The Surgical Treatment of Brachial Plexus Injuries in Adults

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Learning Objectives: After studying this article, the participant should be able to: 1. Describe the mechanisms and pathophysiology of posttraumatic brachial plexus palsies in the adult population. 2. Evaluate clinically a patient with posttraumatic brachial plexus palsy and incorporate in the diagnosis results from electrophysiologic and radiologic studies. 3. Formulate a preoperative treatment plan, describe various reconstructive strategies, and identify the usual postoperative follow-up of the patient. 4. Anticipate the possible functional outcome of brachial plexus reconstruction and identify the factors affecting the outcome.

Posttraumatic brachial plexus palsy is a severe injury primarily affecting young individuals at the prime of their life. The devastating neurological dysfunction inflicted in those patients is usually lifelong and creates significant socioeconomic issues. During the past 30 years, the surgical repair of these injuries has become increasingly feasible. At many centers around the world, leading surgeons have introduced new microsurgical techniques and reported a variety of different philosophies for the reconstruction of the plexus. Microneurolysis, nerve grafting, recruitment of intraplexus and extraplexus donors, and local and free-muscle transfers are used to achieve optimal outcomes. However, there is yet no consensus on the priorities and final goals of reconstruction among the various centers. (Plast. Reconstr. Surg. 106: 1097, 2000.)

HISTORY

Injuries to the brachial plexus with subsequent paralysis of the upper extremity are as old as warfare. Homer, in his Iliad, and Thucydides, in his History of the Peloponnesian War, eloquently described the devastating nature of direct or indirect injury to the upper extremity, with injured chariot drivers constituting the patient population at that time. War, unfortunately, and other events resulting in injuries have stimulated the studying of this clinical entity, even in the modern era.

Anatomic findings of avulsed nerves from the spinal cord were described by Flaubert in 1827,1 and Thorburn in 19002 reported his intraoperative findings and direct repair of the brachial plexus elements in a woman traumatized in an industrial accident. The early operative reports by many authors, such as Clark et al.3 and Taylor,3,4 as was the case with obstetric paralysis, were succeeded by a period of pessimism, mainly as a result of the unfavorable results and the high morbidity and mortality rates encountered.

Advances in surgical and anesthetic techniques during the second half of the century plus a large number of injured soldiers during WWII permitted pioneer surgeons with a great interest in the surgical treatment of these injuries to revisit an old problem. In 1947, Seddon5 published his proposed method of surgical correction of traction injuries with application of long interposition nerve grafting. Despite the poor outcomes reported by this author,6 the introduction of magnification in the treatment of these lesions, and the persistence of other surgeons, such as Millesi in Austria and Narakas in Switzerland, stimulated many around the world. Moreover, the introduction and refinement of new diagnostic modalities such as electromyography, the lamina test, and CT/myelography also helped to promote the surgical treatment of brachial plexus.

EPIDEMIOLOGY

The demographics of brachial plexus palsies have been studied by different authors. In most
studies, including our own patient population, high-velocity motor vehicle accidents account for the majority of the cases (59 percent); most studies report that motorcycle accidents are responsible approximately twice as often as automobile accidents. In other studies, this number has been reported as high as 84 percent. It is interesting, however, to note that the overall incidence of brachial plexus injuries in multi-trauma patients secondary to motor vehicle accidents ranges from 0.67 to 1.3 percent. This number increases to 4.2 percent for victims of motorcycle accidents. This difference can easily be explained by the increased forces applied to the brachial plexus of the unprotected body during a motorcycle accident: the most common type of injury found in this patient population is traction injury, which results in a greater incidence of avulsions as compared with the crush injuries encountered more often in car accidents. Other common causes include (in different percentages according to different studies) industrial accidents, pedestrian vehicle accidents, snowmobile accidents, gunshot wounds, and other penetrating injuries. Other causes of brachial plexus injuries in adults include stretch from falling from a roof or tree, skiing accidents, or iatrogenic insult. Multiple case reports of brachial plexopathy have been published, and a variety of causes have been encountered. Direct compression of the plexus from a hematoma with or without associated bone or vascular injury can induce paralysis of the upper extremity, which if mistreated can lead to permanent deficit. Tumors of the brachial plexus with different pathologic features, such as schwannomas, neurilemmomas, myxomatous cysts, have been reported; they can begin with temporary tingling, which is enhanced by tapping of a sometimes palpable mass, and escalate to true muscle paralysis. Isolated clavicular fractures, if left untreated, can occasionally be responsible for brachial plexus injuries. The symptoms can be delayed and could be caused by direct compression from the formation of callus or bony spur, nonunion, or a subclavian pseudoaneurysm. The brachial plexus, mainly because of lack of mobility, can be vulnerable during anesthesia and surgical procedures such as mastectomies, axillary dissections, and breast augmentations through an axillary approach. Because it is firmly attached to the vertebrae and the prevertebral fascia, the brachial plexus can be stretched inadvertently with retractors or injured directly during percutaneous cannulations. An anesthetized patient is unable to respond to pain, numbness, or weakness, so malposition of a patient with an overstretched neck can cause traction to the plexus, which could be a reason for malpractice claims.

Young men are most commonly affected. In our population of 312 patients with posttraumatic brachial plexus injuries, 88 percent were male and 12 percent female. The age at injury ranged from 4 to 63 years. Both sides were affected equally. These statistics are in accordance with other studies.

MECHANISMS OF INJURY

On the basis of all the above-mentioned causes of injury, three major mechanisms are implicated:

1. Crush type of injury, caused by direct blunt trauma to the neck and upper extremity, with or without associated injuries. The plexus is crushed between the clavicle and the first rib.
2. Traction of the plexus. This is usually combined with flexion of the neck toward the contralateral side and/or hyperextension of the arm. Caudal traction of the arm will usually affect the upper roots and trunks. Cephalad traction will most likely involve the lower plexus.
3. Compression of the plexus from hematomas or adjacent tissue elements that have been injured.

All the above proposed mechanisms can coexist, which usually results in a less-favorable prognosis. In addition to the position of the arm in relation to the neck and the trunk, the velocity and magnitude of force applied to the roots and trunks are of greater importance. In most cases, these factors determine the severity of the injury and affect the overall prognosis.

ASSOCIATED INJURIES

Associated injuries are quite common in this patient population. Because motor vehicle accidents account for most brachial plexus injuries, it is logical to expect multiple organ injuries. In most reports, closed head injuries lead a long list of associated trauma. Injury to the chest (hemopneumothorax or broken ribs) is also very common. Vascular injuries to the subclavian or neck vessels, dislocations of the shoulder, and fractures of the clavicle, scapula,
and long bones are equally frequent. Injuries to the subclavian artery usually involve the proximal or distal third. It should be mentioned that this is often a delayed diagnosis because of the excellent collateral circulation around the shoulder. Abdominal visceral injuries are the most common cause of emergency surgical explorations, followed by decompression of intracranial hematomas.8

PRESENTATION AND DIAGNOSIS

The patient with posttraumatic brachial plexus palsy usually presents in the emergency room with multiple trauma. Potentially life-threatening associated injuries are obviously of prime importance and are treated first. The usual scenario involves a patient being sedated for a few days then medically stabilized. After the patient is weaned of sedation, the paralyzed arm is noticed, and the first evaluation is usually done by a physician not experienced with this type of injury. Because the long-term consequences of such injuries could have deleterious effects on the patient’s lifestyle, evaluation by an expert is necessary so that a management strategy can be established early.

History

The formulation of a diagnosis, treatment plan, and prognosis can be largely accomplished by means of a careful and detailed history and physical examination. Recording data as accurately as possible from the first visit is very important. The mechanism of injury has to be documented. Because most patients are young adults who are involved in motor vehicle accidents, questions pertaining to wearing a helmet or a seat belt or documented positive loss of consciousness could be helpful. Lower velocity injuries, such as falling from a tree or a roof, result in injury usually but not necessarily of a lesser magnitude. If the injury is sustained during an industrial accident, the patient has to be explicit about the circumstances surrounding the injury, describing, for instance, how the upper extremity was caught and pulled by the rotor of a machine or how a heavy object landed on the unprotected shoulder. In many industrial accidents, injuries are caused by peers attempting to free the patient by pulling on the trapped upper extremity. As was mentioned above, documentation of the circumstances of the injury is very important and should be accompanied by other demographic data, such as the patient’s preexisting neurologic status or his or her occupation and handedness. Most patients experience maximum loss of function at the time of injury; therefore, they should be asked about recovery of function during the period between injury and evaluation. When a Horner syndrome is observed, it is important to inquire about prior abnormalities of the pupils or eyelids. Inquiry about the onset, nature, and localization of pain and the use and effectiveness of various analgesics should be made. Lastly, the overall effect of the injury on the patient’s life and his or her expectations regarding surgical treatment should be discussed.

Physical Examination

As with any other disease, the physical examination should be as thorough as possible. In most centers, the results of the clinical examination are reported in preprinted brachial plexus diagrams that include all muscle groups of the upper extremity, sensory mapping, and pain threshold. The patient should be comfortable and undressed from the waist up. While the patient is undressing, it should be observed whether the patient functions independently and how he or she has adapted to the loss of function of the one extremity.

Examination usually begins with inspection of the overall symmetry and observation of obvious scars related to either the initial trauma or subsequent surgery. The range of motion of all joints and the neck is assessed. Some patients with injury to the cervical spine might present with cervical scoliosis. Injury to the sternocleidomastoid muscle should also be noted when the patient is asked to turn his or her head away from the injury. The supraclavicular and infraclavicular areas should be inspected and palpated for obvious scarring or for the existence of bony spurs. Calluses from malunions of the clavicle can be palpated, and their presence could suggest compression of the underlying plexus. Palpation should also include the ipsilateral chest for diagnosis of fractured ribs. This is important when one contemplates harvesting of intercostal nerves as motor donors for brachial plexus reconstruction.

It is important to keep in mind that high velocity trauma quite frequently causes nerve injury at several levels. One should be suspicious of such multilevel injuries if the patient presents with corresponding radiologic findings. In these cases, exploration and recon-
struction of the brachial plexus at the clavicular level only will not yield functional recovery if there is concomitant nerve injury more distally. For example, in documented associated fractures of the humerus, the radial nerve should also be explored through a posterolateral incision at the level of the mid-humerus. In cases of elbow fractures, the ulnar and median nerves should also be explored and repaired at that level.

The examination of passive range of motion of all joints should be done before examination of active range of motion. Limitations in the former are quite common and could mislead the examiner during the active muscle testing. Deficits are most often the result of contractures from inadequate physical therapy. Manual muscle testing begins by observing signs of muscle atrophy, palpation of the tone of each muscle group, and exertion of resistance by the examiner’s hands. It is often necessary to observe supplementary motions that the patient uses to achieve a certain movement. The British Medical Research Council muscle grading scale is used by most physicians. Examination of sensibility should include light touch and moving and static two-point discrimination and should be documented separately in the chart.

The physical examination is not complete without evaluation of the vascularity of the arm. A traction force strong enough to avulse nerve roots from the spinal cord can easily disrupt and damage the subclavian vessels. Moreover, associated fractures of the clavicle can easily cause subclavian vessel injury with subsequent pseudoaneurysm formation. Simple palpation of the radial and ulnar arteries and evaluation using Doppler ultrasound might not be adequate to determine the adequacy of the vascular supply to the arm. If major surgery is contemplated, then angiography might be indicated. A loud bruit over the supraclavicular or infraclavicular area also warrants the need for angiography.

The presence of a Tinel sign, elicited by tapping the supraclavicular area, can be quite useful in differentiating between root avulsion and root rupture. A positive Tinel sign, which is perceived by the patient as tingling in the anesthetic arm or hand, is a strong indicator of rupture. This is important; if it is correlated with intraoperative findings, it means that the reconstructive surgeon has available intra-plexus donors for grafting purposes. It is possible to elicit a Tinel sign by applying a mechanical stimulus at the level of the exit of the various cervical roots in a craniocaudal fashion. It is easier to perform this maneuver with the patient lying down in a supine position and with the head turned away from the lesion. In case of ruptures, the patient typically will respond by pointing with the contralateral hand to the site where the tingling sensation occurs. Thus, if the C4 root is tapped, the patient will localize the elicited sensation over the supracleavicular area. If the C6 root is tapped, the patient will point to the lateral antebraclacial region. At times, this dermatome may include the thumb and the radial dorsum of the hand. The Tinel sign can be repeated on subsequent clinical evaluations and its advancement distally is presumptive evidence of axonal regeneration. Lastly, the eyes of the patient should be examined to determine the presence of Horner syndrome (meiosis, upper eyelid ptosis, and absence of facial sweating on the affected side). A positive Horner’s sign implies disruption of the sympathetic supply to the ipsilateral eye and face through the lower roots (C8 and T1) and is a strong indicator of avulsion of these roots.

Radiologic Evaluation

Patients who sustain brachial plexus injuries are usually evaluated with routine x-rays of the affected extremity at the time of presentation. A complete study of the cervical spine and the involved shoulder with special attention to the clavicle and scapula is absolutely necessary. Depending on the mechanism of injury, fractures of the transverse processes might indicate avulsions of the corresponding roots, due to the attachments of the deep cervical fascia between the cervical roots and the transverse processes. Fractures of the ribs should be diagnosed radiographically because they could indicate injury to the intercostal nerves, a potential source of motor fibers for subsequent neurotization. Fractures of the clavicle and scapula or dissociation of these bony structures from the thorax could indicate a worse supraclavicular injury to the plexus. Bony spicules and calluses formed from fractured clavicles can be visualized with a simple shoulder x-ray and could indicate laceration or compression of the underlying subclavicular plexus. Deep inspiratory and expiratory chest x-rays or, preferably, fluoroscopy of the diaphragm can provide vital information about the function of the phrenic
nerve and its involvement in the injury. This is important when the ipsilateral phrenic nerve is being considered as a motor donor. Moreover, if the intercostal nerves are to be harvested for neurotizations, one has to be sure that the ipsilateral phrenic nerve is functioning.

CT/Myelography

Many reports have been published regarding the value of combined myelography and cervical CT. Since the first application of myelography by Murphy et al. in 1947 to evaluate traction injuries to the plexus, this technique has been modified with the advent of better contrast materials, and its value has been enhanced when it is correlated with a CT scan of the cervical spine. The positive predictive value of combined CT/myelography has been found to be more than 95 percent. In a review article by Walker et al., it is stated that of 76 cervicothoracic levels imaged (C5 to T1), 72 were adequately visualized. Nerve root avulsion or preganglionic disruption was shown at 21 levels. Associated pseudomeningoceles or deformities of the subarachnoid space were visualized in 12 of the 21 avulsion levels (57 percent). Subsequent surgical exploration and intraoperative somatosensory-evoked potentials showed complete preganglionic nerve root avulsion in 22 levels. Only one of the complete avulsions revealed by surgery was not included on the patient’s CT/myelogram. Of the 21 imaged levels, 20 were correctly revealed on CT/myelography. The overall sensitivity of the diagnostic modality was found to be 95 percent and the specificity 98 percent. The main advantage of the CT/myelography is the visualization of pseudomeningoceles, which are usually the result of meningeal tears and subsequent scarring following root avulsion. It is better to perform the myelography at least 1 month after the injury to allow for the pseudomeningocele to be sealed and to prevent the dye from flowing freely to the surrounding spaces. The decision to subject a patient to an invasive procedure such as the myelogram should be made in conjunction with the decision to operate. To achieve better definition of the lesions, water-soluble contrast is used with computed tomography. The cervical CT scan might reveal the absence of rootlets from the corresponding spinal level; this indicates root avulsion. To better use the results of such a study, one should consider that the presence of pseudomeningoceles is strongly indicative of avulsion; however, avulsed roots can exist despite a normal myelogram. Moreover, intact roots can exist in a formed pseudomeningocele if the traction force is strong enough to create a tear in the dura mater but not strong enough to avulse the root from the spinal cord. Because neuroradiology is not pathognomonic, many authors no longer use CT/myelography. Despite reports that claim that CT/myelography is unable to delineate individual nerve rootlets, in our institution we consider high-resolution CT/myelography with thin, contiguous axial sections to be very useful in the preoperative evaluation of the injured patient.

Magnetic Resonance Imaging

MRI has the advantage of good visualization of the brachial plexus beyond the spinal foramen. Many reports have advocated the usefulness of this method in establishing a diagnosis in distal plexus lesions. High field strength MRI with multiplanar views can easily distinguish the nerves at the distal plexus from the surrounding vessels and muscles. On the other hand, good visualization and delineation of the intradural portion of the rootlets are difficult, mainly because of technical deficiencies. Technically, a conventional MRI cannot provide good anatomic depiction of root sleeves and nerves because of the insufficient contrast between the subarachnoid space and the neural structures, a problem caused mainly by cerebrospinal fluid pulsatility. Moreover, correlation of the intradural surgical findings with conventional MRI studies is not reliable in the preoperative diagnosis of root avulsions in 48 to 52 percent of patients. This is mainly because of partial root avulsions and intradural fibrosis. Other studies, however, have estimated the overall sensitivity of magnetic resonance imaging to 81 percent. The diagnostic problems related to conventional MRI can be bypassed with the use of the more advanced three-dimensional magnetic resonance myelography, as advocated by Gasparotti et al., who claims that this new technique has 89 percent sensitivity, 95 percent specificity, and 92 percent diagnostic accuracy. In contrast CT/myelography provides a reliable preoperative diagnosis that correlates with the intraoperative diagnosis in more than 95 percent of patients.
Electrophysiologic Studies

Electrophysiologic studies should be carried out by someone experienced in brachial plexus and peripheral nerve injuries. Axonal discontinuity results not only in predictable pathologic features but also in time-related electrical changes that parallel the pathophysiology of denervation. Wallerian degeneration results in the emergence of spontaneous electrical discharges or fibrillations that will appear at least 3 weeks after the injury. Therefore, a needle electromyogram should be postponed for at least that long. In addition to denervation potentials (fibrillations), a needle electromyogram can also elicit larger potentials (sharp positive waves). These are valuable when there is a question whether muscle denervation is complete or if there is some attempt at reinnervation. Needle electromyogram of the paraspinal muscles, which are innervated by the dorsal rami of the spinal roots, should also be routinely performed; denervation of these muscles provides strong evidence of avulsion of the corresponding roots. On the contrary, if these muscles are electrically intact, then the injury is most likely infraganglionic and the root is most likely ruptured. Of course, voluntary potentials in different limb muscles indicate some neuromuscular continuity. As Bonney and Gilliat demonstrated in 1958, in addition to motor conduction studies, sensory conduction velocities should also be recorded to differentiate between ruptured and avulsed spinal roots. If, in a flail anesthetic arm, normal sensory conduction velocities are elicited, this is a bad prognostic sign that implies root avulsion, which makes spontaneous nerve regeneration impossible.

Many surgeons find the use of intraoperative somatosensory-evoked potentials useful to verify a suspected avulsion of a root or to determine whether resection of a neuroma and interposition nerve grafting should be performed. The advocates of this intraoperative electrophysiologic technique believe that root avulsion is definitely excluded only if direct stimulation of the individual surgically exposed cervical nerve root elicits reproducible cortical somatosensory-evoked potentials. Others believe that intraoperative transcranial electrical motor-evoked potentials can be of use in assessing the connectivity of the roots to the spinal cord.

However, the false positive and false negative recordings are quite high; in addition, this type of study is time consuming and susceptible to electrical interferences in the operating theater. In our institution, we routinely perform intraoperative electrical stimulation of the brachial plexus elements with a DC stimulator at 0.5, 1.0, and 2.0 mA.

SURGICAL PLAN, INTRAOPERATIVE DIAGNOSIS, AND RECONSTRUCTION

The patient is cleared medically and the operation is performed under general anesthesia. Special considerations include the use of light anesthetics, such as sufentanil, and avoidance of any kind of paralytics, so that intraoperative electrical stimulation studies can be performed. The sterile field includes the affected arm, both sides of the neck and bilateral shoulders (in case we need to use contralateral motor donors), the anterior and posterior chest to the midline, and bilateral lower extremities. The incision for the exploration of the brachial plexus is usually parallel to the posterior border of the sternocleidomastoid, then turns laterally over the clavicle and continues along the deltopectoral groove. Some surgeons perform clavicular osteotomies to improve exposure. We do not sacrifice the clavicle or the pectoralis minor to gain exposure to the infraclavicular plexus. Open clavicular osteotomies have the tendency to create malunions and, more often, nonunions. Therefore, they should be avoided. The omohyoid muscle and the transverse cervical vessels are identified and retracted. The phrenic nerve is identified in its usual anatomic position in the anterior border of the anterior scalene muscle, and it is traced superiorly to its C4 and C5 origins. The phrenic nerve is stimulated to verify its integrity, and the movements of the diaphragm are recorded. Sometimes the phrenic nerve is involved in adhesions and is very tightly fixated to spinal nerve C5, which is the first root to be explored. Care should be taken to isolate it and preserve it, except in cases in which it is ruptured; in these cases, if the distal stump cannot be identified, the proximal stump should be used as a donor for neurotization procedures. Then the surgeon should continue with identification and stimulation of the rest of the roots. Neuromas are identified and can extend between the upper roots and the trunks and also distally at the cord or peripheral nerve level. Neuromas can be in continuity or at the end of a ruptured plexus segment; the latter
can be resected back to normal tissue until normal fascicles are visualized. The response of the patient to the resection of a neuroma can also indicate connectivity of the corresponding root to the spinal cord. If the vital signs of a mildly anesthetized patient rise during resection of the neuroma, then one can conclude that the root is in continuity with the spinal cord and not avulsed. This is an important determination, because then the proximal stump of the neuroma could safely serve as an intraplexus motor donor for the reconstruction of the distal plexus. Spinal nerves that feel “empty” to palpation and are pale in appearance and negative to electrical stimulation are usually avulsed. Simultaneously biopsies can be obtained for carbonic anhydrase histochistory or cholinesterase staining. Furthermore, frozen biopsies of a root can determine the amount of scar present and the absence or presence of dorsal root ganglion cells, which indicate a nonreparable lesion. The enzyme carbonic anhydrase can differentiate between motor and sensory fascicles of peripheral nerves. Acetylcholinesterase histochemistry has also been used in conjunction with peripheral nerve surgery because this enzyme can be transported by axonal flow from the cell bodies to the nerve terminals and has higher activities in a motor fascicle than in a sensory one. However, prolonged incubation time (more than 24 hours) needed to visualize the acetylcholinesterase in motor fibers makes this staining technique nonpractical because it means that the patient is subjected to two operative procedures within a 2-day period. Intraoperative nerve action potentials can also assist in distinguishing ruptured from avulsed roots and are used by many authors. The senior author prefers to use electrical stimulation of the identified nerve structures with a DC stimulator at 0.5, 1.0, and 2.0 mA of amplitude. This is especially useful in lesions in continuity, because a decision has to be made to proceed either with neurolysis or resection and interposition nerve grafting.

After exploration, identification of the level, type, and extent of the lesion takes place, and an intraoperative plan is established. Motor and sensory donors are matched to their corresponding distal targets. Intraplexus motor donors, such as the proximal stumps of ruptured roots, yield, in general, better results because they carry a higher number of axons. Extraplexus donors, such as intercostal nerves, the accessory nerve, and the contralateral C7 root, are often used in multiple-root avulsions. Microneurolysis can be used when the explored elements of the plexus are hard on palpation, with dense epineurium that compresses the axons within and with the longitudinal vasa nervosum compromised. To relieve the intraneural pressure, longitudinal epineurectomies can be performed under the operating microscope with a 45-degree-angle diamond knife. These can extend to the perineurial and interfascicular level as indicated. Bulging of the entrapped fascicles strongly indicates that microneurolysis is effective.

Supraclavicular postganglionic lesions (neuromas secondary to root ruptures) are usually treated with a combination of microneurolysis and interposition nerve grafting. Excision of the neuroma to healthy fascicles distally and proximally is of great importance. While excising a partially ruptured lesion, one has to be careful not to downgrade existing function and convert it to a complete one. Direct coaptation of nerve roots or cords following excision of neuromas is almost impossible, except in early cases of penetrating trauma involving the brachial plexus. In all other cases, interposition nerve grafting is indicated. Sural nerves are usually harvested through three or four small incisions on the posterolateral aspect of the calf. Some authors also advocate the endoscopic harvesting of sural nerves. Bilateral saphenous nerves can also be harvested and used as interposition nerve grafts.

Infraclavicular lesions should be explored in their entirety. Healthy proximal and distal stumps should be identified. A combination of microneurolysis and interposition nerve grafting bypassing the neuroma can be used for reconstruction. Again, one should be careful not to downgrade existing function, especially in partially injured elements of the infraclavicular brachial plexus. It should also be mentioned that associated injuries in the infraclavicular area can result in severe scar formation, making the exploration of the infraclavicular plexus tedious.

Root avulsions always carry the worst prognosis and make the reconstruction of the plexus more challenging. A variety of extraplexus donors should be recruited in these cases to reconstruct the distal plexus elements. When the upper plexus roots (C5 and C6) are avulsed from the spinal cord, reconstruction of the shoulder and elbow function can be
achieved by means of the C7 root, which can be sacrificed. In that case, the distal targets innervated by the C7 root can be neurotized with extraplexus motor donors. When the three upper roots (C5, C6, and C7) are avulsed, more extraplexus motor donors are needed for reconstruction. Intercostal nerves, if harvested properly, yield acceptable results, especially for reconstruction of the axillary, triceps, or musculocutaneous nerve. Intercostal nerves are challenging and time-consuming to harvest, and each one may yield approximately 1200 to 1300 myelinated fibers. When neurotization is planned using a larger nerve, such as the musculocutaneous nerve, which is made of approximately 6000 fibers, at least three intercostal nerves in the donor nerve, the better the chance of achieving the targeted muscle; the more axons they carry. Studies in animal models have shown that the mean number of axons was 2145 in the contralateral C7 posterior or anterior division fibers. The distal part of the spinal accessory nerve is routinely used in our center to reconstruct the suprascapular nerve, either by direct end-to-end coaptation or by interposition nerve graft. In this manner, raising of the shoulder is still possible because only the distal portion of the trapezius muscle is downgraded. Other extraplexus donors include the contralateral C7 and the phrenic nerve.

It should be emphasized that even if extraplexus donors have resulted in obtaining useful muscle function at the M3 level, there are limitations, particularly in the number of nerve fibers they carry. Studies in animal models have shown that the number of axons in the donor nerves was partially correlated with functional recovery of the targeted muscle; the more axons in the donor nerve, the better the chance for functional recovery. In a study performed in our center, the myelinated axons of all common extraplexus nerve donors in seven fresh cadavers and the donor nerves used in 50 actual clinical cases were counted. The results were correlated with the functional return of the reconstructed muscles. It was found that the mean number of axons was 2145 in the accessory nerve, 1093 in each intercostal nerve, 1756 in the phrenic nerve, and 893 in the cervical plexus donors; the number of fibers ranged between 5000 and 12000 in the contralateral C7 posterior or anterior division. The percentages of muscle function greater than M3 for each corresponding motor donor were 84 percent for the accessory nerve, 52 percent for the ipsilateral intercostal nerves, 45 percent for the cervical plexus motor donors, 40 percent for the phrenic nerve, and 51 percent for the contralateral C7. One should notice that, despite the higher number of motor fibers in the C7 root anterior and posterior divisions as compared with the accessory nerve, only half the muscles neurotized by the contralateral C7 root achieved a muscle grade above M3, as compared with the 84 percent recovery achieved in the supraspinatus muscle by neurotization from the accessory nerve. This can be explained by the fact that most neurotizations from the XI cranial nerve were direct end-to-end repairs, whereas the neurotization by means of the contralateral C7 necessitated the use of long interposition nerve grafts. Furthermore, direct neurotization of a nerve leading to a single target, such as the suprascapular nerve, is preferential to neurotization of a nerve that leads to multiple muscle targets, such as the median nerve.

In cases of combined-root rupture avulsion (C5/C6 rupture and C7/C8/T1 avulsion or C5 rupture and C6/C7/C8/T1 avulsion), the C5 root, especially in a prefixed plexus, can be used for reconstruction of the musculocutaneous nerve and part of the median nerve. Again, the suprascapular nerve is reconstructed from the distal accessory nerve. In these cases in which the lower roots are avulsed (C8 and T1), hand function is not expected to recover spontaneously, and thus the ulnar nerve can be harvested as a free or pedicled vascularized graft and used for reconstruction. The benefits of a vascularized nerve graft are achieved, including its use in a scarred bed. Moreover, it provides the best milieu for rapid axonal growth. Also, the possibility of scarring at the distal coaptation site is minimized because of faster regeneration and better graft vascularization.

Our strategy regarding the use of the ulnar nerve as a vascularized trunk graft is the following: If C5 and C6 or a large C5 root (as in a prefixed plexus) are ruptured, but the proximal stumps are in continuity with the spinal cord, with simultaneous lower root avulsions, then during the initial brachial plexus reconstruction, the ipsilateral ulnar nerve is used as a free or pedicled vascularized graft to reconstruct the musculocutaneous, the median, and, on occasion, the radial nerve. The vascularized ulnar nerve graft is based on the superior ulnar...
collateral artery and vein. If the C6 root is also avulsed and the C5 root is flat, pale, and electrically nonresponsive, making it inappropriate for reconstruction, then ipsilateral extraplexus donors are used, including partial hypoglossal, partial phrenic, distal accessory, and ipsilateral intercostal nerves. In these cases, the musculocutaneous nerve is reconstructed with a minimum of three intercostal nerves, the distal accessory is given to the suprascapular nerve, and the axillary nerve is neurotized with additional intercostals or with other extraplexus motor donors. During the second stage, the ulnar nerve is harvested as a vascularized interposition nerve graft to neurotize the median nerve from the anterior division of the contralateral C7 root. The triceps branch and/or the radial nerve can be neurotized from motor fibers from the posterior division of the contralateral C7 root. This plan of reconstruction minimizes the possibility of co-contractions of the biceps and triceps, allowing for easier patient reeducation during the rehabilitation phase. In our patient population, co-contractions between antagonistic muscles are very rare, because of careful preoperative and intraoperative planning. However, when co-contractions occur, they are diagnosed easily with the clinical examination and with needle electromyography and are usually treated with negative biofeedback training.

During the first or second stage of brachial plexus reconstruction, we try to leave two banked nerve grafts at the medial and lateral sides of the antecubital fossa for future free-muscle transplantation. In cases of global root avulsion (five avulsions), intraplexus donors obviously are not available, and all reconstruction is carried out from extraplexus donors. The primary goal remains the restoration of shoulder function and stability, elbow flexion, and hand sensation. Banked nerves should be left for future free-muscle transfer for hand reanimation if the patient is judged to be a good candidate. Global avulsion of the brachial plexus carries the worst prognosis among all types of plexus injuries.

The morbidity from harvesting the various extraplexus donors can be minimized by taking only the number of donor fibers needed, such as in partial phrenic or partial hypoglossal transfers, which are used in combination with an end-to-side coaptation and by using intraplexus root donors that have adequate overlap from neighboring myotomes, such as the contralateral C7 root. Thus, when the contralateral C7 root (either the posterior or anterior division) is harvested, the senior author performs selective neurectomies, to match the cross-sectional area of the interposition cross-chest nerve graft (saphenous nerves or vascularized ulnar nerve). Even if one needs to harvest as much as 80 percent of the anterior or posterior division, motor morbidity can be avoided. In our patient population of nearly 50 cases with contralateral C7 transfers, we encountered transient hypoesthesia only in the hand, in the distribution of C7 dermatome, which disappeared by 3 months. At 6 months, there was no discernible motor or sensory deficit in the contralateral normal limb. Similarly, when harvesting the phrenic nerve, the senior author prefers to perform a partial neurectomy combined with end-to-side coaptation, thus preserving the innervation to the diaphragm. Moreover, we avoid harvesting both the phrenic and intercostal nerves in the same patient to prevent the possibility of respiratory compromise.

At the completion of surgery and before ex-
tubation, a custom-made brace with a halo is applied to the patient. This brace keeps the arm abducted 45 degrees and in anterior flexion. The halo prevents lateral movement of the head, reducing the risk of injury to the coaptation sites. This type of immobilization is extremely important, especially in cases in which the repairs have been executed very proximally near the transverse foramina. The brace is removed 6 to 8 weeks later, and the patient’s arm is placed in a sling. The borders of the treated area are marked with methylene blue, and specific instructions are given to the nursing personnel and the family not to touch this area so
that the underlying coaptations will not be traumatized accidentally.

Complications of first-stage reconstruction are rare and include mainly localized wound infection and, very rarely, pneumothorax during intercostal nerve harvesting. Seroma formation after intercostal nerve harvesting, as a result of the extensive dissection, has been observed at times and can be prevented by compression dressing and frequent observation.

**Postoperative Care**

Physical therapy with passive range of motion and slow-pulse electrical stimulation are started with the removal of the brace. Ultrasound therapy for scar manipulation is also recommended for separating the nerve healing from the overlying skin wound. Physical therapy begins at 8 weeks postoperatively with passive range of motion and manual massage over the treated areas. Of great importance is the training of the patient and the physical therapist in all aspects of the new neurotizations. For instance, if intercostal nerves have been used to reinnervate the musculocutaneous nerve, the patient needs to perform the Valsalva maneuver while attempting to flex the elbow to achieve stronger contraction. Our experience shows that following such neurotizations in motivated patients, central nervous system neurons exhibit extreme plasticity, and the patient quickly embraces the new nerve pathways. Furthermore, the motor cortex mapping resembles the physiological biceps area. The physical therapist should also be aware of developing co-contractures in the reinnervated muscles and treat them aggressively with negative or positive biofeedback as needed.

The first follow-up visit is arranged at 6 months after surgery. The patient is instructed to monitor any improvement in function and to document specific dates of recovery. During the first follow-up visit, a needle electromyogram is obtained. At 12-month follow-up, the patient is evaluated fully for return of function, and plans for secondary reconstructions are made.

**Specific Aims of Reconstruction**

When deciding which target muscles are to be reinnervated, the following rules apply:

1. Stability of the shoulder is a very important goal. The return of function in the supraspinatus and deltoid muscles is con-
sidered of prime importance. Unstable and subluxated shoulders very often cause ipsilateral neck pain due to the gravitational effect of the flail arm. Shoulder fusion is never advocated in our center, especially if no adequate scapulothoracic motion is present.\textsuperscript{78}

2. One of the most important functions of

![Fig. 5. Postoperative brachial plexus chart of the patient in Figure 1.](image1)

![Fig. 6. A 26-year-old man from Greece sustained a left brachial plexus palsy secondary to a motorcycle accident. He presented with a totally flail left upper extremity. Note the scars in the upper arm from the open reduction with internal fixation of the humerus and the prominent muscle wasting.](image2)
the upper extremity is bringing the hand to the mouth, for obvious reasons (nourishment). Unless elbow flexion is restored, even hands that have been spared from injury are useless. Therefore, restoration of the biceps is of great importance to the overall function of the upper extremity, and during surgery we try to provide the musculocutaneous nerve with the best motor donors. To ensure good bi-

Fig. 7. Preoperative brachial plexus chart of the patient in Figure 6.

Fig. 8. Exploration of the supraclavicular and infraclavicular plexus 4 months after the injury. The intraoperative diagnosis included ruptured roots (C5 to T1) with neuroma formations at the trunk, cord, and infraclavicular levels. The radial (R), ulnar (U), and median (M) nerves were also injured at the mid-humeral level with extensive scar formation. SS, suprascapular nerve; AX, axillary nerve; MC, musculocutaneous nerve.
The above-mentioned priorities in restorative microsurgery, especially if the denervation time is short, can achieve shoulder stabilization, a certain degree of abduction and external rotation, strong elbow flexion, elbow extension, hand protective sensation, and, in selected cases, reanimation of the hand.

**Free-Muscle Transplantation**

Functioning free-muscle transplantation has become a reconstructive option in cases of delayed patient presentation with long denervation time, or in cases with multiple-root avulsions, especially when the lower roots of the plexus that innervate the hand are involved. Furthermore, this microsurgical technique can be extremely useful when primary reconstruction of the biceps or forearm musculature has
nerve grafts from the contralateral anterior or posterior divisions of the C7 root. With such a transfer, a functional outcome of at least M3 strength (antigravity) can be achieved in the majority of the cases (78 percent).85 Similarly, the gracilis muscles can be transferred to the forearm as free-muscle flaps to restore finger flexion or extension or to substitute for intrinsic muscle function. Electrophysiologic assessment of the free muscle can show contractions as early as 2 to 4 months,86 and full range of contraction can be expected at approximately 6 to 12 months. Of great importance is the condition of the corresponding joints; thus, before any muscle transfer, the adjacent joints need to be free of contractures, otherwise one could end up with a strong muscle unit but no resultant joint excursion. The success of a free-muscle transfer relies on the muscle transferred, the donor nerve selection, and the compliance of the patient. Operative technique and postoperative care are equally important factors in achieving success. Placement of the muscle at optimal tension and adequate flap coverage, along with early aggressive passive motion exercises, allow for grip strength of 50 percent of normal, in case of the transplantation of a gracilis muscle to the forearm for finger flexion.89

Other Secondary Procedures

These procedures are used as adjuvant procedures in patients who have already had brachial plexus reconstruction with appropriate neurotizations, to augment specific functions. They are also of great importance in patients with long denervation times, who are not good candidates for primary microsurgical reconstruction. These include tendon transfers, pedicled muscle transfers, joint fusions, and a variety of osteotomies.

During tendon transfers, the decision has to be made to sacrifice one function to replace or enhance another function. The tendons to be transferred need to be adequately innervated and are selected by clinical examination and needle electromyogram. A common tendon procedure is transfer of the clavicular and acromial insertion of the trapezius with or without fascia lata to the deltoid insertion on the humerus to enhance abduction and reverse subluxation.90 Other transfers around the shoulder area include transfer of the sternoclavicular part of the pectoralis major to the anterior deltoid for anterior flexion or transfer to

Fig. 10. Six years postoperatively, the patient is able to fully abduct (above) and anteriorly flex his arm (center). He has full external rotation (below).
the native biceps for elbow flexion.91 The pec-
toralis minor can also be transferred to the
biceps muscle to strengthen elbow flexion.92 A
classic maneuver is also the rerouting of the
latissimus dorsi tendon around the humerus to
restore dynamic external rotation. In the expe-
rience of the senior author (J.K.T.), this par-
ticular transfer yields better results in children
than in adults. At the elbow level, Steindler
flexorplasty, reattachment of the flexor mass of

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**Fig. 11.** Six years postoperatively, the patient has full elbow flexion (left and center). He is able to grasp and lift a chair above head level (right).

**Fig. 12.** Postoperative brachial plexus chart of the patient in Figure 6.
the antebrachium proximally onto the humerus, can be used also to enhance elbow flexion, alone or simultaneously with other transfers. The latissimus dorsi muscle has been used extensively for restoration of elbow flexion as a pedicled myocutaneous flap. Reanimation of the hand and wrist can also be improved with secondary musculotendinous transfers using local reinnervated targets or targets that have escaped injury. Common transfers include the flexor carpi ulnaris or flexor carpi radialis to the extensor digitorum communis for strengthening finger extension, and the extensor carpi radialis brevis, extensor carpi radialis longus, or brachioradialis to the abductor pollicis longus or extensor pollicis longus for abduction or extension of the thumb. Profundoplasty, in which the missing portion of the flexor digitorum profundus is connected to the functioning part of the flexor digitorum profundus, can be also performed for enhancement of finger flexion.

Rotational osteotomies of the humerus help improve external rotation by 30 degrees and are carried out in collaboration with our orthopedic colleagues. Rotational osteotomies of the radius have also been used in our center to correct supination or pronation deformities. Wrist fusions are usually performed simultaneously with a free-muscle transfer for hand reanimation. This allows a far more accurate setting of tension in the transferred muscle. Despite reports in the literature, we do not advocate fusion of the shoulder as a therapeutic modality. On the contrary, we believe that the primary microreconstruction of the brachial plexus, especially if it is done in a timely manner, will restore satisfactory shoulder stability and function in the majority of the patients.

**PAIN MANAGEMENT IN BRACHIAL PLEXUS INJURIES**

Injury to the brachial plexus can cause severe pain. The incidence varies with each study but affects about 10 to 20 percent of patients with brachial plexus injuries and almost 40
percent of patients with avulsions, especially when the lower C8 and T1 roots are involved. This is caused primarily by the high content of sensory fibers in the lower roots. However, the incidence of intractable pain associated with lower root avulsion in our series relatively is low.

Fig. 15. Preoperative brachial plexus chart of the patient in Figure 13.

Fig. 16. (Left) The patient underwent an exploration of his supraclavicular and infraclavicular right brachial plexus 11 months after the injury. The intraoperative diagnosis was avulsions of C6 to T1 roots. (Center and right) Reconstruction included harvesting of the (1) right ulnar nerve as a free vascularized nerve graft, (2) bilateral sural nerves, and (3) ipsilateral intercostals T5 to T7; reconstruction of the median (M) and musculocutaneous (MC) nerves from C5 with the vascularized ulnar nerve graft; reconstruction of the axillary nerve (Ax) from C5 with sural nerve grafts; direct end-to-end coaptation of the suprascapular nerve (SS) with the accessory nerve (Acc); reconstruction of the triceps and thoracodorsal nerves from ipsilateral intercostals; and coaptation of one intercostal nerve to a sural nerve that was left as a banked nerve to the right upper extremity for future free-muscle transplantation for hand reanimation. R, radial nerve.
Pain usually starts a few days after the pain from the initial trauma subsides and can be intractable. It is commonly described as continuous, burning, and compressing and is frequently located in the hand. Pain can be aggravating and can raise many psychosocial issues for the patient and his or her immediate family. The few studies of pain following brachial plexus injury\textsuperscript{98,99} show that this type of pain is very difficult to treat. Most patients are initially treated with various narcotics, tricyclic antidepressants, antipsychotic drugs, and sympathetic blocks. It has been shown, however, that there is a statistical correlation and temporal relationship between the reduction in pain and returning of motor function\textsuperscript{100,101}; this is also supported by observations in our patient population.\textsuperscript{76} In two cases of intractable pain that were encountered in our series, the intensity of the pain was such that the senior author recommended to the patients to undergo a dorsal root entry zone procedure first, before proceeding with the formal brachial plexus reconstruction. The benefit of following this sequence of events is that, if this procedure is successful, the patient can focus on his rehabilitation without distraction from the pain. It also allows the recon-

\begin{figure}
\centering
\includegraphics[width=\textwidth]{image}
\caption{Six years postoperatively, the patient demonstrates 90-degree abduction (\textit{above, left}), 90-degree external rotation (\textit{above, right and center, left}), and full elbow flexion (\textit{center, right}) and is able to carry objects with his hand (\textit{below}).}
\end{figure}
constructive microsurgeon access to the most accurate preoperative diagnosis of the status of the roots. The dorsal root entry zone (DREZ) procedure was introduced in 1979 by Nashold and colleagues, whose long-term follow-up study of their results showed that this neuroablative procedure, 54 percent of patients with avulsion injuries were afforded good pain relief after 34 months. Other studies showed increased numbers of pain relief as high as 79 percent. Despite evidence in the literature pertaining to limb amputation as a choice for rehabilitation and pain control, we strongly disagree with this procedure, because pain associated with preganglionic injury of the brachial plexus is not relieved by amputation. It is a well-known fact that the best treatment against amputation neuromas is replantation against amputation neuromas is replantation.

**Case Reports**

**Case 1: Supraclavicular Traction Injury**

B.E., a 37-year-old white man, fell from a vertical ladder on concrete and landed on his right shoulder. He presented with deltoid, supraspinatus, and infraspinatus paralysis and was unable to abduct and externally rotate the arm (Figs. 1 and 2). The function of the hand was normal. Preoperatively he also had mild weakness of his biceps muscle and numbness around the shoulder area. The patient did not suffer other associated injuries but complained of severe pain. Denervation time was 2 months. He was initially operated on in another center, where minimal exploration of the plexus was performed that revealed thickening of the suprascapular nerve. No further treatment was carried out at that time. After referral to our center, the patient underwent exploration of the suprascapular nerve that revealed extensive hardening and scarring, primarily around the upper and middle trunks, with involvement of the suprascapular nerve. Extensive microneurolysis with a diamond knife under the operating microscope was performed. Bulging of the released fascicles was noted immediately (Fig. 3). Postoperatively, the patient has excellent return of abduction, external rotation, and anterior flexion of the arm (Figs. 4 and 5). He returned to his previous occupation 5 months after surgery.

**Case 2: Multiple Supraclavicular and Infraclavicular Ruptures**

V.A., a 26-year-old white man from Greece, was involved in a motorcycle accident. He sustained a complete left brachial plexus palsy. Associated injuries included open fracture of the humerus, treated with an external fixator; fractures of the radius and ulna, treated with open reduction with internal fixation; and fractures of the wrist and second metacarpal, which were reduced with Kirschner wires. Two months later, the external fixator was removed and the humeral fracture was fixed with internal plating and autologous bone grafting. Four months after the injury, the patient was referred to our center. A preoperative CT/myelogram revealed no avulsions of all cervical roots, and a preoperative electromyogram showed multiple-root ruptures. Clinically, the patient had no abduction, external rotation, elbow flexion, or elbow extension, and hand function was graded as 0 (Fig. 6). He also had total anesthesia below the elbow level and severe hypesthesia above the elbow (Fig. 7). Total denervation time was 4 months. The patient underwent exploration of the supraclavicular and infraclavicular plexus and the entire arm. There were four levels of injury: at the suprascapular, subclavicular, and infraclavicular areas, and in the arm. Intraoperative findings included (1) rupture of the upper and middle trunk involving roots C5, C6, and C7 with a large neuroma present and (2) a large neuroma underneath the clavicle, corresponding to the suprascapular nerve and the posterior cord, with sparing of the thoracodorsal nerve. In the infraclavicular region, the axillary, median, and musculocutaneous nerves were ruptured, and multiple neuromas and excessive scarring were present. The radial, median, and ulnar nerves were ruptured and extensively scarred at the mid-humeral level, resulting in large nerve gaps; this injury was associated with a left humeral fracture (Fig. 8). The reconstruction included the following (Fig. 9):

- Extensive microneurolysis of C5, C6, C7, C8, and T1 roots.
- Reconstruction of the suprascapular nerve with two sural nerve grafts (6 cm) from the C5 root.
- Reconstruction of the axillary nerve from the posterior cord with three sural nerve grafts (12 cm).
- Reconstruction of the radial nerve with four sural nerve grafts (13 cm) from the posterior cord.
- Reconstruction of the median nerve involved three sural nerve grafts 35 cm long, from the proximal stump of the median nerve in the infraclavicular area to the distal stump of the median nerve in the elbow region.
- Reconstruction of the musculocutaneous nerve involved three sural nerves grafts 15 cm long, from the exit of the musculocutaneous nerve from the lateral cord to its entry into the biceps muscle.

Six years postoperatively, the patient has anterior shoulder flexion of 120 degrees (pectoralis major 4+), abduction of 90 degrees (supraspinatus and deltoid graded as 4), latissimus dorsi of 4+, external rotation of 90 degrees (infraspinatus 3+), full elbow flexion (biceps 4), full elbow extension (triceps 4), and protective sensation in the hand with a useful gross grip (Figs. 10 through 12).

**Case 3: Multiple-Root Avulsions**

A.T., a 13-year-old white boy, was an unbelted passenger when he was ejected from a car during a motor vehicle accident. Associated injuries included a Le Fort II fracture, fractures of the radius and ulna, and soft-tissue hematomas.
He was referred to our center with right global brachial plexus palsy. Clinically, the patient had only some trapezius function. All other muscle groups were graded as 0. The patient also had a total anesthetic arm (Figs. 13). A preoperative electromyogram indicated a global plexopathy with avulsions of C7, C8, and T1 roots. A preoperative CT/myelogram showed pseudomeningoceles at three levels (C7, C8, and T1) and absent rootlets from C6 to T1 (Fig. 14). The total denervation time was 11 months (Fig. 15). The patient underwent an exploration of the right supraclavicular and infraclavicular plexus. The intraoperative diagnosis was avulsions of C6 to T1 roots (Fig. 16, left). The reconstruction of the brachial plexus included the following (Figs. 16, center and right):

- Harvesting of: the ulnar nerve as a vascularized free graft; bilateral sural nerves; and T5, T6, and T7 ipsilateral intercostals.
- Neurotization of the suprascapular nerve directly from the distal accessory nerve.
- Direct coaptation of the thoracodorsal to the T5 intercostal nerve.
- Direct neurotization of T6 to the triceps branch.
- Coaptation of T7 to a sural nerve graft that was tunneled as a banked nerve to the right upper extremity for future free-muscle transfer.
- Reconstruction of the musculocutaneous nerve and the median nerve through a free vascularized ulnar nerve graft from C5.
- Reconstruction of the axillary nerve from C5 with two sural nerve grafts.

Six years following the reconstruction of the plexus, the patient is able to abduct his arm 90 degrees, externally rotate it 90 degrees, and fully flex and extend the elbow with strength (biceps and triceps were graded as M4). He is also able to grasp and lift objects with his right hand (Figs. 17 and 18).

**RESULTS**

Results of different neurotizations have been published by many authors. At least 2 to 3 years of follow-up are required to evaluate results. These outcome studies should be reported according to the different reconstructive methods and techniques used for restoration of each function.61

A serious outcome study performed in our institution involved 263 patients operated on by the senior author from 1978 to 199675; 204 had adequate follow-up. From this series, it is clear that intraplexus donors consistently yielded better results. This is probably true not only because of the higher fiber numbers encountered in the proximal stumps of the ruptured roots but also because it is a more “physiologic” reconstruction, which makes the postoperative recovery of function easier. Most authors agree with this statement105 and believe that, even with only two roots available for reconstruction, a good functional outcome can be expected.

Based on the outcomes when extraplexus donors were used, direct neurotization of the...
suprascapular nerve from the accessory nerve yielded 75 percent good and excellent results. 

The spinal accessory nerve has also been used for restoration of elbow flexion in avulsion injuries, with coaptation to the musculocutaneous nerve. Good function of the biceps at the M3+ level has been reported for more than 70 percent of the patients. 

Intercostal nerves are probably superior to all other extraplexus donors when they are used for reconstruction of the musculocutaneous or triceps nerves. Different studies have reported good function of the biceps (M3+ and above) after neurotization with intercostals for 63 to 81.8 percent of patients. The mean time for recovery of function with this neurotization has been reported to be 12 months. On the contrary, the recovery of the distal radial nerve and the motor part of the median nerve is not expected to be good. However, the intercostal nerves can restore protective sensibility to the hand in a large number of patients. This experience on the use of the intercostal nerves is comparable with the senior author’s experience.

In our center, use of the selective contralateral C7 technique as a contralateral intraplexus donor is strongly advocated. When the anterior division of this root is connected through a vascularized ulnar nerve graft to the median nerve or the musculocutaneous nerve, good results can be expected in almost 60 percent of these patients. Poorer results can be expected for the radial nerve. In global avulsions, because recovery from the ulnar nerve cannot be expected, the ulnar nerve can be harvested as a vascularized nerve graft based on the superior ulnar collateral artery. This technique can yield better results as compared with the use of sural or saphenous nerve cross-chest grafts, owing to the rich blood supply of the vascularized ulnar nerve and to the great number of fibers that it can carry. In our practice, we routinely use the contralateral C7 root as a motor donor for banked cross-chest nerve grafts for selected targets or future use for free-muscle transfers. In the senior author’s hands, as has also been reported by other surgeons, only minor tingling and hypesthesia can be expected at the donor-side hand that resolve within 6 months.

The ipsilateral cervical plexus motor donors usually do yield only modest functional results, mainly because of the small number of fibers. On the contrary, the phrenic nerve can provide acceptable elbow flexion at the M3+ level for almost 84 percent of patients within 1 year of neurotization and with no respiratory deficit. However, one should be cautious of avoiding extensive ipsilateral intercostal nerve harvesting if the phrenic nerve has already been injured.

In global avulsions and in late presentations, secondary procedures, such as local or free-muscle transfers, are required to improve the overall function. In general, better outcomes can be expected for young adults with short denervation times.

Conclusions

The treatment of brachial plexus lesions is complicated and requires a thorough understanding of the brachial plexus macroanatomy, microanatomy, and function. Also, persistence from both the surgeon and the patient is needed for achieving the best results. The clinical examination should be thorough and carefully documented. In addition, radiographic evaluation of the plexus by means of a CT/myelogram and electrophysiologic studies including a Lamina test can assist in establishing a preoperative diagnosis. Realizing the expected goals of the reconstruction and discussing these goals extensively with the patient are of great importance. Subsequently, the restorative microsurgeon can establish the strategies for the microreconstruction of the brachial plexus.

The preoperative diagnosis of the lesion can be confirmed intraoperatively with a combination of electrical stimulation of all roots and distal plexus components and histochemistry. Working closely with the anesthesiologist and maintaining the patient under light anesthesia are also very important. Elevation of the vital signs while resecting a root will provide valuable information and will determine whether the involved roots are avulsed or in continuity with the spinal cord. Roots in continuity following resection to healthy fascicles can be used for motor donors. In general, intraplexus donors yield better results, mainly because of the higher content of axon numbers and also because they provide a more “physiologic” type of reconstruction, which requires less retraining for the patient. Extraplexus donors, such as the accessory nerve, the intercostal nerves, the phrenic nerve, or the cervical plexus nerves, are used mainly when multiple roots are avulsed. The higher the number of roots
avulsed, the more the need for harvesting extraplexus motor donors for neurotizations. Extraplexus donors are of extreme value and can yield good functional results for specific types of reconstruction, i.e., intercostal nerves to musculocutaneous neurotization or accessory nerve to suprascapular nerve neurotization.

The factors affecting the functional outcome have also been studied. The denervation time, i.e., the period between the original trauma and the surgical reconstruction, is the most important. The sooner the patient presents for brachial plexus reconstruction, the better the outcome. The age of the patient is a second important factor. Younger patients are expected to have better chances of functional nerve regeneration and this is shown by most outcome studies; however, older patients with brachial plexus lesions should be also explored and their brachial plexus reconstructed. Despite the complexity of the microsurgical procedures and the prolonged recovery period, the surgical correction of brachial plexus injuries has become routine in recent years. Advances in microsurgical techniques and postoperative rehabilitation can eliminate amputation of the arm as a surgical option and can facilitate the return to society of a high number of patients who until recently were not considered a productive part of the workforce.

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Self-Assessment Examination follows on page 1123.
1. TINGLING UPON TAPPING OF THE SUPRACLAVICULAR AREA USUALLY MEANS:
A) Healing fracture of the clavicle.
B) Pseudoaneurysm of the subclavian artery.
C) Fluid collection.
D) Root connectivity with the spinal cord.

2. A POSITIVE HORNER’S SIGN MEANS:
A) Injury to the upper roots of the brachial plexus.
B) Normal hand function.
C) The patient has a concomitant ophthalmologic problem.
D) Lower-root avulsions.

3. PSEUDOMENINGOCELES IN A CT/MYELOGRAM MOST LIKELY MEAN:
A) The roots most likely are connected to the spinal cord.
B) The roots most likely are totally or partially avulsed.
C) The interventional radiologist injured the root.
D) Intact dural sheath.

4. END NEUROMAS OF THE ROOTS WHEN FOUND SHOULD BE:
A) Stimulated.
B) Excised and grafted.
C) Sent for biopsy.
D) All of the above.

5. EXTRAPLEXUS MOTOR DONORS INCLUDE:
A) The contralateral intercostal nerves.
B) The saphenous nerves.
C) The ipsilateral cervical motors and accessory nerve.
D) None of the above.

6. GOALS OF BRACHIAL PLEXUS RECONSTRUCTION IN GLOBAL PARALYSIS INCLUDE:
A) Shoulder stabilization.
B) Protective sensation in the hand.
C) Elbow flexion.
D) All of the above.

7. REINNERVATION OF THE IPSILATERAL LATISSIMUS DORSI MUSCLE IS IMPORTANT FOR:
A) Cosmetic reasons.
B) Stabilization of the scapula.
C) Transfer to the arm as a pedicled muscle to strengthen elbow animation.
D) Restoration of finger flexion as a free-muscle transfer.

8. FREE MUSCLES FOR SUCCESSFUL RESTORATION OF ELBOW FLEXION INCLUDE:
A) The contralateral latissimus dorsi and the rectus femoris muscle.
B) The adductor longus muscle.
C) The gracilis muscle.
D) None of the above.
9. PAIN IN BRACHIAL PLEXUS INJURIES:
   A) Is psychological in origin and should be treated with counseling.
   B) Can be severe in high-velocity penetrating injuries.
   C) Always requires surgical treatment.
   D) Is associated with upper-root avulsion.

10. THE BEST PROGNOSIS AFTER BRACHIAL PLEXUS INJURY CAN BE EXPECTED:
    A) In older patients.
    B) In multiple-root avulsions.
    C) In long denervation times.
    D) None of the above.

To complete the examination for CME credit, turn to page 1241 for instructions and the response form.