Traumatic Brachial Plexus Injury in the Pediatric Population

31

Harvey Chim, Allen T. Bishop, Robert J. Spinner, and Alexander Y. Shin

Contents

Statement of Financial Disclosure: The authors declare that they had no financial interests or commercial associations relevant to this study.

H. Chim • A.T. Bishop • R.J. Spinner • A.Y. Shin (✉)
Department of Orthopedic Surgery, Division of Hand Surgery, Mayo Clinic, Rochester, MN, USA
e-mail: chim.harvey@mayo.edu; bishop.allen@mayo.edu; spinner.robert@mayo.edu; shin.alexander@mayo.edu

J.M. Abzug et al. (eds.), *The Pediatric Upper Extremity*,
DOI 10.1007/978-1-4614-8515-5_31

Abstract

Traumatic brachial plexus injuries in children are very rare. A particular characteristic of pediatric patients is a high incidence of root avulsions. Compared to adults, children also have minimal deafferentation pain and a higher incidence of associated skeletal injuries and exhibit faster recovery. The approach to children with traumatic brachial plexus injuries can be divided into three groups based on age. In very young children (<4 years of age), management is focused on restoring and maximizing hand function, similar to patients with obstetric brachial plexus injuries. In children more than 12 years of age, management is similar to that in adult patients. For these patients, the priorities for restoring function, in order of importance, are elbow flexion, shoulder abduction and/or stability, hand sensation, wrist extension and finger flexion, wrist flexion and finger extension, and lastly, intrinsic hand function. This approach relies on maximizing function while prioritizing movements that have the least distance for nerves to regenerate to target muscles. For children in between 4 and 12 years of age, treatment priorities are controversial. In this chapter, the approach to and workup of children with traumatic brachial plexus injuries is described, as well as treatment options such as nerve grafts, nerve transfers, and free functioning muscle transfers.

Introduction

Traumatic brachial plexus injuries (BPI) present a complex problem that leads to severe impairment, disability, and hardship. Treatment is best provided through multidisciplinary management at tertiary centers with experience in diagnosis, surgical treatment, and rehabilitation. The number of brachial plexus injuries in adults continues to rise due to the prevalence of extreme sports and increasing number of survivors of motor vehicle accidents (Shin et al. 2005); hence, treatment protocols for adult patients are well established and constantly evolving. However, the incidence of these injuries in the pediatric population is much lower and the literature on pediatric traumatic brachial plexus injuries correspondingly scarce. Boome reported an overall incidence of 1.1 % of pediatric out of all brachial plexus lesions in his series – 16 cases in 14 years (Boome 2000).

In adults, the most common cause of brachial plexus injuries remains motor vehicle accidents involving motorcycles or bicycles, leading to around 70 % of these injuries (Narakas 1985). In the pediatric population, these injuries are most often caused by motor vehicle accidents involving children as passengers or pedestrians. Data from the National Pediatric Trauma Registry of the United States (Dorsi et al. 2010) showed an incidence of 0.1 % of traumatic brachial plexus injuries in pediatric multitrauma patients. Common associated injuries include head injuries (intracranial bleeds, skull fractures), upper extremity vascular injury, and fractures of the humerus, ribs, clavicle, scapula, and spine.

A particular characteristic of pediatric patients is a high incidence of root avulsions, comprising two-thirds of patients in some series (Dumontier and Gilbert 1990; El-Gammal et al. 2003). Compared to adults, children also have minimal deafferentation pain and a higher incidence of associated skeletal injuries and exhibit faster recovery.

The approach to children with traumatic brachial plexus injuries can be divided into three groups based on age. In this context, “children” are defined as those patients with open growth plates. In very young children (<4 years of age), management is focused on restoring and maximizing hand function, similar to patients with obstetric brachial plexus injuries (Waters 1999; Terzis and Kokkalis 2008). In children more than 12 years of age, management is similar to that in adult patients. For these patients, the priorities for restoring function, in order of importance, are elbow flexion, shoulder abduction and/or stability, hand sensation, wrist extension and finger flexion, wrist flexion and finger extension, and lastly, intrinsic hand function. This approach relies on maximizing function while prioritizing movements that have the least distance for nerves to regenerate to target muscles. For children in

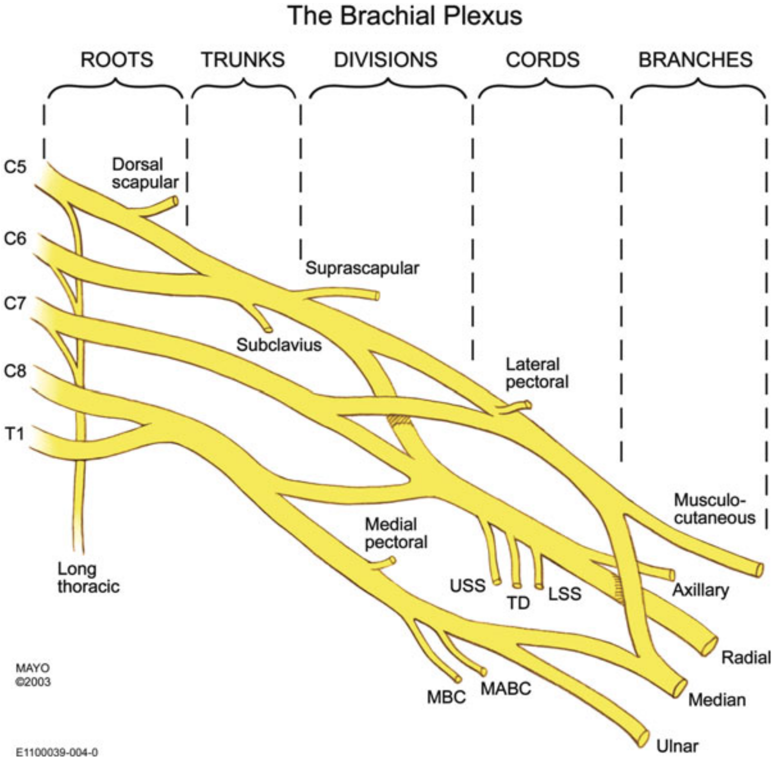


Fig. 1 Anatomy of the brachial plexus, which is broadly divided into roots, trunks divisions, cords, and branches. *LSS* lower subscapular nerve, *MABC* medial antebrachial cutaneous nerve, *MBC* medial brachial cutaneous nerve, *TD* thoracodorsal nerve, *USS* upper subscapular nerve (By permission of Mayo Foundation for Medical Education and Research, All rights reserved)

between 4 and 12 years of age, treatment priorities are controversial; however, the trend has been for performing nerve transfers to restore elbow flexion and shoulder abduction, due to the high incidence of root avulsions (Gilbert et al. 2006).

Pathoanatomy and Applied Anatomy

The brachial plexus is derived from five cervical nerve roots, typically C5, C6, C7, C8, and T1 (Fig. 1). There may be contributions to the plexus from C4; this is termed a "prefixed" plexus, with an incidence ranging from 28 % to 62 %. T2 may also contribute to the plexus; this is termed a "postfixed" plexus, with an incidence ranging from 16 % to 73 % (Kerr 1918). Each spinal nerve root is formed by the confluence of the ventral and dorsal nerve rootlets as they pass through the spinal foramina. The dorsal root ganglion contains cell bodies of the sensory nerves and lies within the confines of the spinal canal and foramen. Hence, a preganglionic injury is defined as one where individual spinal roots are avulsed off the spinal cord, while a postganglionic injury is one located distal to the dorsal root ganglion (Fig. 2). Low-energy traction injuries may lead to stretch injuries (Fig. 2c), with potential for spontaneous recovery. High-energy injuries are associated with more severe damage to each nerve root, which may lead to rupture of the postganglionic segment, with no potential for recovery without surgery. In the pediatric population, preganglionic injuries are particularly common. A preganglionic lesion has no possibility of spontaneous recovery – hence, surgical reconstruction is mandatory for recovery of meaningful upper extremity function.

The C5 and C6 nerve roots merge to form the upper trunk, C7 continues as the middle trunk, and C8 and T1 combine to form the lower trunk. The confluence of C5 and C6, termed Erb's point, is also the spot where the suprascapular nerve arises. Each trunk then divides into an anterior and posterior division and passes deep to the clavicle. The

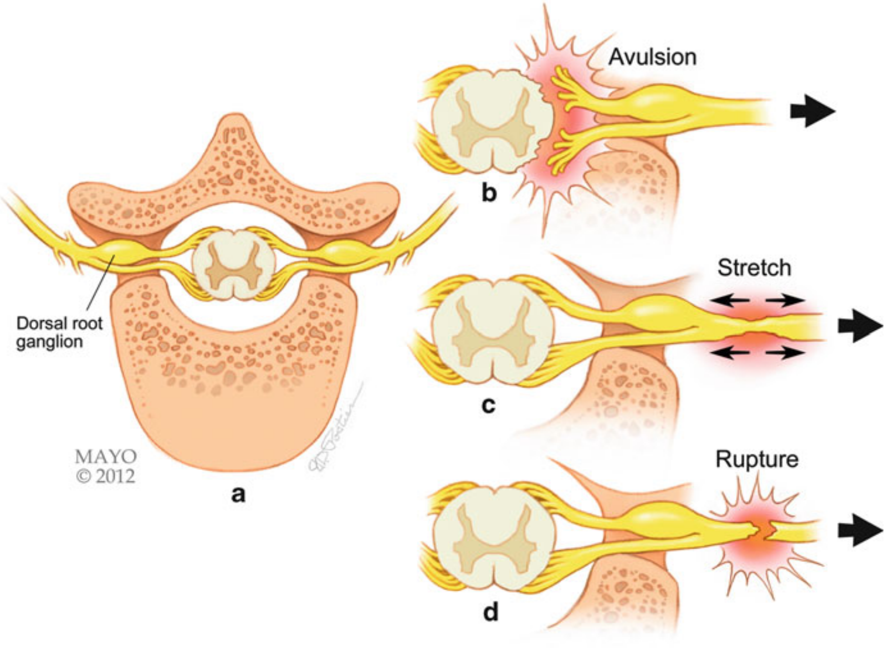


Fig. 2 Injury to the brachial plexus can cause different injuries to each nerve root at preganglionic or postganglionic level. (**a**) Normal spinal cord and roots; (**b**) Avulsion injuries are preganglionic and cannot be repaired; (**c**) stretch injuries are postganglionic and have potential for spontaneous recovery; (**d**) rupture injuries can be repaired with surgery (By permission of Mayo Foundation for Medical Education and Research, All rights reserved)

three posterior divisions merge to form the posterior cord, while the anterior divisions of the upper and middle trunks combine to form the lateral cord. The anterior division from the lower trunk continues as the medial cord. The lateral cord divides into two terminal branches: the musculocutaneous nerve and the lateral cord contribution to the median nerve. The posterior cord continues as the axillary and radial nerves, and the medial cord contributes to the ulnar nerve and the median nerve. The portion of the brachial plexus formed by roots and trunks is located above the clavicle and termed the *supraclavicular* plexus; the portion formed by the divisions is found behind the clavicle and termed the *retroclavicular* plexus; the portion of the plexus formed by cords and terminal branches is termed the *infraclavicular* plexus.

A number of terminal branches emanate from the roots, trunks, and cords. The C5 root has a contribution to the phrenic nerve, dorsal scapular nerve (rhomboids), and long thoracic nerve (serratus anterior, also with contributions from C6 and C7). The suprascapular nerve (supraspinatus and infraspinatus) and nerve to subclavius muscle originate from the upper trunk. The lateral cord gives off the lateral pectoral nerve, while the medial cord gives off the medial pectoral nerve, medial brachial cutaneous nerve, and medial antebrachial cutaneous nerve. The posterior cord gives off the upper subscapular nerve (subscapularis), thoracodorsal nerve (latissimus dorsi), and lower subscapular nerve (subscapularis, teres major). Through careful and detailed testing of the function of muscles supplied by individual terminal nerve branches, the exact level of the injury to the brachial plexus can be determined. The sympathetic ganglion for T1 is located close to the T1 root and provides sympathetic innervation to the head and neck. Hence, a preganglionic injury at T1 level manifests clinically as Horner's syndrome, characterized by ptosis, miosis, and anhidrosis on the affected side. In children, Horner's syndrome can also lead to heterochromia (difference in eye color between both eyes). A lack of sympathetic stimulation in childhood can interfere with melanin pigmentation of the melanocytes in the superficial stroma of the iris.

Assessment

A complete history and physical examination, together with imaging and electrodiagnostic tools, allow localization of the level and severity of the injury to the brachial plexus. The aim of the preoperative workup is to determine the level of the injury – preganglionic (root level) or postganglionic (trunk, division, cord, or branches) – and also the severity of the lesion (partial or complete) for each component of the brachial plexus injured. This allows prognostication of recovery and a decision to be made for surgery. If no recovery is observed within the first 3–6 months, surgery is indicated. A preganglionic injury at one or more levels has little to no chance of recovery; hence, earlier intervention may be indicated.

Signs and Symptoms

A history of the mechanism of injury can be obtained from the patient or parents. High-energy injuries, for example, from motor vehicle accidents, have a lower chance of spontaneous recovery than low-energy injuries. Sharp injuries from lacerations should be explored acutely or subacutely. Gunshot wounds, in contrast, should be observed as many of these will exhibit spontaneous recovery over time.

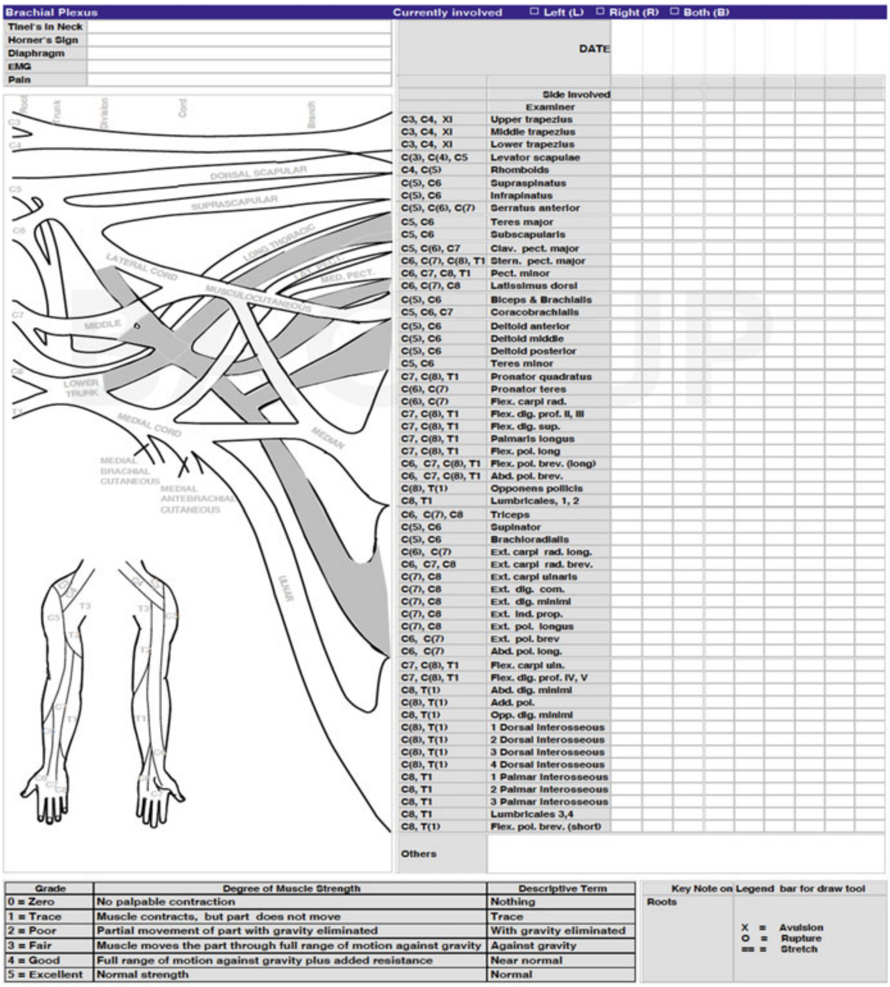
As other injuries may be associated with the injury to the brachial plexus, management of these takes precedence in the multitrauma patient. Management follows acute trauma life support (ATLS) principles, with attention to the airway, breathing and circulation taking priority, followed by treatment of other life- and limb-threatening injuries. A detailed examination of the various components of the brachial plexus should be performed when the patient is stable and able to cooperate with the examiner. The exam should be recorded in a manner that allows for comparison of dates (Fig. 3). Serial detailed examinations help determine the presence or absence of nerve recovery and prognosis for spontaneous improvement.

In an older child, a detailed systematic examination of the brachial plexus may be possible, together with documentation of muscle strength following the modified grading system of the British Medical Research Council (BMRC) for adults (M0 to M5) (Mendel and Florence 1990; Table 1). Note that a patient cannot have grade 3 power unless there is full active motion against the existing passive range of motion.

A preganglionic lesion can be diagnosed through the presence of Horner’s syndrome, which suggests a root avulsion at the T1 level. Additional muscles that are innervated close to the spinal cord provide further evidence of a preganglionic lesion. Paralysis of the serratus anterior muscle, manifest through winging of the scapula (may be very difficult to examine secondary to paralysis of other periscapular muscles), suggests a lesion proximal to the long thoracic nerve, formed by the C5, C6, and C7 nerve roots. Atrophy of the rhomboids and parascapular muscles also suggests a preganglionic lesion proximal to the origin of the dorsal scapular nerve. Examination of individual sensory dermatomes may sometimes be unreliable due to overlap from other nerves or anatomical variation.

Different patterns of injury may be predicted based on the mechanism of injury. Upper brachial plexus injuries (Fig. 4) occur in motorcyclists who fall with the shoulder forced downward and the head pushed to the other side. Lower brachial plexus or pan-plexus injuries (Fig. 5) may occur during fall from height through hyperabduction of the injured upper extremity.

Examination of donor nerves should also be performed if nerve transfer is contemplated as a treatment option, such as the spinal accessory nerve, nerve to triceps, and medial pectoral nerve. Presence of a Tinel’s sign and tenderness in the supraclavicular or infraclavicular area suggests a postganglionic lesion, while absence of these suggests a preganglionic lesion. An advancing Tinel’s sign is a prognosticator and suggests a recovering lesion. Minimal preservation of movement in tested muscle groups suggests a partial



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

Fig. 3 The Mayo brachial plexus evaluation form. This allows complete assessment of the entire extent of the injury at a glance (By permission of Mayo Foundation for Medical Education and Research, All rights reserved)

Table 1 BMRC scale for muscle strength

0: No muscle contraction visible
1: Muscle contraction is visible but there is no movement
2: Active movement is possible with gravity eliminated
3: Active movement against gravity
4-: Active movement against gravity and slight resistance
4: Active movement against gravity and moderate resistance
4+: Active movement against gravity and strong resistance
5: Normal power

injury with a greater potential for recovery. Examination of stability, active, and passive range of motion of all joints should also be assessed. Concomitant spinal cord injury should be ruled out by performing a full neurological examination of the upper and lower extremity, testing for power, sensation, and reflexes. Finally, a vascular exam should be performed, as the subclavian or axillary artery can be ruptured or damaged in substantial injury to the brachial plexus.

Fig. 4 Patterns of brachial plexus injury are predictable. Upper brachial plexus injuries occur when the shoulder is forced downward and the head pushed to the opposite side, for example, following a motorcycle crash (By permission of Mayo Foundation for Medical Education and Research, All rights reserved)

Fig. 5 Patterns of brachial plexus injury are predictable. Avulsion of the lower nerve roots with stretch and rupture of the upper nerve roots occurs, in this case during a fall from a tree, through catching a branch with the injured upper extremity causing hyperabduction and injury to the plexus (By permission of Mayo Foundation for Medical Education and Research, All rights reserved)

In younger children and infants, evaluation of single muscles is not easy and the patient often not cooperative or able to tolerate a lengthy physical examination. The muscle grading system of Gilbert and Tassin (1984) has been proposed (M0 = complete paralysis; M1 = perceptible contraction; M2 = weak movements; M3 = normal muscle); however, it is our practice to attempt to use the BMRC grading as not to confuse muscle grading systems. The posture of the child can be used to evaluate the level of injury. Paralysis of the upper roots is suggested by the upper limb being held in internal rotation and pronation, with no abduction possible. Slight flexion of the elbow may suggest involvement of C5, C6, and C7, while full extension of the elbow suggests involvement of only C5 and C6. In complete involvement of the brachial plexus, the entire upper extremity

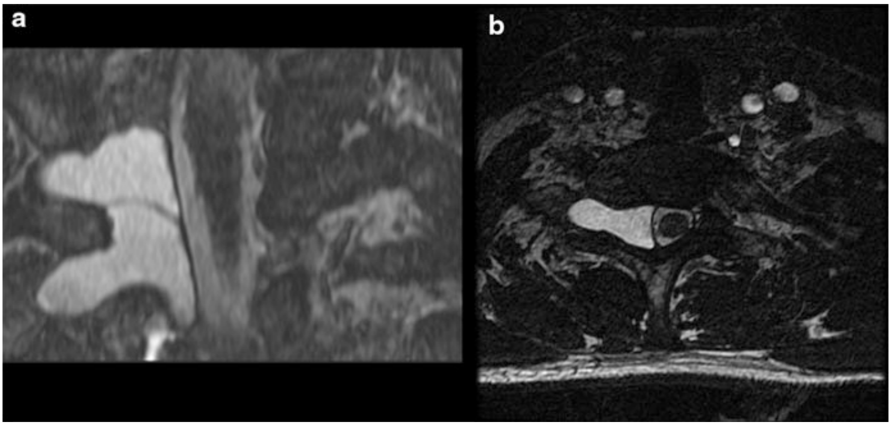


Fig. 6 CT myelogram of patient with root avulsion on right at C6 and C7 levels. (**a**) Large pseudomeningocele extending into the right neural foramen at C7-T1 level on coronal view; (**b**) the same pseudomeningocele seen on axial view (By permission of Mayo Foundation for Medical Education and Research, All rights reserved)

is flail. Horner's syndrome may also be observed in a preganglionic lesion involving the C8-T1 roots.

Assessment of sensation in younger children and infants is similarly difficult. Often, children will only respond to testing with painful stimuli. Tinel's sign may be used to assess for the level of the lesion and presence of nerve regeneration. In addition, in children, deafferentation pain is absent; hence, unlike in adults, patients with preganglionic lesions will seldom exhibit pain. Disturbances of the sympathetic system may be observed in the immediate period following injury, such as anhidrosis, cyanosis, and edema.

Imaging and Electrodiagnostic Studies

Radiographs of the cervical spine, shoulder, and chest should be obtained as part of the workup. Transverse fractures of the cervical vertebrae suggest preganglionic injuries with root avulsion. Fractures of the clavicle or ribs (first or second) may be associated with injuries to the brachial plexus. Fractures of other ribs may preclude the use of intercostal nerves as a donor nerve for nerve transfer (Kovachevich et al. 2010). An elevated hemidiaphragm suggests damage to the phrenic nerve and a possible preganglionic injury.

Computed tomography (CT) myelography is very useful in determining the presence of preganglionic injury. This is usually performed at least 3–4 weeks after the injury. This delay allows blood clot in the area of the avulsed cervical root to resorb and for a pseudomeningocele to form. CT myelography has been shown to have a diagnostic accuracy ranging from 70 % to 95 % for detection of nerve root avulsion compared to plain myelography alone (Carvalho et al. 1997; Doi et al. 2002). Presence of a pseudomeningocele is associated with preganglionic injury in 98 % of cases (Nagano et al. 1989; Fig. 6).

Magnetic resonance imaging (MRI) is also useful in evaluating patients with suspected root avulsion (Fig. 7) and allows better visualization of the entire brachial plexus. Large neuromas, abnormalities of the rootlets, inflammation and edema, as well as mass lesions can be visualized using MRI. While CT myelography should still be considered the first-line imaging modality in suspected nerve root avulsion, MRI using an overlapping coronal-oblique slice technique has been shown to be as reliable as CT myelography in detecting nerve root avulsion, with a diagnostic accuracy of 93 % (Doi et al. 2002).

Electrodiagnostic studies are pivotal in localizing and determining severity of injury in the brachial plexus. Baseline nerve conduction studies (NCS) and electromyography (EMG) should be

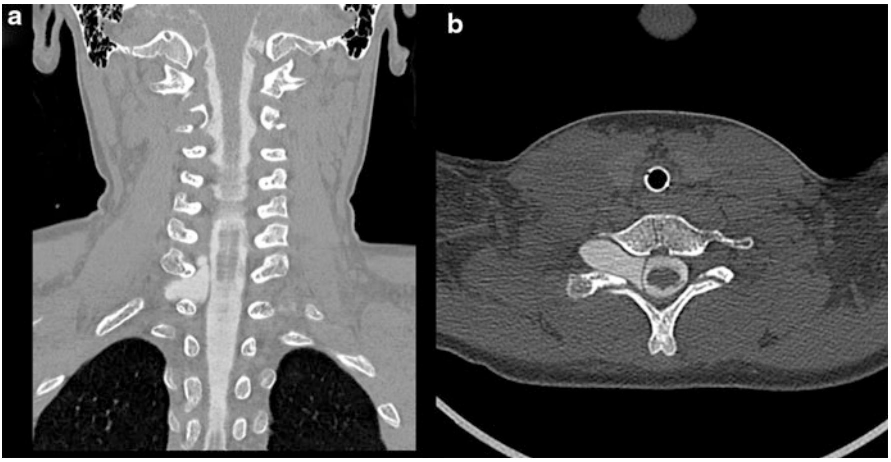


Fig. 7 MRI of patient with pseudomeningoceles at right C6, C7, and T1 levels. (**a**) Two right-sided cervical pseudomeningoceles are seen on coronal view; (**b**) axial view of one pseudomeningocele (By permission of Mayo Foundation for Medical Education and Research, All rights reserved)

performed 3–6 weeks after injury, after Wallerian degeneration has occurred. Serial follow-up studies can then be performed every 6–10 weeks to assess for recovery, complementing findings on physical examination for the purposes determining if there will be spontaneous recovery or if surgical reconstruction is necessary.

Nerve conduction studies include testing of motor and sensory nerves. Motor nerve testing is useful in detecting more distal injuries and conduction blocks in incomplete injuries. In traumatic brachial plexus injuries, amplitudes of compound muscle action potentials (CMAPs) are in general low. Sensory nerve testing is useful in determining whether a root injury is pre- or postganglionic. In a preganglionic injury, the dorsal root ganglion is spared injury even though it is detached from the spinal cord; hence, sensory nerve action potentials (SNAPs) are preserved. However, the patient is insensate in the associated sensory nerve distribution. There is excellent correlation between C6 (superficial radial nerve), C7 (median sensory to long digit), C8 (ulnar sensory nerve to small digit), and T1 (medial antebrachial cutaneous nerve) nerve root levels and individual peripheral sensory nerves in the upper extremity, aiding in localizing the level of the lesions in the brachial plexus. C5 and C6 innervate the lateral antebrachial cutaneous nerve, and this can be tested as part of sensory nerve evaluation for C5.

EMG provides the most reliable assay of motor nerve injury. Fibrillation potentials and positive sharp waves, indicative of denervation, can be seen in proximal muscles as early as 10–14 days and in distal muscles in 3–6 weeks. Motor unit analysis can determine the presence of injury in individual muscles. Polyphasic motor units occur in the presence of injury or pathology, while nascent potentials indicate axonal regeneration. Reduced recruitment of motor unit potentials can be demonstrated immediately after injury. Testing of individual muscles can help to distinguish preganglionic from postganglionic lesions. For example, denervation of the paraspinal muscles, rhomboids, and serratus anterior is a strong indicator of a preganglionic lesion as these muscles are innervated by branches from the cervical roots. Unfortunately, EMG recovery does not always equate with clinical recovery, and evidence of clinical recovery may not be detected through EMG in complete lesions, despite ongoing regeneration, when target end organs are more distal.

Intraoperative electrodiagnostic studies are useful prior to making a definitive surgical decision. These include the use of nerve action potentials (NAP), somatosensory and motor evoked potentials (SSEPs and MEPs) and CMAPs. The presence of a NAP distal to a lesion indicates preserved axons in an incomplete lesion or significant regeneration, with a correspondingly better prognosis (Kline and Happel 1993). Hence, neurolysis alone without additional treatment may be sufficient. The presence of an SSEP and MEP suggests continuity between the peripheral nervous system and the spinal cord via a dorsal root and ventral root, respectively. Hence, an SSEP and MEP is only present in postganglionic lesions. As lesions are not necessarily all or none, there may be situations where the SSEP is present and MEP absent or vice versa. In such cases, the viability of the root becomes difficult to ascertain, and correlation with EMG, clinical findings, and radiographic findings is necessary. CMAPs are useful in partial lesions where the magnitude of the lesion is proportional to the number of functioning axons.

Injuries Associated with Traumatic Brachial Plexus Injury

Brachial plexus injuries are often caused by high-energy trauma; hence, there are often substantial concomitant injuries. When a patient is evaluated in the emergency room, standard ATLS principles should be followed and the airway, breathing, and circulation stabilized prior to a search for other life- and limb-threatening injuries.

Injuries that should be evaluated include traumatic brain injuries and spinal cord injuries as well as vascular injuries, ipsilateral upper extremity musculoskeletal injuries, scapulothoracic dissociation, pneumothorax, hemothorax, and rib fractures. Treatment of these injuries takes precedence initially over the brachial plexus injury.

Classification

Brachial plexus injuries can be classified by the cervical/thoracic nerves involved, level of the injury, and severity of each nerve injury according to the Seddon (1975) and Sunderland (1978) classifications.

Determination of the cervical/thoracic nerves involved in the injury as well as level of the injury is based on clinical examination supplemented by imaging studies, as described previously. The level of the injury can be broadly divided into preganglionic root, supraclavicular plexus (roots and trunks), retroclavicular plexus (divisions), and infraclavicular plexus (cords and branches). Different authors have described various classifications for the level of injury, pursuant on their individual surgical strategies. Narakas (1981) describes dividing the level of injury into five levels (supraganglionic root, infraganglionic spinal nerve, infraganglionic trunk, and retroclavicular and terminal branches). Chuang (2010) alternatively divides brachial plexus injuries into four levels (Level 1, preganglionic root injury including spinal cord, rootlets, and root injuries; Level 2, postganglionic spinal nerve injury limiting the lesion to the interscalene space and proximal to the suprascapular nerve; Level 3, preclavicular and retroclavicular BPI including trunks and divisions; Level 4, infraclavicular BPI including cords and terminal branches proximal to the axillary fossa).

The severity of the injury to each nerve is classified according to the Seddon/Sunderland classification, with five levels of nerve injury. Seddon initially described three basic types of peripheral nerve injury, which was expanded to five types by Sunderland. In neurapraxia (first-degree injury), a focal physiologic conduction block exists at the site of nerve injury, with the endoneurium, perineurium, and epineurium remaining intact. This typically recovers spontaneously within days to weeks and does not require surgical intervention. In axonotmesis (second- to fourth-degree injury), the connective tissue framework of the nerve is preserved, but the axon is disrupted to varying extents, resulting in Wallerian degeneration distal to the site of nerve injury with a disruption of nerve conduction. In a second-degree injury, the axon is disrupted, but the endoneurium, perineurium, and epineurium are preserved. Nerve regeneration and recovery of motor and sensory function are expected but may take months to years. In third-degree injury, the axon and endoneurium are disrupted, but the perineurium and epineurium are intact. In a fourth-degree injury, the axon, endoneurium, and perineurium are disrupted, while the epineurium remains intact. In third- and fourth-degree injuries, regeneration occurs variably or may not occur at all; hence, these lesions often require surgical intervention. In neurotmesis (fifth-degree injury), the nerve is completely disrupted; hence, surgical intervention is necessary. Fifth-degree injuries include preganglionic avulsions and postganglionic ruptures of the brachial plexus.

Outcome Tools

There is no clear consensus on the best instrument to measure outcomes after brachial plexus reconstruction in either the adult or pediatric patient. The BMRC muscle strength scale is the most common tool used, on a scale from M0 to M5. However, this tool has a number of limitations including its lack of precision and inter-rater reliability as well as a wide range of strength covered by grade of M4 (MacAvoy and Green 2007; Shahgholi et al. 2012). The Disabilities of the Arm, Shoulder and Hand (DASH) score is the most validated measure of upper extremity function (Dowrick et al. 2005) and has been useful as an outcome tool following brachial plexus reconstruction; however, it is not validated for the pediatric population.

A number of outcome tools are used to assess outcomes following obstetric brachial plexus injury and reconstruction, and there may be a role to adopting them to infants or young children following traumatic brachial plexus injury. The most widely used tool is the Mallet classification (Abzug and Kozin 2010), which measures integrity of muscles innervated by the upper brachial plexus. The arm is tested in five different movements: abduction, external rotation, hand behind head, hand to back, and hand to mouth. Each movement is classified from grade 0 to V. A recent modification was proposed, the addition of a hand to belly button category, which tests the child's ability to reach to midline. Other tools used include the Toronto Test Score (Bae et al. 2003), Active Movement Scale, and Gilbert shoulder classification.

Differences Between Adult and Pediatric Injuries

In pediatric patients, surgical reconstruction options are affected by the presence of open growth plates and potential growth that may affect the long-term results of certain procedures. The most active physes in the upper extremity include the proximal humerus, which accounts for 80 % of longitudinal growth (Pritchett 1991) and the distal radius. The length of the humerus grows approximately 1.3 cm in boys and 1.2 cm in girls from age seven until skeletal maturity, while the length of the radius grows approximately 1.0 in boys and 0.9 cm in girls from age seven until skeletal maturity (Pritchett 1988). Boys usually reach skeletal maturity between 16 and 17 years old, while girls reach skeletal maturity between 14 and 15 years old.

Therefore, in the pediatric population, the use of functional free muscle transfer should be done so with care as the transferred muscle may not grow in proportion with the rest of the upper extremity and lead to joint contractures. Additionally, secondary procedures that cross joints, such as tendon transfers, tenodesis, and joint fusions, may lead to joint contractures and limitation of function of the affected limb.

Treatment Options

Surgery has been shown to be beneficial for patients in traumatic brachial plexus injuries with no hope for spontaneous recovery or in the absence of clinical or electrodiagnostic evidence of recovery. The mechanism of injury provides a vital clue to decide the possibility for spontaneous recovery. In sharp or blunt injuries causing lacerations, all patients should undergo surgical exploration as the possibility of spontaneous recovery is low. In gunshot wounds, many patients will recover spontaneously as the majority of injuries are neuropraxic and caused by the shock wave from the passage of the projectile. Hence, nonoperative management is preferred initially. In traction injuries, the indication and timing for surgery are more controversial and would depend on the type and exact mechanism of injury. Early exploration of the brachial plexus between 3 and 6 weeks should be performed if there is a high suspicion of root avulsion. In general, surgical exploration of the brachial plexus should be performed by 6 months of injury and is not performed more than 12 months after the injury as results are poor, as the time for nerve regeneration to the target muscle is greater than the time of survival of the denervated motor end plate.

Nonoperative Management

Indications/Contraindications

In patients waiting for surgery or those treated conservatively, physical therapy is essential to strengthen functioning muscles, maintain range of motion, and prevent stiffness and joint contractures. Occupational therapy may be useful in modification of the patient's workplace setting and home environment to improve the patient's functional ability and also in use of orthoses and adaptations (Booney 1998). Specific indications and contraindications for pure nonoperative management of traumatic brachial plexus injuries are listed below (Table 2). However, rehabilitation has a role to play in all surgical patients as well, both preoperatively and postoperatively.

Table 2 Traumatic brachial plexus injuries: nonoperative management

Indications	Contraindications
Mechanism of injury: gunshot wounds, certain traction injuries	Mechanism of injury: sharp lacerations, root avulsions
Patient expectations: unrealistic goals, unwillingness to undergo surgery	Patient expectations: agreeable with surgical reconstruction
Spontaneous ongoing recovery in involved elements	Lack of improvement on clinical and electrophysiologic testing

Techniques

Physical/Occupational Therapy Recommendations

The main goals in treatment of traumatic brachial plexus injury patients are prevention of secondary deformities, maintenance of passive range of motion, pain suppression, sensory rehabilitation for recovery of somatosensory deficits, treatment of developmental disregard, and postoperative care (Smania et al. 2012).

Due to the long time needed for reinnervation of muscles following BPI, muscle atrophy will lead to muscle imbalance, and subsequent secondary deformities of the upper extremity are commonplace. Hence, an important component of rehabilitation consists of the prevention of joint contractures.

Passive movements of the injured upper extremity can be combined with an orthoses, such as elbow and hand splints, to avoid joint stiffness and to maintain range of motion. Biofeedback can be used to lessen cocontraction. Botulinum toxin injections can be used for the treatment of imbalanced muscles. It is particularly important to avoid deformities such as internal rotation of the shoulder, which markedly reduces function and ability to care for one's self and may also lead to glenohumeral dysplasia.

While neuropathic pain after BPI is a major concern in adult patients, in the pediatric population, deafferentation pain is often absent, despite having a greater chance of preganglionic injury. However, if this becomes an issue in older pediatric patients, multidisciplinary management is mandatory for optimal patient care. Different modalities of treatment are used, such as pharmacotherapy, physical therapy, transcutaneous electrical nerve stimulation (TENS), and psychosocial intervention, all playing important roles in pain management.

Following a peripheral nerve injury, patients develop altered profiles of neural impulses. Hence, sensory reeducation is useful to reprogram the brain through the use of cognitive learning techniques and graded tactile stimuli to improve tactile gnosis (Jerosch-Herold 2011). Exercises including perception of different shapes and textures as well as localization of stimuli help retrain the brain to recognize sensory stimuli through cortical plasticity. Developmental disregard, or behavioral suppression of motor activity in the impaired limb, has been treated through a targeted technique, the constraint-induced movement therapy (CIMT) (Fritz et al. 2012). This aims to increase use of the impaired limb by limiting use of the non-affected upper extremity. CIMT has been proposed to work through changes in behavioral approach by the patient with subsequent cortical reorganization in the brain (Hoare et al. 2007).

Postoperative rehabilitation is key to achieving good functional results. An example is passive stretching of muscles to prevent secondary deformities such as maintaining external rotation of the shoulder to minimize glenohumeral joint deformity. Following nerve transfers, induction exercises are also used by patients (Terzis and Kostopoulos 2007) to help the donor nerve to fire and reactivate the reinnervated muscle.

Outcomes

The literature is scarce on objective outcomes of rehabilitation through physical and occupational therapy. However, it is the experience of most other brachial plexus surgeons that physical and occupational therapies, both in the preoperative and postoperative periods, are essential to optimize outcomes following surgical reconstruction of the brachial plexus.

Operative Management

Indications/Contraindications

Surgical management is indicated when spontaneous recovery is impossible, for example, in root avulsions or in the absence of clinical and electrodiagnostic evidence of recovery by 6 months after injury. There are few absolute contraindications to surgical reconstruction of the brachial plexus. These include the unwillingness of the patient to undergo the surgical procedure with subsequent prolonged rehabilitation or unrealistic goals of the patient. Other contraindications include patients who exhibit spontaneous ongoing recovery and those with life-threatening conditions precluding surgery. Patients presenting late (more than 12 months after injury) are not candidates for primary plexus reconstruction but may be candidates for free functioning muscle transfer.

Timing of Surgery

Immediate exploration and repair is performed in patients with a sharp open injury of the brachial plexus. Surgery allows direct visualization and repair of injured elements. For patients with blunt injuries to the brachial plexus without chances of recovery, surgery is performed about 3–4 weeks after the injury to allow the zone of nerve injury to delineate. In patients with a high suspicion of root avulsion, surgery can be performed even earlier.

Delayed surgery is performed in patients with a chance for spontaneous recovery. Exploration may be delayed up to 6 months after the inciting injury, particularly for patients where the mechanism of injury suggests that spontaneous recovery is possible, such as low velocity gunshot wounds or closed traction injuries. Lack of progressive recovery on clinical examination and electrophysiologic studies is an indication for surgery.

Finally, secondary reconstruction through procedures such as free functioning muscle transfer (FFMT), tendon transfers, and adjunctive procedures are performed for patients who present late (more than 12 months after injury). In these patients, primary plexus reconstruction is associated with poor results.

Primary Reconstruction

Primary reconstruction of the brachial plexus consists of a number of surgeries and may consist of direct nerve repair, neurolysis, nerve grafting, and nerve transfers with or without free functioning muscle transfer. This is performed either in an immediate or delayed fashion. The exact series of procedures performed may sometimes only be decided after adequate exploration and exposure of the brachial plexus to determine the injured elements.

Direct repair of nerve ends may be performed in an immediate fashion after sharp lacerations.

Neurolysis alone may be sufficient if the nerve is in continuity and a nerve action potential (NAP) is obtained (Kim et al. 2003). Nerve grafting is indicated with ruptures or postganglionic neuromas that do not conduct a NAP across the injured segment. Typically, sural nerve graft is harvested and used to bridge the gap as multiple cables.

Nerve transfer (neurotization) is indicated in preganglionic injury/root avulsions or to accelerate reinnervation of target muscles by shortening the distance needed for the nerve to regenerate to the motor end plate. A less important functional nerve is sacrificed and coapted to a more vital denervated distal nerve. Common nerve transfers used for shoulder abduction include spinal accessory nerve or phrenic nerve to suprascapular nerve as well as transfer of the triceps motor branch to the axillary nerve. These nerve transfers have the advantage of the donor and recipient nerves being in close proximity, therefore obviating the need for nerve grafting. Double and even triple nerve transfers have been shown to improve shoulder abduction compared to that achieved with a single nerve transfer only (Cardenas-Mejia et al. 2008).

Nerve transfer for elbow flexion can be performed using either the intercostal nerves with direct coaptation to the biceps motor branch or the spinal accessory nerve with an interpositional nerve graft (Songcharoen et al. 1996). Patients with a history of rib fractures, chest tube placement, or thoracotomy may not be appropriate candidates for intercostal nerve transfer as there is a possibility that the nerve may have been damaged during these procedures. More recently, the Oberlin transfer (Teboul et al. 2004), consisting of transfer of a fascicle from the ulnar nerve to motor branch of the biceps, has been used with excellent results. Intraoperative nerve stimulation is used to identify the fascicles that stimulate wrist flexion (flexor carpi ulnaris) and used as a donor for nerve transfer. Double nerve transfers to restore elbow flexion have been described, consisting of a fascicle from the ulnar nerve to the motor branch of the biceps and also a fascicle from the median nerve to the motor branch to the brachialis (Mackinnon et al. 2005). This has been shown to have improved outcomes (Mackinnon et al. 2005; Liverneaux et al. 2006) in some studies; however, other studies have shown similar outcomes to single nerve transfer (Carlsen et al. 2011). These common nerve transfers are further described in detail subsequently.

Other donor nerves used include the medial pectoral nerve, which can be transferred to the musculocutaneous nerve or motor branch to biceps. Contralateral C7 nerve root can also be used for restoration of shoulder or median nerve function and may be an attractive alternative for the very young pediatric traumatic brachial plexus group (age <4 years). However, outcomes are poor in adult patients with risk of donor-site morbidity, including permanent motor and sensory loss (Sammer et al. 2012).

Surgical Approaches to the Brachial Plexus for Primary Reconstruction

Except in patients where specific nerve transfers have been selected as the treatment modality, the brachial plexus should be exposed to identify the injured elements that may be amenable to primary repair, neurolysis, or nerve grafting. A supraclavicular approach allows exposure of the nerves and trunks, while an infraclavicular approach allows exposure of the cords and terminal branches. Exposure of the divisions can be exposed through either approach and may also require a clavicular osteotomy.

A transverse incision is usually used approximately 2.5 cm cephalad to the clavicle. This is a cosmetically appealing exposure that can be extended by an incision following the sternocleidomastoid and the deltopectoral interval if needed (Figs. 8 and 9). The infraclavicular incision begins at the clavicular insertion of the sternocleidomastoid muscle, continues laterally toward the coracoid process, and extends laterally to the deltopectoral groove and the arm.

Following exposure of the injured elements, intraoperative electrodiagnostic assessment is performed routinely by our group, including the use of somatosensory evoked potentials (SSEPs), motor evoked potentials (MEPs), and nerve action potentials (NAPs). SSEPs and MEPs test the integrity of the intraforaminal and intraspinal sensory and motor pathways and help test whether

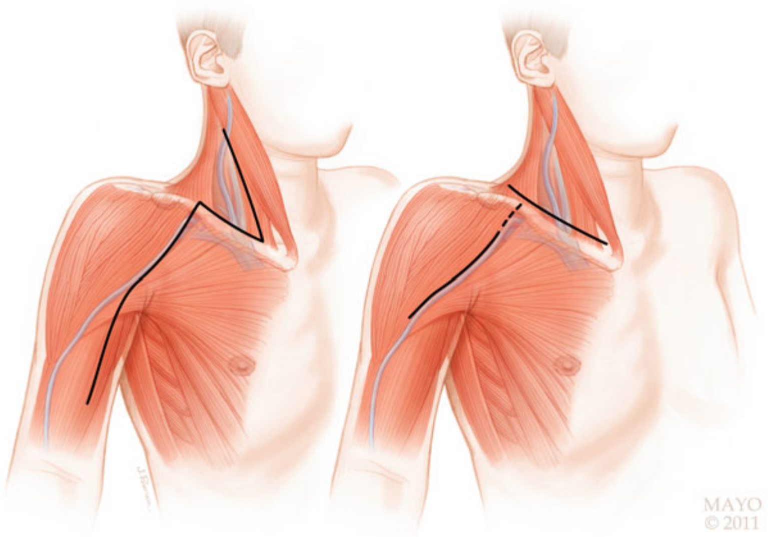


Fig. 8 The brachial plexus can be exposed through a transverse incision approximately 2.5 cm cephalad to the clavicle. This can be extended cephalically through an incision posterior to the sternocleidomastoid muscle and caudally through an incision at the deltopectoral interval, if needed (By permission of Mayo Foundation for Medical Education and Research, All rights reserved)

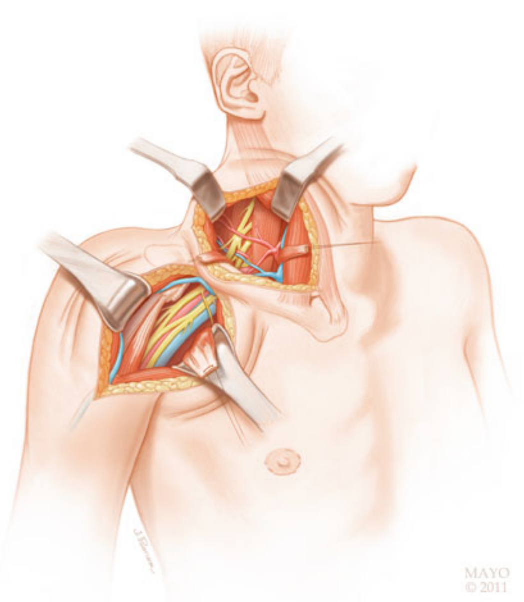


Fig. 9 The entire brachial plexus can be explored through this surgical approach (By permission of Mayo Foundation for Medical Education and Research, All rights reserved)

the spinal nerves are in continuity with the spinal cord. Hence, they are useful for testing the integrity of a proximal nerve considered for nerve grafting, as well as testing for preganglionic injury. NAPs test for the presence of functioning sensory and motor axons over a nerve segment and are useful for testing a neuroma-in-continuity to determine if the lesion has potential for spontaneous recovery (Kline and Happel 1993; Kline and Hudson 1995).

Table 3 Spinal accessory nerve (SAN) to suprascapular nerve (SSN) transfer: case checklist

OR table: normal table
Position: supine with neck turned to contralateral side; shoulder and neck elevated off table with bump
Equipment: nerve stimulator, intraoperative electrophysiologic monitoring, operating microscope
Tourniquet: sterile for lower extremity
Precautions: avoid muscle relaxants, long-acting paralytic agents, and agents depressing cortical responses (inhalational agents should not be used until neuromonitoring is completed)

Surgical Procedure: Spinal Accessory Nerve (SAN) to Suprascapular Nerve (SSN) Transfer

Preoperative Planning

Details of the surgical procedure should be discussed with anesthesia (Table 3), in particular the need for avoidance of muscle relaxants, long-acting paralytic agents, and agents depressing cortical responses. As the surgical procedure is often a long one, patients should have a urinary catheter inserted, with sequential compression devices and adequate padding of bony prominences. A sterile tourniquet may be required if sural nerve grafts need to be harvested. An underbody warming device is beneficial to keep the patient's body temperature normal. The entire upper extremity is prepared and draped to allow free movement of the entire arm; the ipsilateral neck, mandible, hemithorax, axilla, and upper extremity (with bilateral lower extremities if it is anticipated that sural nerve grafts will be needed) should be prepared and draped. A nerve stimulator and electrodes required for intraoperative electrophysiologic monitoring should be available, as well as an operating microscope.

Positioning

The patient is placed in the supine position with the neck turned to the contralateral side. The shoulder and neck are elevated off the table with a small midline bump.

Technique

See Fig. 10, Tables 4 and 5.

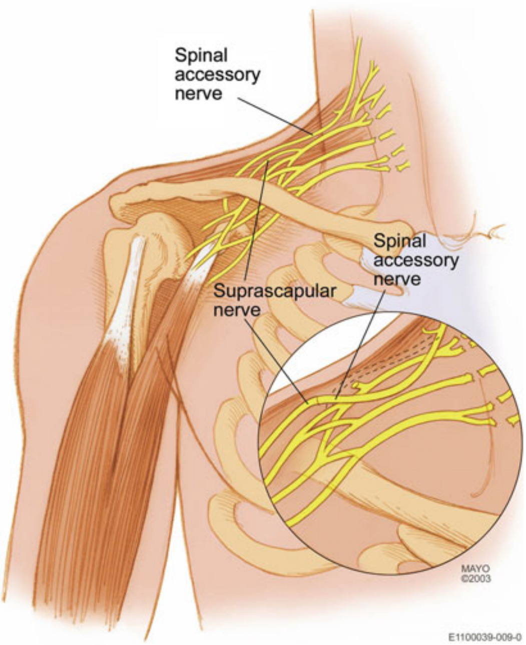


Fig. 10 Transfer of spinal accessory nerve to suprascapular nerve for restoring shoulder abduction (By permission of Mayo Foundation for Medical Education and Research, All rights reserved)

Table 4 Spinal accessory nerve (SAN) to suprascapular nerve (SSN) transfer: surgical steps

Transverse incision over distal clavicle
Identify SAN several centimeters above clavicle on anterior surface of trapezius, confirm with electrical stimulation
Dissect SAN as far distally as possible, preserve proximal branch to upper portion of trapezius
Divide SAN distally
Identify SSN at suprascapular notch, divide superior transverse ligament (optional, if area of injury is proximal to suprascapular notch)
Dissect SSN as far proximally as possible to origin from upper trunk
Divide SSN proximally
Suture SAN to SSN with 9/0 ethilon sutures, reinforce transfer with fibrin glue
Close in layers

Surgical Procedure: Transfer of Triceps Motor Branch to Axillary Nerve

Preoperative Planning

This is similar to that for SAN to SSN transfer, including the case checklist.

Positioning

The patient is placed in a supine position with the arm placed across the patient's chest and held by an assistant. A posterior approach to the arm is used.

Technique

See Fig. 11, Tables 6 and 7.

Surgical Procedure: Ulnar Nerve Fascicular Transfer to Biceps Motor Branch

Preoperative Planning

This is similar to that for SAN to SSN transfer, including the case checklist.

Positioning

The patient is placed in the supine position with the arm outstretched on an arm table. This allows access to medial aspect of the arm, where the incision is made in the groove between the biceps and triceps muscles.

Table 5 Spinal accessory nerve (SAN) to suprascapular nerve (SSN) transfer: postoperative protocol

Type of immobilization: shoulder immobilization
Length of immobilization: 3 weeks
Rehabilitation protocol: physiotherapy started 3 weeks postoperatively, targeted at maintaining passive motion of all joints. Active muscle exercises started after signs of motor reinnervation appear, focused on reeducation and strengthening of muscles (typically 8–12 months postsurgery)

Technique

See Fig. 12, Tables 8 and 9.

Surgical Procedure: Median Nerve Fascicular Transfer to Brachialis Motor Branch

Preoperative Planning

This is similar to that for SAN to SSN transfer, including the case checklist.

Positioning

The patient is placed in the supine position with the arm outstretched on an arm table. This allows access to medial aspect of the arm, where the incision is made in the groove between the biceps and triceps muscles.

Technique

See Fig. 13, Tables 10 and 11.

Figure 14 shows a double nerve transfer for restoration of elbow flexion, consisting of transfer of a fascicle from the ulnar nerve to the motor branch of the biceps and also a fascicle from the median nerve to the motor branch to the brachialis.

Surgical Procedure: Intercostal Nerve Transfer to Musculocutaneous Nerve

Preoperative Planning

This is similar to that for SAN to SSN transfer, including the case checklist.

Positioning

The patient is placed in the supine position with the arm outstretched on an arm table. This allows access to medial aspect of the arm, where the incision is made in the groove between the biceps and triceps muscles.

Technique

See Tables 12 and 13. Intercostal nerves can be transferred to the biceps branch (Fig. 15) or directly to the musculocutaneous nerve (Fig. 16).

Outcomes of Nerve Transfers

The literature supports the effectiveness of nerve transfers over nerve grafts in adults. However, little is written about the outcomes of nerve transfer in the pediatric traumatic plexus population. In a systematic review of 31 studies comparing the efficacy of nerve transfers and nerve grafting for traumatic upper plexus palsy (Garg et al. 2011), it was found that pooled international data strongly favored dual nerve transfer over traditional nerve grafting for restoration of shoulder and elbow function. The study found that, for patients who underwent nerve transfer for restoration of elbow flexion, 83 % and 96 % of 299 patients in total achieved elbow flexion strength of grade M4 or greater and M3 or greater, respectively. In contrast, for patients who underwent nerve grafts, only 56 % and 82 % of 57 patients in total achieved elbow flexion strength of grade M4 or greater and M3 or greater, respectively. Similarly, 74 % (total 54) of patients who underwent dual nerve transfers for should function had shoulder abduction strength of grade M4 or greater compared to 35 % (total 57) of patients who underwent single nerve transfer and 46 % (total 28) of patients who underwent nerve grafting.

Little and colleagues recently reported on the outcomes of elbow flexion with median and/or ulnar nerve fascicle transfer in C5-6 and C5-7 palsies in 31 patients with neonatal brachial plexus palsy (Little et al. 2014). Indications for nerve transfer included root avulsion, dissociative recovery, late presentation, and failed nerve graft reconstruction. Concomitant procedures were performed in 63 % of cases including long head

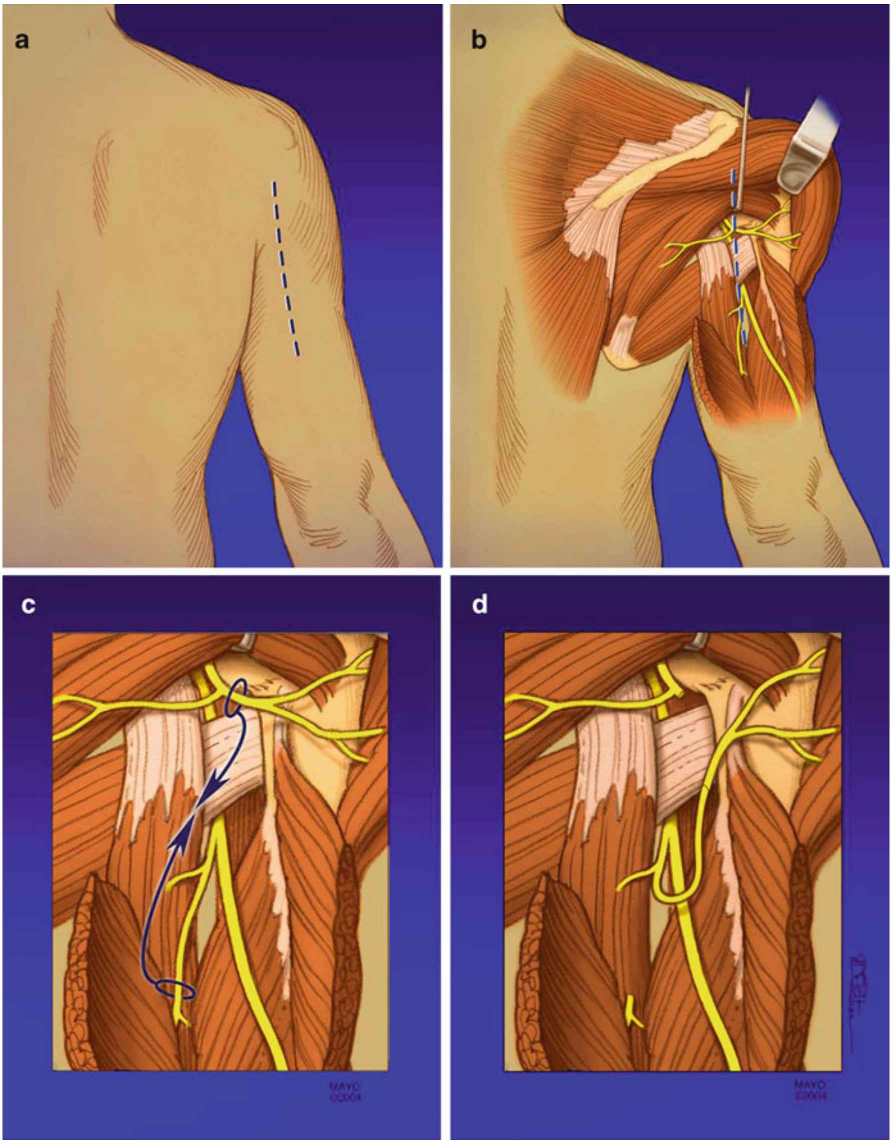


Fig. 11 Transfer of triceps branch to the axillary nerve for restoring shoulder abduction. (**a**) Longitudinal incision over posterior arm; (**b**) exposure of the nerve to triceps and axillary nerve; (**c**) triceps branch (*below*) is transferred to the axillary nerve (*above*); (**d**) completion of nerve transfer (By permission of Mayo Foundation for Medical Education and Research, All rights reserved)

of triceps to axillary nerve transfer, shoulder internal rotation contracture release, and tendon transfer for external rotation; however, the results of these procedures were not reported. The primary outcome measure was postoperative elbow flexion and supination as measured on the Active Movement Scale (AMS). Of the 31 patients, 27 (87 %) obtained functional elbow flexion (AMS $\geq$ 6), and 24 (77 %) had full flexion recovery (AMS = 7). Of the 24 patients for whom supination recovery was recorded, 5 (21 %) obtained functional recovery (AMS $\geq$ 6).

Table 6 Transfer of triceps motor branch to axillary nerve: surgical steps

Longitudinal incision on posterior arm from acromion to midarm
Retract deltoid anteriorly
Identify axillary nerve in quadrilateral space
Mobilize axillary nerve proximally – identify anterior and posterior divisions. Separate anterior division from posterior division and divide as proximal as possible (alternatively, divide entire nerve and then separate anterior division from posterior)
Open interval between long and lateral heads of triceps
Identify motor branch to long head of triceps, confirm with electrical stimulation
Mobilize and divide triceps motor branch distally
Suture triceps motor branch to anterior division axillary nerve with 9/0 ethilon sutures, reinforce transfer with fibrin glue
Close in layers

Table 7 Transfer of triceps motor branch to axillary nerve: postoperative protocol

Type of immobilization: shoulder immobilization
Length of immobilization: 3 weeks
Rehabilitation protocol: physiotherapy started 3 weeks postoperatively, targeted at maintaining passive motion of all joints. Active muscle exercises started after signs of motor reinnervation appear, focused on reeducation and strengthening of muscles

Free Functioning Muscle Transfer (FFMT)

FFMT involves the transfer of a muscle from a distant donor site to the upper extremity, with microvascular coaptation of vessels and its nerve, to replicate the function of a muscle in the affected upper extremity. The muscle most commonly used for this purpose is the gracilis muscle, which has the advantage of a long distal tendon which reaches into the forearm for hand reanimation, as well as a proximal location of its nerve, which allows more rapid reinnervation of the muscle following neurotization. The thoracoacromial artery and cephalic vein are the most common vessels used for anastomosis of the functional muscle, followed by the thoracodorsal artery and vein. FFMT was first reported for delayed reconstruction (>12 months after injury) (Ikuta et al. 1979) or as a salvage procedure after failed nerve reconstruction. However, it has been used increasingly to provide reliable elbow flexion where primary reconstruction with nerve grafts or nerve transfers is not possible.

Doi et al. (2000) described a double free functioning gracilis muscle transfer aimed at achieving prehension in patients with pan-plexal injuries. In stage I (Fig. 17), the first FFMT is neurotized by the spinal accessory nerve and used to restore elbow flexion and wrist or finger extension. In stage II (Fig. 18), performed 6–8 weeks after the initial surgery, the second FFMT is neurotized by the fifth and sixth intercostal nerves to restore finger flexion, together with the use of the third and fourth intercostal nerves to neurotize the motor branch of the triceps for elbow extension and coaptation of the intercostal sensory rami to the medial cord of the brachial plexus to restore hand sensibility.

In the pediatric population, contractures of joints have been noted following FFMT occurring secondary to decreased growth of the FFMT in comparison to the rest of the upper extremity. Therefore, FFMT should be cautiously applied. There are situations, however, where there are no other alternative, and patients and parents need to be counseled regarding its use.

Surgical Procedure: Double Free Functional Gracilis Muscle Transfer

Preoperative Planning

This is similar to that for SAN to SSN transfer, including the case checklist.

Positioning

The patient is placed in the supine position with the leg abducted for harvest of the gracilis muscle.

Technique

See Tables 14 and 15.

Outcomes

Little data exists in the literature on outcomes of FFMT in children. Zuker and Manktelow (2007)

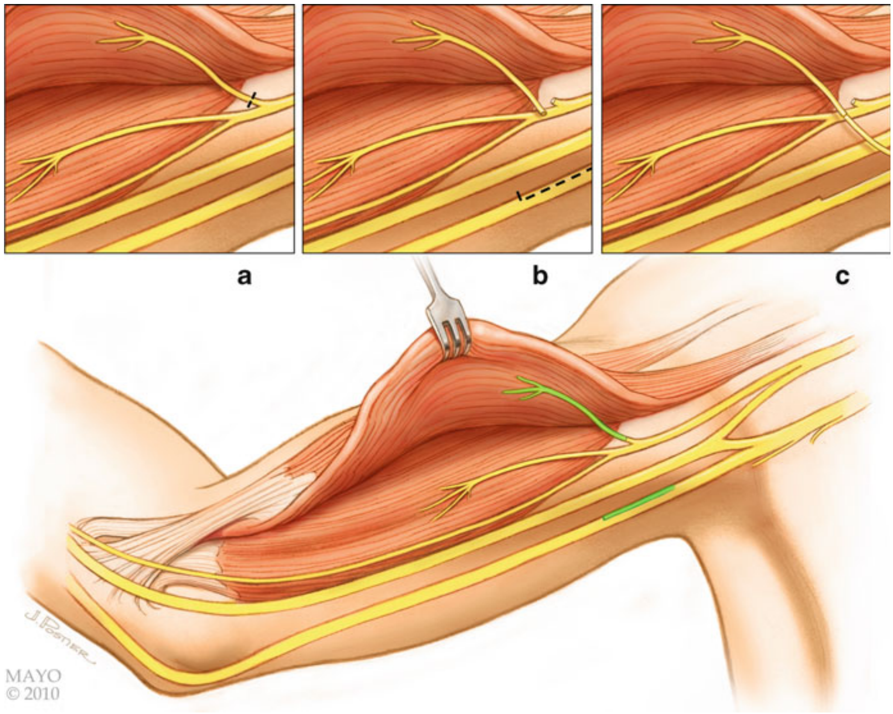


Fig. 12 Transfer of ulnar nerve fascicle to biceps motor branch (Oberlin's method) for restoring elbow flexion. (**a**) Biceps motor branch is identified and dissected from musculocutaneous nerve. (**b**) A nerve stimulator is used to select an ulnar nerve fascicle responsible for wrist flexion without affecting intrinsic hand function; this is then isolated with internal neurolysis. (**c**) The selected fascicle is divided and transferred to the biceps motor branch (By permission of Mayo Foundation for Medical Education and Research, All rights reserved)

Table 8 Ulnar nerve fascicular transfer to biceps motor branch: surgical steps

Longitudinal medial skin incision in proximal arm
Identify musculocutaneous nerve and its three branches (motor branch to the biceps, motor branch to brachialis, lateral antebrachial cutaneous nerve)
Divide motor branch of biceps as far proximal as possible
Identify ulnar nerve, perform intraepineurial dissection using loupes or operating microscope
Identify posteromedial fascicles innervating mostly flexor carpi ulnaris with aid of electrical stimulation
Divide one or two chosen fascicles under magnification
Suture ulnar nerve fascicles to biceps motor branch nerve with 9/0 ethilon sutures, reinforce transfer with fibrin glue
Close in layers

Table 9 Ulnar nerve fascicular transfer to biceps motor branch: postoperative protocol

Type of immobilization: shoulder immobilization
Length of immobilization: 3 weeks
Rehabilitation protocol: physiotherapy started 3 weeks postoperatively, targeted at maintaining passive motion of all joints. Active muscle exercises started after signs of motor reinnervation appear, focused on reeducation and strengthening of muscles

reported muscle contracture as soon as 2 months after surgery and grip strength reaching 25 % of the normal side. Another series of four patients (Bahm and Ocampo-Pavez 2008) reported FFMT for delayed treatment of obstetric brachial plexus palsy in children between 6 and 13 years of age. In this series with a 2-year follow-up, M3 grasp was achieved in three out of four children. Further studies are needed to assess long-term outcomes of FFMT in children.

Secondary Reconstruction

Procedures such as tendon transfers, shoulder arthrodesis, and wrist and hand arthrodesis can improve function in the upper extremity or are considered when there is no further recovery.

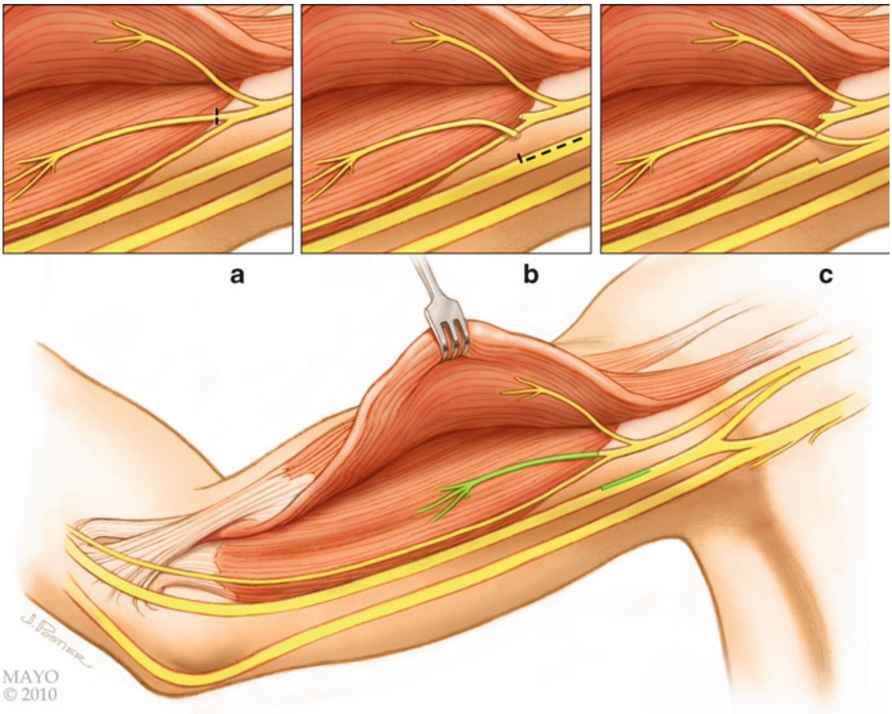


Fig. 13 Transfer of median nerve fascicle to brachialis motor branch for restoring elbow flexion. (**a**) Brachialis motor branch is identified and dissected from the musculocutaneous nerve. (**b**) A nerve stimulator is used to select a median nerve fascicle responsible for wrist flexion without affecting intrinsic hand function; this is then isolated with internal neurolysis. (**c**) The selected fascicle is divided and transferred to the brachialis motor branch (By permission of Mayo Foundation for Medical Education and Research, All rights reserved)

Table 10 Median nerve fascicular transfer to brachialis motor branch: surgical steps

Longitudinal medial skin incision in proximal arm
Identify musculocutaneous nerve and its three branches (motor branch to the biceps, motor branch to brachialis, lateral antebrachial cutaneous nerve)
Divide nerve to brachialis proximally (may require careful dissection of brachialis branch of lateral antebrachial cutaneous nerve)
Identify median nerve near brachial artery and vein, perform intraepineurial dissection using loupes or operating microscope
Identify fascicle innervating flexor carpi radialis with aid of electrical stimulation
Divide chosen fascicle under magnification
Suture median nerve fascicle to brachialis motor branch nerve with 9/0 ethilon sutures, reinforce transfer with fibrin glue
Close in layers

Table 11 Median nerve fascicular transfer to brachialis motor branch: postoperative protocol

Type of immobilization: shoulder immobilization
Length of immobilization: 3 weeks
Rehabilitation protocol: physiotherapy started 3 weeks postoperatively, targeted at maintaining passive motion of all joints. Active muscle exercises started after signs of motor reinnervation appear, focused on reeducation and strengthening of muscles

Preferred Treatment

General Philosophy

We divide our approach to children with traumatic brachial plexus injuries into three groups based on age. In very young children (<4 years of age),

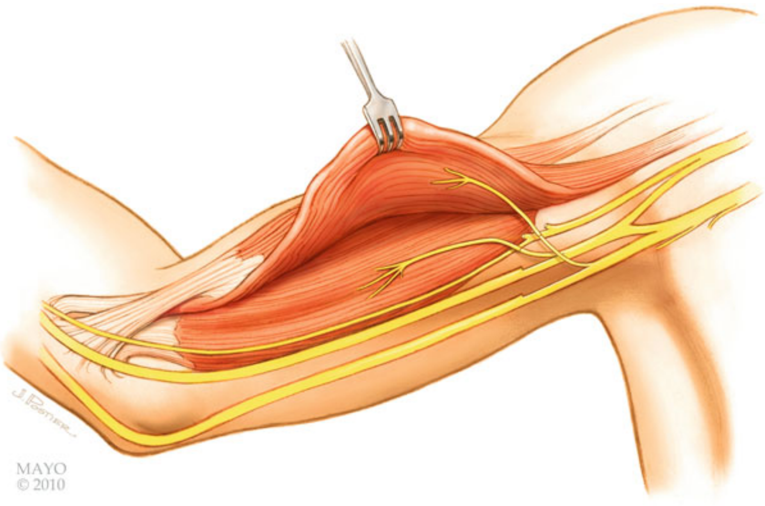


Fig. 14 Ulnar nerve fascicular transfer to the biceps motor branch and median nerve fascicular transfer to the brachialis motor branch are often performed together (By permission of Mayo Foundation for Medical Education and Research, All rights reserved)

Table 12 Intercostal nerve transfer to musculocutaneous nerve: surgical steps

Inframammary incision extending from midaxillary line to costochondral junction for exposure of 3rd to 6th intercostal nerves
Elevate subcutaneous tissue and pectoralis major and minor muscles, protect intercostobrachial nerve
Anterior surface of rib incised, periosteum circumferentially elevated while protecting underlying pleura
Elevate rib with umbilical tape to allow dissection of intercostal nerve
Periosteal sleeve of rib in midclavicular line incised, intercostal nerve (motor branch) identified with aid of nerve stimulator and dissected
Intercostal nerve dissected to costochondral junction anteriorly and midaxillary or posterior axillary line posteriorly
Procedure repeated for other intercostal nerves
Each intercostal nerve transected distally and passed through serratus anterior muscle to axillary region
Longitudinal medial skin incision in proximal arm
Identify musculocutaneous nerve and its three branches (motor branch to the biceps, motor branch to brachialis, lateral antebrachial cutaneous nerve)
Divide motor branch of biceps as far proximal as possible if planning transfer to biceps branch. This is performed if the biceps branch has sufficient length for direct transfer; otherwise, intercostal nerve transfer to the musculocutaneous nerve directly is chosen
Suture intercostal nerves to biceps motor branch or directly to musculocutaneous nerve with 9/0 ethilon sutures, reinforce transfer with fibrin glue. Neurorrhaphy should be done with arm externally to 90° or to the patient's own limit of passive external rotation if less than 90° and abducted 90° to reduce tension on the repair
All wounds closed in layers

management is focused on restoring and maximizing hand function, similar to patients with obstetric brachial plexus injuries. Subsequent priorities include restoration of elbow and shoulder function. The brachial plexus is explored and nerve grafts performed from viable roots first, with nerve transfers if required. In pan-plexus injuries, the priority is to restore hand function through reinnervation of the medial cord through nerve grafts if this is possible. In preganglionic injuries, the only option may be nerve transfers.

In children greater than 12 years of age, management strategy is similar to adult patients. For these patients, the priorities for restoring function, in order of importance, are elbow flexion, shoulder abduction and/or stability, hand sensation, wrist extension and finger flexion, wrist flexion and finger extension, and lastly, intrinsic hand

Table 13 Intercostal nerve transfer to musculocutaneous nerve: postoperative protocol

Type of immobilization: shoulder immobilization
Length of immobilization: 3 weeks
Rehabilitation protocol: physiotherapy started 3 weeks postoperatively, targeted at maintaining passive motion of all joints. Active muscle exercises started after signs of motor reinnervation appear, focused on reeducation and strengthening of muscles. There will be a lifelong limitation of abduction and external rotation to prevent avulsing the intercostal nerve to biceps motor branch (or musculocutaneous nerve), typically to 90° external rotation and 90° abduction

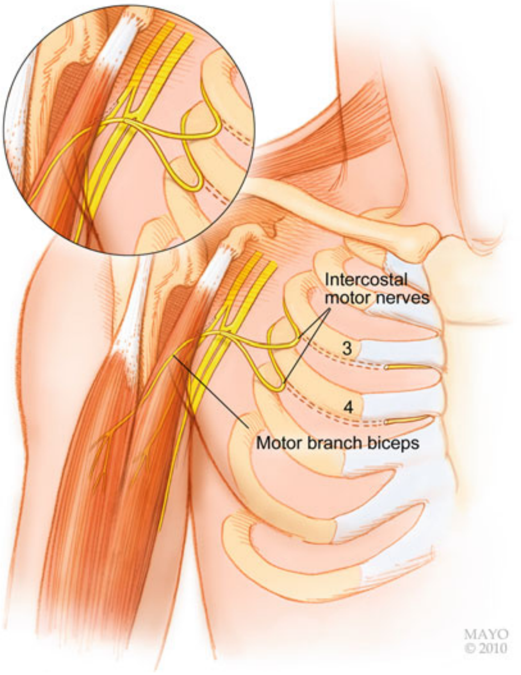


Fig. 15 Intercostal nerve transfer to the biceps motor branch for restoring elbow flexion (By permission of Mayo Foundation for Medical Education and Research, All rights reserved)

function (which is often impossible to obtain). This approach relies on maximizing function while prioritizing movements that have the least distance for nerves to regenerate to target muscles.

For children in between 4 and 12 years of age, treatment is controversial due to a paucity of literature. Nerve transfers have been used predominantly to restore elbow flexion and shoulder abduction due to the high incidence of root avulsions (Gilbert et al. 2006; Goubier et al. 2008; Miller et al. 2013). Donor nerves that do not work well in adults, for example, contralateral C7, may result in better outcomes in the pediatric age group due to their enhanced regenerative capacity. In general, because of continued growth during childhood, we try to avoid secondary reconstructive procedures such as free functioning muscle transfer, tenodesis, and joint fusion, which may interfere with skeletal growth. FFMT may result in contractures due to differential growth between the functioning muscle and the child.

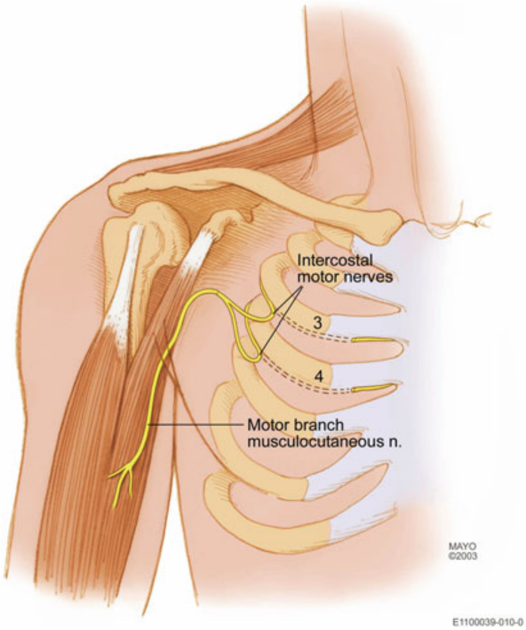


Fig. 16 Intercostal nerve transfer to the musculocutaneous nerve for restoring elbow flexion (By permission of Mayo Foundation for Medical Education and Research, All rights reserved)

Upper Trunk (C5-6 Injury) in Pediatric Patients >4 Years

In these patients, we would explore the brachial plexus. In the presence of a functional C5 nerve stump, nerve grafts to the posterior division of the upper trunk and suprascapular nerve serve to reinnervate the shoulder. In patients presenting

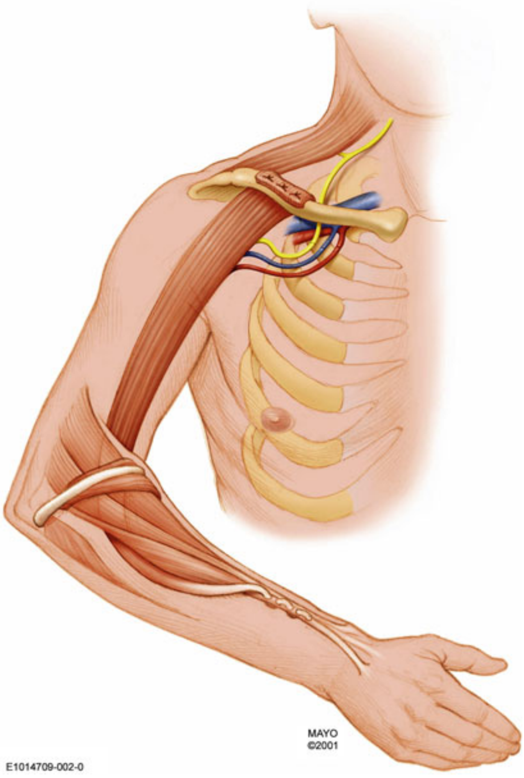


Fig. 17 Stage I of the double free gracilis muscle transfer, neurotized by the spinal accessory nerve, aims to restore elbow flexion and wrist or finger extension (By permission of Mayo Foundation for Medical Education and Research, All rights reserved)

later (more than 6–9 months after injury) or without a functional C5 nerve stump, our preference is to perform double nerve transfer (SAN to SSN and nerve to triceps to axillary nerve) for shoulder function. For recovery of elbow function, we would perform either a single or double nerve transfers (ulnar nerve fascicle to biceps motor branch and median nerve fascicle to brachialis motor branch).

Pan-Plexus Injury in Pediatric Patients >4 Years

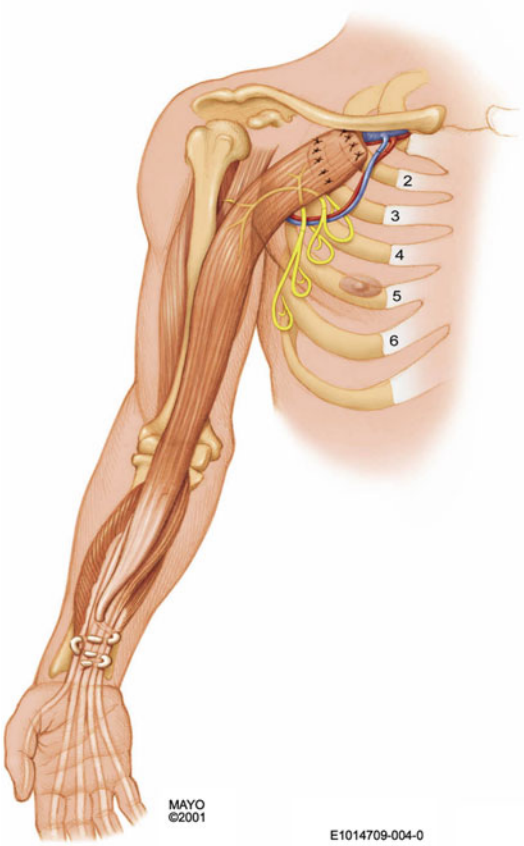


Fig. 18 Stage II of the double free gracilis muscle transfer. The 3rd and 4th intercostal nerves are used to neurotize the motor branch of the triceps muscle to restore elbow extension, while the 5th and 6th intercostal nerves are used to neurotize the gracilis to restore finger flexion (By permission of Mayo Foundation for Medical Education and Research, All rights reserved)

In these patients, priority rests in restoring elbow flexion, then shoulder abduction. If exploration of the supraclavicular plexus reveals functional nerve stumps, nerve grafts are used to reinnervate the axillary and suprascapular nerves for shoulder function. If additional roots are available, nerve grafts are used to target elbow flexion (via the anterior division of the upper trunk). Use of contralateral C7 may be an alternative to younger patients and should be avoided in the older age children. Spinal accessory and intercostal nerves should also be considered in restoring shoulder function and elbow flexion. In older children nearing skeletal maturity, FFMT neurotized by the intercostal nerves is an option to restore elbow flexion or can be used as part of a double transfer (Doi) to obtain elbow flexion and finger flexion.

Table 14 Functional free muscle transfer: surgical steps

Longitudinal incision over pes anserine
Distal gracilis tendon identified and isolated
Distal medial thigh incision made to identify myotendinous junction of gracilis
Anterior limb of elliptical incision around proximal skin paddle made, fascia over adductor longus incised
Pedicle and obturator nerve identified in interval between adductor longus and gracilis
Posterior limb of elliptical incision made, fascia over adductor magnus incised
Resting tension of muscle marked with sutures at 5 cm intervals
Distal tendon divided and passed to proximal wound
Proximal tendon released from pubic ramus
Vascular pedicle and nerve ligated and divided
Flap transferred to upper extremity, proximal tendon secured to acromion/clavicle
Vascular anastomoses performed, typically to thoracoacromial artery and cephalic vein
Suture of obturator nerve to donor nerve
Suture of distal tendon of functional muscle to target muscle in proper tension
Close in layers

Table 15 Functional free muscle transfer: postoperative protocol

Type of immobilization: shoulder immobilization in 30° of abduction and flexion and 60° of internal rotation with elbow in 100° of flexion, wrist in neutral position, and fingers in forced flexion or extension, depending on reconstruction
Length of immobilization: 4 weeks
Rehabilitation protocol: low-intensity electrical stimulation starting 3rd postoperative week and continuing until EMG-confirmed reinnervation noted in muscles, then EMG biofeedback techniques to train muscles to move elbow and fingers

Surgical Pitfalls and Prevention

Surgical pitfalls include those associated with substantial surgery. Each portion of the brachial plexus reconstruction is complex and requires attention to detail. The detailing of all the pitfalls and prevention is beyond the scope of this chapter, as each type of surgery has its own set of intraoperative and postoperative complications.

Summary

Pediatric patients with traumatic brachial plexus injuries are a rare patient population. Unique treatment is required, customized to the patient's age and growth stage, as well as to the type of injury. In general, for patients less than 4 years of age, the aim is to maximize hand function. For those between 4 and 12 years of age, the literature at the moment does not provide enough information to dictate the best modality or course of treatment. For patients older than 12 years, treatment follows that for the adult population.

Some nerve transfers inappropriate in adults may be appropriate for children, for example, use of contralateral C7 as a donor nerve, due to the greater regenerative capacity of children. There is a considerable need to obtain more outcome data to determine the optimal treatment regime for children. However, even with existing data from the adult population on brachial plexus reconstruction, selection of optimal treatment for pediatric patients remains highly controversial.

References

Abzug JM, Kozin SH. Current concepts: neonatal brachial plexus palsy. Orthopedics. 2010;33:430–5.

Bae DS, Waters PM, Zurakowski D. Reliability of three classification systems measuring active motion in brachial plexus birth palsy. J Bone Joint Surg Am. 2003;85A:1733–8.

Bahm J, Ocampo-Pavez C. Free functional gracilis muscle transfer in children with severe sequelae from obstetric brachial plexus palsy. J Brachial Plex Peripher Nerve Inj. 2008;3:23.

Boome R. Traumatic brachial plexus surgery in children. In: Gupta A, Kay SPJ, Scheker LR, editors. The growing hand: diagnosis management of the upper extremity in children. London: Mosby; 2000. p. 653–7.

Booney G. Iatropathic. In: Birch R, Bonney G, Wynn Parry C, editors. Surgical disorders of the peripheral nerves. London: Churchill Livingstone; 1998. p. 293–333.

Cardenas-Mejia A, O'Boyle CP, Chen KT, Chuang DC. Evaluation of single, double and triple nerve transfers for shoulder abduction in 90 patients with supraclavicular brachial plexus injury. Plast Reconstr Surg. 2008;122:1470–8.

Carlsen BT, Kircher MF, Spinner RJ, Bishop AT, Shin AY. Comparison of single versus double nerve transfers for elbow flexion after brachial plexus injury. Plast Reconstr Surg. 2011;127:269–76.

Carvalho GA, Nikkhah G, Matthies C, et al. Diagnosis of root avulsions in traumatic brachial plexus injuries: value of computerized tomography myelography and magnetic resonance imaging. J Neurosurg. 1997;86:69–76.

Chuang DCC. Brachial plexus injury: nerve reconstruction and functioning muscle transplantation. Semin Plast Surg. 2010;24:55–66.

Doi K, Muramatsu K, Hattori Y, et al. Restoration of prehension with the double free muscle technique following complete avulsion of the brachial plexus: indications and long-term results. J Bone Joint Surg Am. 2000;82:652–66.

Doi K, Otsuka K, Okamoto Y, et al. Cervical nerve root avulsion in brachial plexus injuries: magnetic resonance imaging classification and comparison with myelography and computerized tomography myelography. J Neurosurg. 2002;96(3 Suppl):277–84.

Dorsi MJ, Hsu W, Belzberg AJ. Epidemiology of brachial plexus injury in the pediatric multitrauma population in the United States. J Neurosurg Pediatr. 2010;5:573–7.

Dumontier C, Gilbert A. Traumatic brachial plexus palsy in children. Ann Chir Main Memb Super. 1990;9:351–7.

Dowrick AS, Gabbe BJ, Williamson OD, Cameron PA. Outcome instruments for the assessment of the upper extremity following trauma: a review. Injury. 2005;36:468–76.

El-Gammal TA, El-Sayed A, Kotb MM. Surgical treatment of brachial plexus traction injuries in children, excluding obstetric palsy. Microsurgery. 2003;23:14–7.

Fritz SL, Butts RJ, Wolf SL. Constraint-induced movement therapy: from history to plasticity. Expert Rev Neurother. 2012;12:191–8.

Garg R, Merrell GA, Hillstrom HJ, Wolfe SW. Comparison of nerve transfers and nerve grafting for traumatic upper plexus palsy: a systematic review and analysis. J Bone Joint Surg Am. 2011;93:819–29.

Gilbert A, Tassin JL. Réparation chirurgicale du plexus brachial dans la paralysie obstétricale. Chirurgie. 1984;110:70–5.

Gilbert A, Pivato G, Kheiralla T. Long-term results of primary repair of brachial plexus lesions in children. Microsurgery. 2006;26:334–42.

Goubier JN, Teboul F, Papadogeorgou E. Nerve transfers in children with traumatic partial brachial plexus injuries. Microsurgery. 2008;28:117–20.

Hoare B, Imms C, Carey I, Wasiak J. Constraint-induced movement therapy in the treatment of the upper limb in children with hemiplegic cerebral palsy: a Cochrane systematic review. Clin Rehabil. 2007;21:675–85.

Ikuta Y, Yoshioka K, Tsuge K. Free muscle graft as applied to brachial plexus injury- case report and experimental study. Ann Acad Med Singapore. 1979;8:454–8.

Jerosch-Herold C. Sensory relearning in peripheral nerve disorders of the hand: a web-based survey and Delphi consensus method. J Hand Ther. 2011;24:292–8.

Kerr AT. The brachial plexus of nerves in man, the variations in its formation and branches. Am J Anat. 1918;23:285–395.

Kim DH, Cho YJ, Tiel RL, Kline DG. Outcomes of surgery in 1019 brachial plexus lesions treated at Louisiana State University Health Sciences Center. J Neurosurg. 2003;98:1005–16.

Kline DG, Happel LT. Penfield lecture: a quarter century's experience with intraoperative nerve action potential recording. Can J Neurol Sci. 1993;20:3–10.

Kline DG, Hudson AR. Nerve injuries. Operative results for major nerve injuries, entrapments and tumors. Philadelphia: WB Saunders; 1995.

Kovachevich R, Kircher MF, Wood CM, et al. Complications of intercostal nerve transfer for brachial plexus reconstruction. J Hand Surg Am. 2010;35:1995–2000.

Little KJ, Zlotolow DA, Soldado F, Cornwall R, Kozin SH. Early functional recovery of elbow flexion and supination following median and/or ulnar nerve fascicle transfer in upper neonatal brachial plexus palsy. J Bone Joint Surg Am. 2014;96:215–21.

Liverneaux PA, Diaz LC, Beaulieu JY, et al. Preliminary results of double nerve transfer to restore elbow flexion in upper type brachial plexus palsies. Plast Reconstr Surg. 2006;117:915–9.

MacAvoy MC, Green DP. Critical reappraisal of medical research council muscle testing for elbow flexion. J Hand Surg Am. 2007;32:149–53.

Mackinnon SE, Novak CB, Myckatyn TM, Tung TH. Results of reinnervation of the biceps and brachialis muscle with a double fascicular transfer for elbow flexion. J Hand Surg Am. 2005;30:978–85.

Mendel JR, Florence J. Manual muscle testing. Muscle Nerve. 1990;13:S16–20.

Miller JH, Garber ST, McCormick DE, et al. Oberlin transfer and partial radial to axillary nerve neurotization to repair an explosive traumatic injury to the brachial plexus in a child: case report. Childs Nerv Syst. 2013;29(11):2105–9. doi: 10.1007/s00381-013-2131-7.

Nagano A, Ochiai N, Sugioka H, et al. Usefulness of myelography in brachial plexus injuries. J Hand Surg Br. 1989;14:59–64.

Narakas A. Brachial plexus surgery. Ortho Clin North Am. 1981;12:303–23.

Narakas AO. The treatment of brachial plexus injuries. Int Orthop. 1985;9:29–36.

Pritchett JW. Growth and predictions of growth in the upper extremity. J Bone Joint Surg Am. 1988;70:520–5.

Pritchett JW. Growth plate activity in the upper extremity. Clin Orthop Relat Res. 1991;268:235–42.

Sammer DM, Kircher MF, Bishop AT, Spinner RJ, Shin AY. Hemi-contralateral C7 transfer in traumatic brachial plexus injuries: outcomes and complications. J Bone Joint Surg Am. 2012;94:131–7.

Shin AY, Spinner RJ, Steinmann SP, Bishop AT. Adult traumatic brachial plexus injuries. J Am Acad Orthop Surg. 2005;13:382–96.

Seddon H. Surgical disorders of the peripheral nerves. 2nd ed. New York: Churchill Livingstone; 1975.

Shahgholi L, Bengtson KA, Bishop AT, Shin AY, Spinner RJ, Basford JR, Kaufman KR. A comparison of manual and quantitative elbow strength testing. Am J Phys Med Rehabil. 2012;91:856–62.

Smania N, Berto G, La Marchia E, et al. Rehabilitation of brachial plexus injuries in adults and children. Eur J Phys Rehabil Med. 2012;48:483–506.

Songcharoen P, Mahaisavariya B, Chotigavanich C. Spinal accessory neurotization for restoration of elbow function in avulsion injuries of the brachial plexus. J Hand Surg Am. 1996;21:387–90.

Sunderland S. Nerves and nerve injuries. 2nd ed. New York: Churchill Livingstone; 1978.

Teboul F, Kakkar R, Ameur N, Beualieu JY, Oberlin C. Transfer of fascicles from the ulnar nerve to the nerve to the biceps in the treatment of upper brachial plexus injury. J Bone Joint Surg Am. 2004;86:1485–90.

Terzis JK, Kostopoulos VK. The surgical treatment of brachial plexus injuries in adults. Plast Reconstr Surg. 2007;119:73e–92.

Terzis JK, Kokkalis ZT. Outcomes of hand reconstruction in obstetric brachial plexus palsy. Plast Reconstr Surg. 2008;122:516–26.

Waters PM. Comparison of the natural history, the outcome of microsurgical repair, and the outcome of operative reconstruction in brachial plexus birth palsy. J Bone Joint Surg Am. 1999;81.

Zuker RM, Manktelow RT. Functioning free muscle transfers. Hand Clin. 2007;23:57–72.