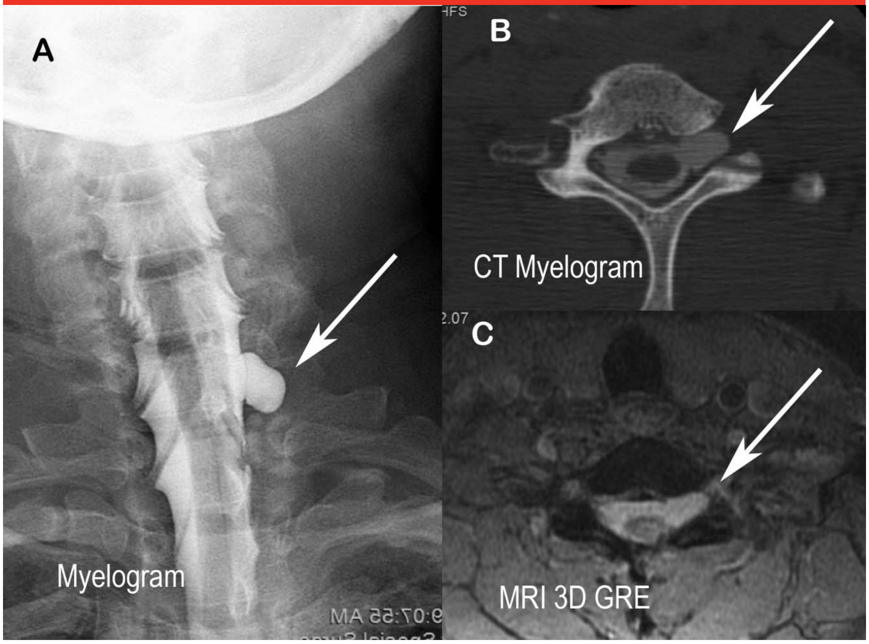
An example nerve muscle chart facilitating the organized documentation of presurgical and postsurgical manual motor testing. Muscles are graded according to the modified British Medical Research Council Scale (Reproduced with permission from the Mayo Foundation for Medical Education and Research, Rochester, MN.).

Figure 5



Radiographs showing the evaluation of brachial plexus root avulsion of the same patient. **A**, Traditional cervical myelogram demonstrating pseudomeningocele (white arrow), suggestive of a root avulsion. **B**, Cervical CT myelogram demonstrating pseudomeningocele (white arrow). **C**, Cervical MRI (3D gradient echo) showing the same pseudomeningocele (white arrow).

potentials (SSEPs and MEPs). NAPs directly test a nerve's ability to conduct a signal across a lesion. Evaluation of the spinal nerve(s) for continuity of the sensory and motor rootlets with the spinal cord can be performed with SSEPs and MEPs, respectively. Implications of intraoperative electrophysiologic testing exist. NAPs can predict reinnervation months before conventional EMG techniques.[19] The presence of an NAP across a lesion (neuroma-in-continuity) suggests that recovery will occur after neurolysis without the need for additional treatment, whereas an absent NAP would suggest that no regeneration has occurred, suggesting the need for additional treatment. The absence of SSEPs and MEPs would be consistent with a preganglionic lesion, whereas intact SSEPs and MEPs would be consistent with a postganglionic injury. In preganglionic injuries, the spinal nerve cannot be used as a donor for nerve grafting, whereas in postganglionic lesions, the spinal nerve can be used as a donor.

Concepts of Surgical Management

Indications for Surgery

Surgery should be performed in the absence of clinical and electrodiagnostic evidence of recovery or when spontaneous recovery is not possible. Selecting when and on whom to operate remain two of the most difficult decisions in brachial plexus surgery. It is imperative for the surgeon and patient to understand that the goal of surgical reconstruction is restoration of motor function and protective sensation. It will not restore function to preinjury levels nor will it address severe neuropathic pain associated with avulsion injuries. The goal is for antigravity motion with some resistance to gravity to improve activities of daily living of specific muscle groups.

Timing of Surgery

A time-dependent degeneration occurs at the level of the motor end plate after division of a motor nerve. If the nerve signal is not restored in sufficient time, an irreversible change occurs at the motor end plate, rendering the muscle functionless despite a nerve signal reaching it.[11] Timing of surgery or intervention is dependent on the mechanism and type of injury. Immediate exploration and primary repair is indicated in sharp open injuries with acute nerve deficits. This facilitates easier identification of nerve ends and primary end-to-end repair of the injured nerves. With blunt open injuries with rupture of the nerve(s), the ends of the torn nerve should be tagged and a delayed repair performed 3 to 4 weeks later to allow the zone of injury to demarcate. Low-velocity gunshot wounds should be observed as most of these injuries are neurapraxic injuries; however, high-velocity gunshot wounds are associated with notable soft-tissue damage and usually mandate surgical exploration.[20]

The exact timing of surgery for closed injuries is controversial. The timing is determined by mechanism and type of injury, physical examination, electrodiagnostic studies, imaging findings, and surgeon preference. Operating too early may not allow sufficient time for spontaneous reinnervation, and waiting greater than 6 months may lead to failure of the motor end plate and failure of reinnervation. Early exploration and reconstruction (such as, between 3 and 6 weeks) is indicated when there is a high suspicion of root avulsion because waiting for spontaneous reinnervation is essentially futile.

Routine exploration is performed between 3 and 6 months after injury, allowing time for spontaneous reinnervation. Results from delayed (6 to 12 months) or late (>12 months) surgery are often disappointing because the time for the nerve to regenerate to the target muscles is greater than the survival time of the motor end plate after denervation. In these cases, alternatives to primary nerve surgery or transfers should be considered (FFMT and tendon transfers).

Priorities of Reconstruction

Elbow flexion is the highest priority in restoring function to the completely flail extremity, followed by shoulder stability, abduction, and external rotation. Reconstruction of wrist and hand function is very challenging because of the long distance from the site of injury and the slow rate of nerve regeneration. Traditional methods of nerve reconstruction will not reach the motor end plates of the distal muscles before muscle atrophy. However, FFMT can be used to obtain hand function; in this case, elbow extension is important as the FFMT crosses the anterior elbow and requires an agonist to allow for hand function. Finally, protective hand sensibility should be considered when and if possible. Often, no enough nerve donors are available to provide all desired functions.

Determinants of Treatment

Type of Nerve Injury

Preganglionic injuries cannot be grafted because they are discontinuous from the spinal cord. Postganglionic injuries can be grafted as they remain in continuity with the spinal cord and are a viable nerve source for reconstruction of distal targets.

Pattern of Injury

Pan-plexus avulsions represent a very different injury than upper trunk avulsions of C5 and C6. In pan-plexus avulsions, the source of nerves for reanimation of the extremity is all extraplexal (outside the brachial plexus) and typically includes the spinal accessory nerve (SAN), ICNs, and contralateral C7 nerve. In these injuries, exploration of the brachial plexus and evaluation of the roots for a possible viable donor nerve is essential, because it may give the patient an additional source for reconstruction. In patients with C5-C6 injuries, the brachial plexus should also be explored for possible viable C5 or C6 roots. C5-C6 injury patients also have the option of a combination of intraplexal and extraplexal nerve transfers from their functioning C7-T1 nerves. The C5-C7 and C5-C8 injuries represent other patterns where there may potentially be both viable proximal nerve roots and functioning distal nerves for use as nerve transfers.

Whatever the pattern of injury, a list of potential nerve sources should be generated. The most common donor nerves include the SAN, the ICNs, the triceps nerve, fascicles of the median and ulnar nerves, the phrenic nerve, and the contralateral C7. In a pan-plexus injury, all donor nerves must come from outside the plexus and this includes the SAN, ICNs, phrenic, and contralateral C7. For C5-C6 injuries, the potential sources include viable postganglionic roots of C5 or C6, ipsilateral C7, intraplexal sources (fascicle of the ulnar or median nerve or triceps branches) and extraplexal nerves (spinal accessory nerve or ICNs).

Surgical Management

Primary reconstruction is the initial surgical management and may include nerve surgery/reconstruction (eg, direct repair, neurolysis, nerve grafting, nerve transfers) and/or soft-tissue procedures (eg, FFMT, tendon transfers). Secondary reconstruction may be necessary to improve function and includes soft-tissue reconstruction (eg, tendon/muscle transfer, FFMT, capsulotomies) and osseous procedures (eg, arthrodesis, osteotomy). Nerve grafting or transfers are not recommended in patients who are >12 months from injury (in some very specific cases, distal nerve transfers may be considered 12 to 18 months after injury). Combinations of nerve grafting, nerve transfers, FFMT, tendon transfers, tenodesis, and selected arthrodesis have allowed for improved outcomes.

Primary Reconstruction

Intraplexal Nerve Grafting

Nerve grafting is performed with postganglionic injuries and viable donor spinal nerves. For example, in a postganglionic injury, there may be a viable proximal nerve root (most commonly C5 or C6). This nerve root can be grafted to the distal stump, bypassing the area of injury. Interpositional grafts (cable grafts of sural or other cutaneous nerves) are coapted between nerve stumps without tension using microsurgical techniques. Although the philosophy of distal nerve transfers has become more popular with avoidance of exploration of the roots, we suggest viable nerve roots be considered and used when available.

Nerve Transfer

Nerve transfer can be performed for preganglionic injury or to accelerate recovery in postganglionic injuries by decreasing the distance between the site of nerve repair and the motor end plate. A functioning nerve of lesser importance is transferred to the more important denervated distal nerve. Nerve transfers should be performed within 6 months of injury; however, this time frame can be extended to up to 1 year (or potentially slightly longer for some distal nerve transfers), because the time to (and distance for) reinnervation is decreased. Donor nerves for transfer can be extraplexal (eg, SAN, ICNs, phrenic nerve, and contralateral C7) or intraplexal (eg, medial pectoral nerve, ulnar nerve fascicle, median nerve fascicle, triceps branches).

Free Functioning Muscle Transfer

FFMT is the transplantation of a muscle and its neurovascular pedicle to a new location to assume a new function. The muscle is innervated by transferring an expendable donor motor nerve of the FFMT; circulation is restored to the muscle through microsurgical anastomosis of the artery and vein to donor vessels (typically thoracoacromial artery and cephalic vein). Within 6 to 9 months, the transferred muscle starts to reinnervate, eventually gaining independent function. FFMTs were initially indicated in patients who presented late or as a salvage procedure with failed previous nerve reconstruction. Based on the success with FFMT in secondary surgery, it has been incorporated into a strategy for early reconstruction to obtain elbow flexion and rudimentary grasp in patients with pan-plexus injuries.[7]

The gracilis is the most commonly used because of its proximally based neurovascular pedicle (which allows earlier reinnervation) and its long tendon length (which reaches into the forearm for hand reanimation).[21-23]

Common Patterns of Injury

Upper Trunk

In the upper trunk injury (C5-C6), there is loss of shoulder abduction, external rotation, and stability and elbow flexion. The supraclavicular brachial plexus is explored and viable nerves identified with intraoperative SSEP and MEP.

Two Viable Spinal Nerves

If two viable nerve roots are available (typically C5 and C6), these are used to restore shoulder function and elbow flexion. C5 is grafted (sural nerve cable graft) to the suprascapular nerve and posterior division of the upper trunk (to axillary nerve) and C6 is grafted to the anterior division of the upper trunk (to musculocutaneous nerve). This will not only restore motor function but also offer restoration of sensibility. Some surgeons, however, will advocate for all nerve transfer surgery instead of nerve grafting. Alternatively, a hybrid of nerve grafting to shoulder and nerve transfer for elbow flexion can be done. An ulnar nerve fascicle transfer to the biceps motor branch, also known as the Oberlin transfer, is a reliable transfer to restore elbow flexion.[24] The addition of a transfer from the median nerve to the brachialis nerve branch has been advocated by several authors,[25,26] however, several studies have not demonstrated statistically notable improved strength from the second nerve transfer.[10,27] Understanding the various options in this scenario of a C5-C6 palsy is important because options chosen typically depend on surgeon and patient preferences.

One Viable Spinal Nerve

For upper trunk injuries with one viable nerve root, the viable spinal nerve can be grafted to the suprascapular nerve and posterior division of the upper trunk, and the distal nerve transfer(s) described previously are performed for elbow flexion.

No Viable Spinal Nerve

In the scenario of no viable proximal nerve roots (all preganglionic), distal nerve transfers to restore shoulder external rotation, and abduction and elbow flexion are the only option. For shoulder stability, abduction, and external rotation, a common strategy is to perform two nerve transfers: a SAN to SSN transfer[27] and a branch of the radial nerve to triceps to anterior division of the axillary nerve transfer.[8] The SAN is transferred to the SSN, either from an anterior or posterior approach. The triceps branch nerve to anterior division of the axillary nerve transfer is effective to restore deltoid strength. Elbow flexion is restored by either a single or double nerve transfer as previously described.

Pan-plexus Injuries

Pan-plexus injuries have the greatest variability in reconstructive option. Minimal surgical offering would be for shoulder stability and elbow flexion. Newer techniques offer some ability for recovery of rudimentary grasp. Some patients, despite counsel, still request amputation. The reconstructive options depend on the number of viable spinal nerves. Nerve donors are severely limited and the identification of a viable proximal nerve can have a notable impact on the patient's outcome. The surgeon should take an inventory of all available donor nerves including spinal nerves, the SAN, ICN, phrenic, and contralateral C7. Many permutations exist. For restoration of shoulder function, a viable nerve can be grafted as described earlier. Alternatively, the SAN to SSN transfer can provide limited external rotation, stability, and abduction; some feel that the SAN should be preserved for use in restoring elbow flexion or for powering an FFMT[28] or preserved for a later lower trapezius tendon transfer for shoulder external rotation.[29] In such scenarios, the shoulder can be stabilized with a glenohumeral arthrodesis.[30] For restoration of elbow flexion extraplexal donor nerves such as SAN and ICNs (Figure 6) are considered. These donor nerves can be transferred to the musculocutaneous nerve (or biceps motor branch) with or without an interpositional nerve graft.[21,31] Ideally, no interpositional nerve graft will be necessary as this would require axons to travel a longer distance and traverse two nerve repair sites, thus limiting functional return.

Another donor nerve that gained a resurgence in pan-plexus injury is the contralateral C7.[32] This donor nerve can be used for several different targets, but is most popular for restoring lower trunk function.[32] The prevertebral route of the contralateral C7 to the lower trunk and musculocutaneous nerve with ipsilateral humeral shortening has been advocated by a group of Chinese surgeons.[32] However, a systematic review demonstrated that outcome measures of contralateral C7 transfer were insufficient to critically evaluate these patients.[33] Although good outcomes have been published by some,[32] concerns with donor site morbidity and lack of independent function of the extremity have limited its use.[34]

FFMT in primary reconstruction has resulted in markedly improved outcomes.[7] Doi et al[22] described using a double FFMT (gracilis) that enabled prehension to patients with complete brachial plexus lesions. The goals of this two-stage operation are to restore both elbow flexion and extension as well as wrist extension and finger flexion. We have modified this approach into a single FFMT in combination with other nerve transfers to achieve rudimentary grasp (Figure 7, A and B).

Protective sensation can be obtained if there are viable nerves grafted to targets, which contribute to the median nerve (anterior division of upper trunk) or by transfer of sensory ICNs to the lateral cord contribution of the median nerve. The protective sensation is rudimentary, and sensation is referred to the chest wall when the hand is touched.

Some patients will request amputation believing that it will alleviate the severe neuropathic pain. The surgeon must understand that the neuropathic pain is generated from the spinal cord injury associated with the avulsion injury and that amputation will not solve this pain.[35] If there is mechanical pain from the weight of the arm, amputation may be helpful. We avoid amputation in the acute setting and recommend nerve reconstruction and time to determine the results of surgery. Amputation can be considered after recovery and after appropriate evaluation by amputee clinic and qualified prosthetist.[35]

For injuries that occur at the cord or division level, corroborating the clinical examination and neurodiagnostic studies becomes more challenging to localize the injury pattern. A thorough knowledge of innervation patterns, serial examination, and neurodiagnostic studies are necessary. Treatment of these injuries is beyond the scope of this review.

Secondary Reconstruction

When there has been no further recovery or when function can be further improved or refined with surgical intervention, secondary reconstruction is considered. Options include tendon transfer, FFMT, shoulder arthrodesis, and wrist and hand arthrodesis. Tendon transfer can only be done if there are existing functioning muscles. FFMT can be performed to improve the strength of a weakly reinnervated biceps or triceps if there is a viable donor nerve and adequate donor vessel. Arthrodesis is useful for secondary reconstructive surgery of the shoulder, wrist, and hand. Shoulder fusion can be performed as a salvage procedure for the persistently painful subluxating shoulder should the nerve surgery fail to result in shoulder stability. Other bony procedures, such as humeral derotational osteotomy, thumb axis arthrodesis, wrist fusion, or finger joint arthrodesis, can improve function.

Figure 6

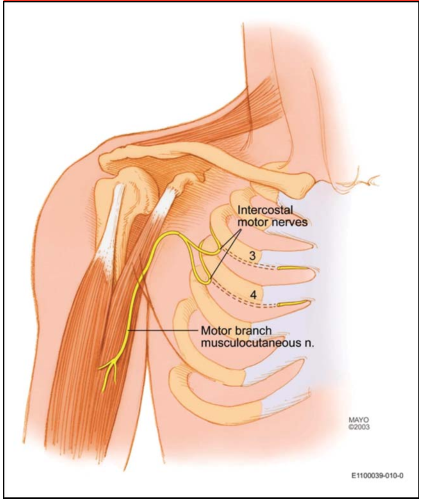


Diagram showing the nerve transfer of two intercostal nerves to the motor branch of the musculocutaneous nerve. (Reproduced with permission from the Mayo Foundation for Medical Education and Research, Rochester, MN.).

Postoperative Management

The patients are typically immobilized for 3 weeks after nerve reconstruction. Since the nerve repairs are performed with no tension, gentle range of motion is allowable after 3 weeks. If ICNs are used as donor nerves, the patients will have a lifetime abduction/external rotation restriction to prevent rupture of the repair.

After surgical intervention, the patient and his/her family must understand recovery of nerve function is a slow and arduous process. Nerve regeneration occurs at a rate of 1 mm a day or 1 inch per month. Clinical results may not be seen for 1 to 2 years. The shorter the distance to the target muscle, the more rapid the time to reinnervation. While waiting for reinnervation to occur, patients' joint mobility therapy is necessary to prevent contractures. The efficacy of electrical stimulation in preserving motor end plates remains controversial and has not demonstrated efficacy

Figure 7

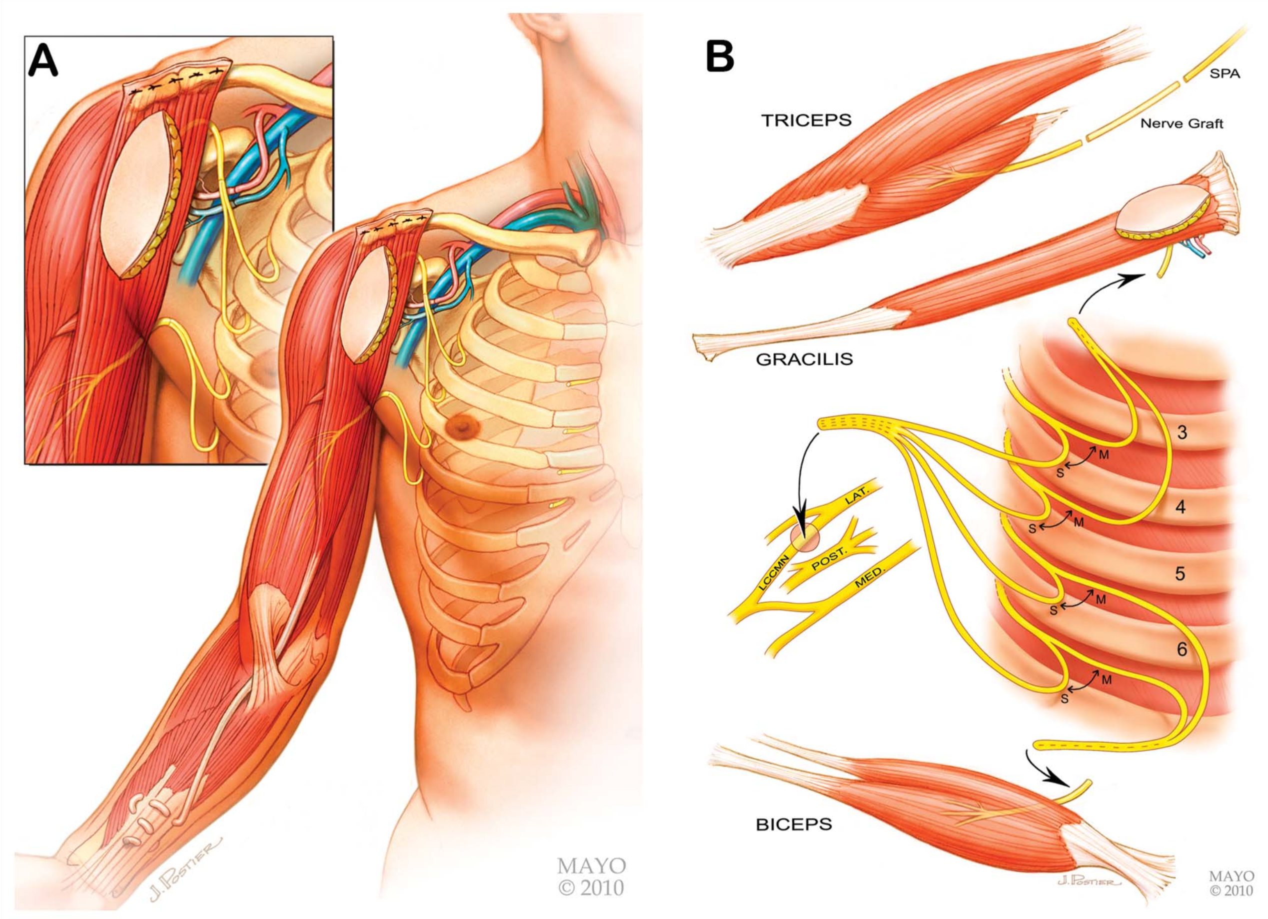


Diagram showing a single-stage alternative for reconstruction of upper extremity function in pan-plexus injuries. **A**, The contralateral functioning gracilis is harvested and neurotized by two intercostal motor nerves and anastomosed to the thoracoacromial trunk (inset). The gracilis is attached proximally to the clavicle and routed under the lacertus fibrosus and distally woven into the deep finger flexors. Two additional intercostal motor nerves are neurotized to the motor branch of the musculocutaneous nerve. **B**, The spinal accessory nerve is neurotized to the triceps using an interpositional nerve graft (superior schematic). Four intercostal sensory nerves are transferred to the lateral cord contributing to the median nerve for restoration of hand sensation (inferior schematic). The biceps and gracilis muscle are neurotized, as described in A. This procedure allows for rudimentary grasp in a single-stage operation (Reproduced with permission from the Mayo Foundation for Medical Education and Research, Rochester, MN.).

in humans.[36] Follow-up at 6- to 8-month intervals for a minimum of 2 to 3 years (preferably 5 years) is recommended to assess for full recovery and determination of potential secondary reconstructions to improve function.

Neuropathic Pain

Neuropathic pain is common in AT-BPI[37] and more than half will experience neuropathic pain.[38,39] Patients with root avulsions can develop neuropathic pain similar to spinal cord injury patients, given the proximity of the avulsion to the spinal cord.[40] Nerve reconstruction cannot reliably relieve neuropathic pain in patients with preganglionic injury (as the source of pain at the spinal cord level) but may be effective in those with postganglionic injury. In postganglionic injury, a component of the pain may be the proximal stump. If the proximal stump is nerve grafted, giving the axons a route to follow, neuroma formation may be prevented. Although this may decrease pain caused by neuroma formation, it will not address spinal cord-generated pain.[40]

The neuropathic pain management is difficult and includes pharmacologic and surgical intervention. Pharmacologic options consist primarily of anticonvulsants (gabapentin, pregabalin) and antidepressants (amitriptyline, duloxetine), both providing some degree of pain relief.[41] For intractable neuropathic pain unresponsive to pharmacologic intervention, dorsal root entry zone ablation,[42] spinal cord and deep brain stimulation may be considered. Pain rehabilitation with behavioral medicine techniques may also be effective for long-term management of chronic pain after AT-BPI.

Summary

Injuries to the adult brachial plexus are intimidating to the orthopaedic surgeon who may be managing concomitant injuries. The injury can be devastating to the patient and is difficult for the patient and family to comprehend. A thorough understanding of the anatomy, clinical evaluation, radiologic and electrodiagnostic studies, treatment options, and proper timing of surgical intervention for different injury mechanisms will enable the treating surgeon to offer optimal care. Even in severe pan-plexal injury, treatment options offer patients the ability to obtain elbow flexion, limited shoulder abduction with shoulder stability, and hope for limited but potentially useful hand function.

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