# Brachial Plexus Treatment

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## Abstract

Brachial plexus injuries are devastating injuries that affect primarily young healthy males. For the total plexus injury, current surgical treatments have failed to achieve normal restoration of limb function but some practical goals are obtainable. This review article summarizes existing logic and approach for managing these catastrophic injuries.

**KEY WORDS**: Brachial plexus, treatment

## History

The earliest reports of the surgical management of brachial plexus injuries appeared around beginning of 20th centuries. Thoburn (1) in 1903 described a surgical repair of an injury to the brachial plexus. In the early 1900s Taylor (2) presented a series the surgical results of plexus surgery with significant functional improvement Similarly, Davis, et al.(3) reviewed the surgical treatment of brachial plexus injuries and suggested that significant functional improvement could be expected after surgery. This initial enthusiasm for brachial plexus surgery in the early part of the century was followed by a pessimistic outlook as several reports documented poor results with surgical intervation (4,5). Even in 1963, Seddon (6) condemned brachial plexus surgery except for injuries to the upper trunk with complete palsies, which had a hopeless prognosis. Moreover, Yeoman (7), in 1961, proposed the amputation of the arm associated with arthrodesis of the shoulder.

Many surgeons, however, were less aggressive. Hendry (8) was definitely against amputation. He favored, when feasible, a partial reanimation of the paralyzed limb through musculotendinous transfers. Midway between these extreme attitudes of suppressing an extremity or performing limited reconstruction, at that time, there were still surgeons resorting to multiple arthrodeses such as the early fusion of the shoulder in C5,C6 lesions and, in exceptional cases, an arthrodesis of the elbow and wrist in C5, C6,C7 and C7, C8, Tl lesions. Renewed enthusiasm for operative management of these injuries awaited the introduction of microneurosurgical technique and nerve grafting. Millesi pioneered the use of nerve grafts to manage these injuries (9). With the development of improved techniques, improved results followed. Kline and Nulsen (10) Narakas (11), Gilbert and Tassin (12) Brunelli (13), Merle and Deburge (14),Alnot et al (15), Allieu (16), Leffert (17) and Terzis (18) and have all made important contributions toward the operative management of brachial plexus injuries.

## Decision Making

1. *Immediate surgery* (within 24 hours) should be done in acute cases where sharp injury is present or vascular surgery is required because of major vessel injury. a) If the nerve is found to be sharply transected, then it should be acutely repaired. If a blunt injury has occurred, and the nerve appears injured, the stump should be tagged and a delayed repair performed at 2 to 4 weeks. b) Gunshot wounds should be immediately explored only if vascular surgery is required. Otherwise, observation and delayed surgery is recommended, because missile injury often leaves the nerve in continuity and many of these injuries are neuropraxias which resolve spontaneously. However, some of these lesions become neuromas in continuity and require later surgical intervention with techniques such as neurolysis, resection, or grafting.

2. *Early Period* (Less than 3 months)
In cases where root avulsion is present, the surgical timing is important. The diagnosis and determination of root avulsion is a key step. These root avulsion injuries have a hopeless prognosis for nerve recovery; therefore, surgery should be done as soon as feasible (2 to 3 weeks after injury). Since in this situation neurotization is a reasonable option, it is of paramount importance to keep in mind that results of neurotization are dependent upon early muscle reinervation. Delay in treatment can jeopardize the final outcome.
3. Intermediate Period (3 to 6 months post-injury) Generally speaking, surgical intervention should be performed during this period in closed traction injuries if the clinical and electrodiagnostic studies suggest no improvement in the neurological status. These injuries potentially that have the best prognosis for spontaneous recovery since there may be a spectrum of involvement (neuropraxias to neurotemetic lesions). It is felt therefore, that serial examinations is most critical during this period in determining whether surgical intervention is necessary. EMG's and clinical examinations can provide significant information to determine if recovery is progressing or heading to a plateau. After reasonable amount of time (3 to 4 months) with no improvement in proximal muscle reinnervation, then surgical exploration should be considered.

4. *Delayed Period* (6-12 months). This is unfavorable timing for surgical intervention. Results of nerve grafting deteriorate after 6 months. There is however, some improvement that is still possible to be obtained until approximately 12 months or so.
5. Late Period (greater than 12 months). Majority of authors don't advise nerve repair at this time. Treatment options in these patients to consider include:
a.) Functional free muscle transfer
(Extraplexal neurotization)
b.) Tendon transfer(s)
c.) Joint fusion
d.) Pain management
e.) Nerve transfer(s)

LOCALIZATION OF THE NEUROLOGICAL LESION

Regarding the level of injury, the most important aspect (which is germane to understanding this injury) is: Is there continuity between roots and cervical spine ( CNS)? The level of lesions of the plexus can be classified as supra or infraganglionic lesions of the trunk and lesions involving the cords. Any combination of these levels may occur (19).
**Level I** Supraganglionic lesions are those proximal to the spinal ganglia. The roots are avulsed from the cervical cord and as a result, motor fibers degenerate but sensory fibers are still intact and therefore electrical conductivity is preserved for afferent impulses. As a result of this high injury level, a neuroma does not form and Tinel's sign is absent. There are no changes in the vegetative system as the connections with the sympathetic ganglia are also intact. The deep neck muscles show evidence of denervation. This is a useful fact since electrodiagnostic testing can sample these muscles to assess their neuro-

logical status and help localize the level of the lesion(s). **Level II** Infraganglionic lesions are peripheral to the spinal ganglia. Both motor and sensory axons degenerate, electrical conductivity is lost, a neuroma forms, and Tinel sign is present. Both gray and white rami lose connection with the sympathetic ganglia. The deep neck muscles remain innervated through the intact dorsal branch. Damage may involve both the supra and the infraganglionic portion of the same root. **Level III** In lesions of the trunks, there are signs of neuroma formation with a positive Tinel's sign, all conductivity is lost, and vegetative functions are disturbed. Muscles, whose nerves leave the plexus more proximally, are spared i.e. levator scapalae, rhomboid, and serratus anterior. **Level IV** Lesions of the cords are accompanied by neuromas in the supra or infraclavicular regions. The supra- and infraspinatus muscles remain intact. There may be a combination of supra- and infraclavicular lesions.

Extent of injury is also important in determining the treatment strategy. Patients may have different patterns of injuries. Most common is **upper** brachial plexus (Figure 1.). **Lower** brachial plexus injury is much less common (Figure 2). **Total** brachial plexus is present when all roots are affected, but still some function is preserved (Figure 3). **Global** brachial plexus has the worse prognosis in which all innervations have been disrupted and none of the extremity musculature demonstrates movement i.e., flail extremity (Figure 4.). In clinical practice, there can be many different variations of the injured brachial plexus. The treatment strategy therefore needs to be individualized taking into consideration the patient, time of presentation, the extent of the injury and lastly the resources and skill of the treating physician and team members.

## Surgical Goals and Priorities

In general, proximal muscle groups have better prognosis for recovery than distal muscle groups. There is less distance for nerve regeneration to traverse and less axons are necessary for successful reinnervation. In addition, less time to reinervation means less muscle atrophy and less neural fibrosis. As such, attention on brachial plexus reconstruction has focused on proximal muscle groups and those groups that can provide the most useful upper extremity function. Restoration of elbow flexion is the **first** priority in the treatment of the injured plexus. Placement of the hand in a position to be useful is impossible without adequate elbow flexion. The **second** priority is shoulder stabilization and **last** is wrist and hand prehension. The order of this priority is set based on the realistic goals of success in restoration of the function rather than the actual importance in the functional need of that limb; hence, it is somewhat misleading. Probably the most important function would be the prehension, but due to the less likelihood of restoration capability many surgeons have traditionally neglected using our current repair techniques, attempt to restore this function. A combination of surgical options can be used to accomplish these goals. Surgical decision making is continued intraoperatively as the availability of donors and determination of deficits are addressed via a number of different options. The options for surgical reconstruction include microneurolysis, primary nerve repair, nerve grafts, nerve transfers, tendon transfers, free muscle transfers, and the stabiliza-

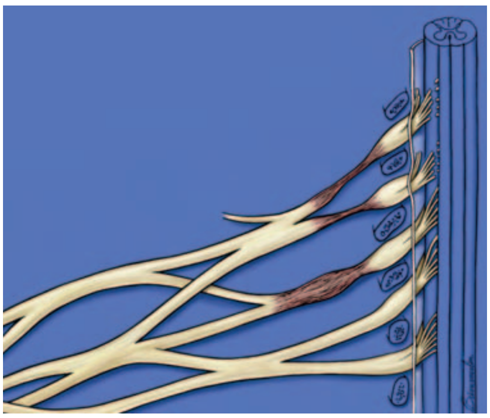

FIGURE 1. Upper Brachial Plexus with double level injuries on C5, C6 (level I and level II) and neuroma in continuity on C7.

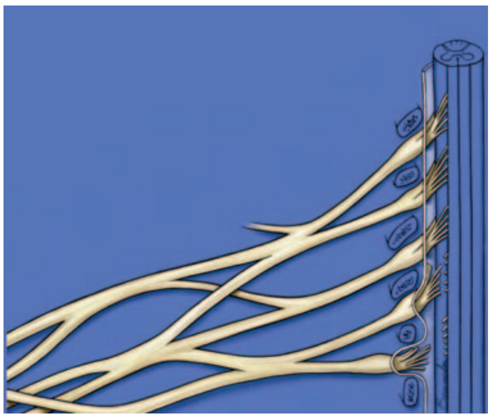

FIGURE 2. Lower Brachial Plexus with C7 and C8 avulsion.

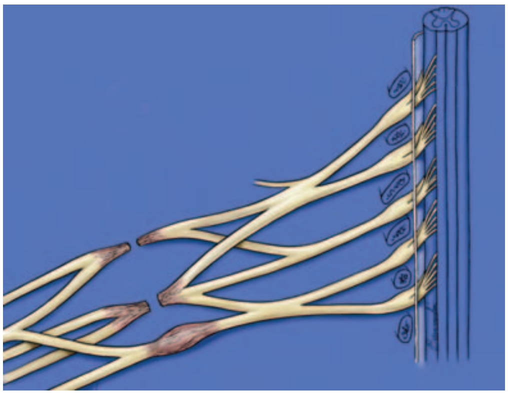

FIGURE 3. Total Brachial plexus with lateral and posterior cord complete transection and medial cord neuroma in continuity.

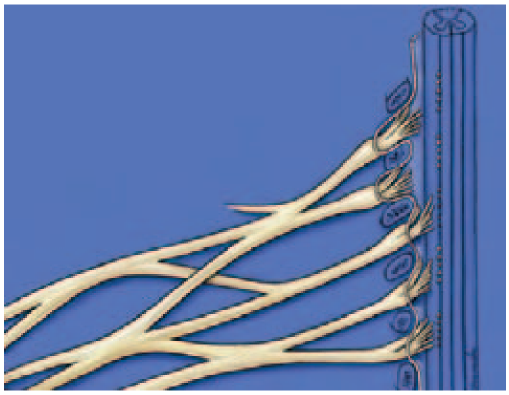

FIGURE 4. Global Brachial plexus with complete avulsion of all C5-T1 roots (clinically presenting as a flail arm with no motor or sensory preservation).

tion of joints via arthrodesis and tenodesis. The determination of which option to use is based on nerve availability, surgical goals and lastly patient's and surgeon's expectations. This often varies on an individual basis.

## Intraoperative Evoked Potentials

Intraoperative evoked potentials can be useful to verify a suspected nerve root avulsion or to determine whether neuroma resection and interposition nerve grafting should be performed. If direct stimulation of an exposed nerve root causes a reproducible cortical somatosensory evoked potential, then it is likely that a nerve root avulsion is not present. Another method of assessing root-to-cord continuity is via intraoperative transcranial electrical motor-evoked potentials. Intraoperative evoked potentials are also useful for addressing a neuroma in continuity. Stimulating and recording across a neuroma-in-continuity should produce a reproducible signal if axons are intact. If there is a significant demonstrable axonal continuity present then a neurolysis is all that may be required. If, on the other hand, there is no response, this usually indicates that extensive intraneural fibrosis is present, and therefore, the neuroma and adjacent nerve tissue is resected and nerve grafting is performed.

## Surgical Approach

The patient needs to be placed in semi-sitting, supine position with the surgical field prepped out from the entire neck starting at the mandible on both sides and the operative shoulder, the chest wall from the midline sternum to the medial border of the scapula, and bilateral lower extremities. If you are considering the use of contralateral nerve as a donor nerve, then bilateral shoulders must be included in the sterile field. The incision for the exploration of the brachial plexus starts at the posterior border of the sternocleidomastoid muscle and then continues laterally above the clavicle (Figure 5.). At the level of the coracoid process, the incision follows down the deltopectoral groove. The external jugular vein is the first important landmark. Spinal accessory nerve lies posterior to this structure. Transverse cervical artery is potential source of bleeding and good anastomosis for vascular graft. Both external jugular vein and transverse cervical artery are divided along with the omohyoid muscle in the supraclavicular fossa. The upper and middle trunks lie posterior to this muscle. Anterior and middle scalene muscles come next in the field. Between these muscles, the trunks of the plexus emerge. The phrenic nerve located anterior to the anterior scalene muscle should be identified and protected to prevent iatrogenic injury. After identification of the neural element of the C5 root, one can trace the lower nerve roots and identify the beginning of the brachial plexus (Figure 6.). These neural elements can be inspected to determine whether they are avulsed, ruptured, partially injured or intact. If the lesion is extended to the infraclavicular region, the clavicle can be osteotomized and the incision extended into the deltopectoral groove. Pectoralis minor muscle detachment provides access to cords of plexus with lateral cord being most prominent. After this exploration and identification of the level, type, and extent of the lesion, an intraoperative plan is established. It is essential not to miss multilevel injuries. Sometimes, neurolysis of the nerves must be performed to truly evaluate the condition of the fascicles.

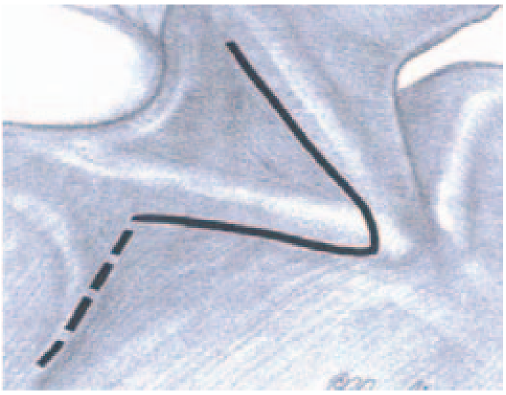

FIGURE 5. Classical incision for brachial plexus exploration. Lower, doted line can be extended if injuries extend infraclavicularly. Clavicle osteotomy can be made if necessary.

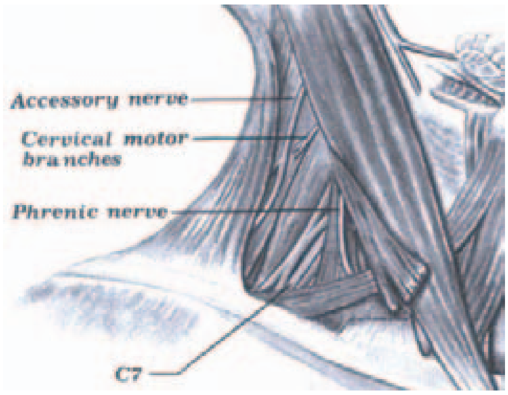


FIGURE 6. Anatomical position of brachial plexus passing between anterior and middle scalene muscles is presented.

## Surgical options

1. Direct *nerve repair* is seldom possible. It is primarily indicated for acute sharp injuries.
2. *Nerve repair with interpositional grafts* is the most commonly used option for postganglionic injuries. The sural nerve is the most commonly used donor nerve. It can provide up to 35 cm in length. Ipsilateral cutaneous nerves of arm and forearm are the next source of neural tissue. The saphenous nerves may also be used. Vascularized grafts such as ulnar grafts have also been used for large defects and to provide larger conduit for greater quantity of axonal regeneration. Vascularized ulnar nerve can be used as a free nerve graft (epineurium is partially cut and fascicles are split into several grafts, Figure 7) (20, 21). The vascularized ulnar nerve can also be used as a pedicled graft if the nerve is rotated on its vascular pedicle of superior ulnar collateral artery, and as a free nerve graft for bridging the long distance for performing a contralateral C7 transfer. If a ruptured nerve is found, it would be most likely accompanied by the presence of the neuroma at the distal stump. The neuroma stumps can be excised to the healthier fascicles, both distally and proximally. A difficult decision arises when there is a mixed injury within a single cord with some intact functioning nerve along with the neuroma-in-continuity. When faced with this dilemma, one must utilize the help of the microscope and attempt to separate out the intact fascicles from the

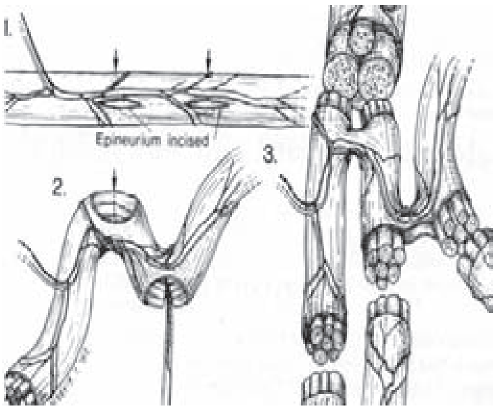


FIGURE 7. Split vascularized nerve graft.

FIGURE 8. In upper part is intraoperative presentation of middle trunk and in lower part interpositional grafts for C5 and C6 nerve roots.

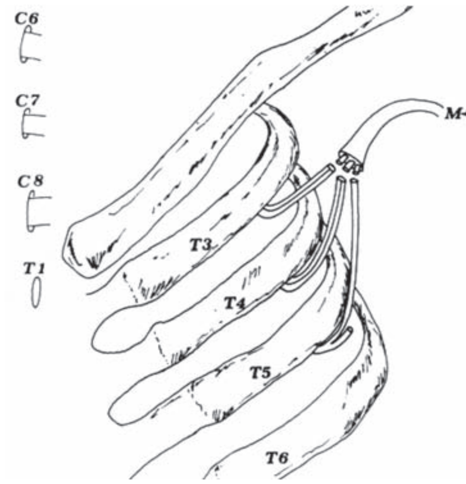


FIGURE 9. Neurotization of musculocutaneous nerve with 3rd, 4th and 5th intercostals.

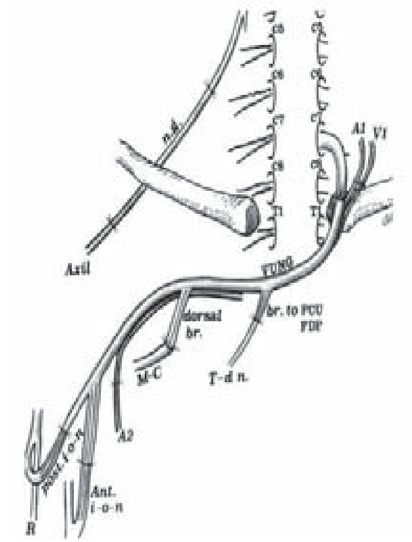


FIGURE 10. Vascularized ulnar nerve graft (VUNG) used for bridging contralateral C7 to anterior interosseus (Ant. i-o-n) posterior interosseus (Post i-o-n), musculocutaneous (M-C) and thoracodorsal nerve (T-d n).

neuroma. This can be a very tedious task, but without this careful step you may downgrade the existing function and convert the partial injury to a complete one. Another technique, is to use intraoperative electrodiagnostic testing to guide the surgical decision making. Once the injured zone has been identified and excised, the interpositional nerve grafts can be used for the repairs (Figure 8). Excisions of the zone of injury and tension free repairs are critical steps regardless of repair techniques (22).

## Nerve transfers

Nerve transfers are typically indicated for preganglionic lesions or when injuries are so proximal that the likelihood of recovery is extremely poor. The suitability of one nerve as a donor in nerve transfer procedures is determined by anatomic proximity, the extent of brachial plexus injury, donor nerve morbidity and the number of nerve fibers (23, 24). Numerous donors nerves that can be used for nerve transfers are available including: spinal accessory, phrenic nerve, intercostals nerves, contralateral C7 vascularized ulnar nerve, branch to the FCU (Oberlin transfer), and the 5th and 6th cervical nerve stumps. *Spinal accessory nerve (SAN)* use may not impact on the functional status of trapezius because of its dual innervation. Harvesting of this nerve should be performed after the take off of 1 or 2 branches to the SCM muscle to prevent paralysis of this muscle. It has approximately 2000 fibers. The SAN most commonly is used for reconstruction of the suprascapular nerve but neurotization of the musculocutaneous nerve (MCN) has also been successful (25, 26). The *phrenic nerve* arises mainly from C4 with some contribution from C3 and C5. Pulmonary function must be carefully evaluated preoperatively. This transfer is contraindicated in age of less than 2 years. In almost 3/4 of patients, pulmonary function will be diminished postoperatively. Vital capacity usually decreases from 10 to 15 %. Full recovery can be expected during first year. Coaptation with suprascapular nerve is the most effective, because interposition graft is not necessary due to proximity. The musculocutaneous (MCN) and axillary nerve (AN) can be also connected but with interpositional grafts (27). *Intercostal neurotization* procedures have good results if the coaption is performed directly into the recipient nerve. Coaptation with interpositional nerve graft do not have as favorable results as the direct technique. Each intercostal has 1200 fibers. Usually 3rd, 4th and 5th intercostals nerves are used (Figure 9.). Higher intercostals have more sensory fibers but problems with scapular winging make harvesting these nerves prohibitive. Higher intercostals have more sensory fibers. Most common nerve to undergo neurotization is the musculocutaneous nerve (MCN). Neurotization procedures of the median, ulnar, and radial nerve do poorly (28). *Contralateral C7* transfer in recent literature has received a lot of attention. C7 root nerve allows large numbers of nerve fibers to be obtained. It is indicated in Global and Total avulsion plexus injuries. It has great capacity with 18000 to 40000 nerve fibers. The transfer is most commonly combined with a vascularized ulnar nerve graft (Figure 10.). It can be used partially (50 %) or entire root. Before sacrificing the C7 nerve root, a diagnostic marcaine injection for assessment of the extremity functional loss should be made. With this transfer, donor deficits do not appear to be significant and the clinical results of C7 root transfer to the median nerve have shown some recovery of sensibility, but poor forearm and hand motor recovery. The increased distance and time required for axonal regeneration for distal motor recovery results in irreversible changes in the motor end plates and neuromuscular junction. Therefore, this is not a good option for distal reconstruction. On the other hand, interestingly, shortening of the arm in addition to the contralateral C7 nerve has been done and has demonstrated some distal motor recovery (29). *Ulnar nerve transfer* (Oberlin transfer) is relatively simple technique used for neurotization of musculocutaneous nerve (MCN) in upper root with great return of functional elbow flexion with minimal donor morbidity. Recovery rate is excellent in 90 % of patients with M4 results. Donor fascicles should be assessed intraoperatively with a nerve stimulator. The branch going to the FCU is usually selected for the transfer. The Oberlin transfer has the advantage of rapid reinnervation. The proximity of the transfer to the motor endplates of the biceps or brachialis muscles has allowed relatively early recovery of elbow flexion between two and five months. No permanent deficits are noted in the ulnar nerve distribution; however, transient paresthesia can occur (30,31). This concept has been expanded by McKinnon to include a double transfer using the Oberlin and a branch to the flexor digitorum superficialis (FDS) of the middle or ring finger and transferring it to either the brachialis or biceps and thereby innervating these two muscle groups to give very impressive clinical results with minimal clinical deficits. Hypoglossal and medial pectoral neurotization are described but rarely used in practice. Ulnar nerve and 5$^{th}$ and 6$^{th}$ cervical roots stumps nerve have shown to be effective and reliable transfers, however the best results were seen with combined donor transfers due to the increase in the quantity of the neurons, less axonal mixing, shorter distances to the motor end plates and shorter operative time.

## Free Functional Muscle Transfers

In the past, the functional free muscle transfers have been set aside for the neglected cases of total brachial plexus palsy such as the patients who are about two or more years out from the initial injury without any treatments. However, this method of reconstruction has been more widely accepted in recent time as the primary treatment of the complete root avulsion injury, bypassing the option of nerve transfer for some surgeons. The benefit of this procedure in comparison to the other surgeries is that this is one of the only procedures that can essentially provide the patient with acceptable function of prehension after a complete brachial plexus root avulsion. This procedure is much more technically demanding and does allow a higher percentage of patients to obtain more functional prehension which is the most important function of the hand. The free gracilis innervated flap is commonly used for elbow flexion. Restoration of elbow function is one of the first reconstructive goals. The proximal gracilis muscle is attached to the clavicle and distal portion is performed by weaving gracilis tendon into the biceps tendon (Figure 11.). The technique, popularized by Dr. Kazuteru Doi in Japan aims to restore the following four major functions (32):

a.) Independent voluntary finger flexion and extension
b.) Independent voluntary elbow flexion and extension
c.) Protective sensation in hand
d.) Hand stabilization

In Doi's reconstruction, the first free muscle transfer, the contralateral gracillis muscle, latissimus dorsi, or rectus femoris muscle, neurotized by the ipsilateral spinal accessory nerve. The free muscle transfer is spanned from the acromion, anterior to biceps, under the origin of the mobile wad as a pulley, and then tenodesed to the extensor tendons of the digits. This is to provide functions of elbow flexion and finger extension (Figure 12.). The second free-muscle transfer, neurotized by the fifth and sixth intercostal nerves is placed from the second rib, medial arm, under the flexor pronator origin and tenodesed to the flexor tendons. This transfer is to restore the flexion of the fingers once the neurotized muscle has been innervated. The third procedure is the neurotization of the denervated triceps muscle. This is performed during the second muscle transfer to restore the finger flexion. The fourth procedure, which is also performed during the second free muscle transfer, is to provide the sensibility to the hand by neurotization of the predominant sensory fibers of the median nerve with the sensory rami of the intercostal nerves or supraclavicular nerves (Figure 13). The result of this procedure with 32 patients demonstrated 96 % of satisfactory elbow function and 65% of satisfactory prehension. These

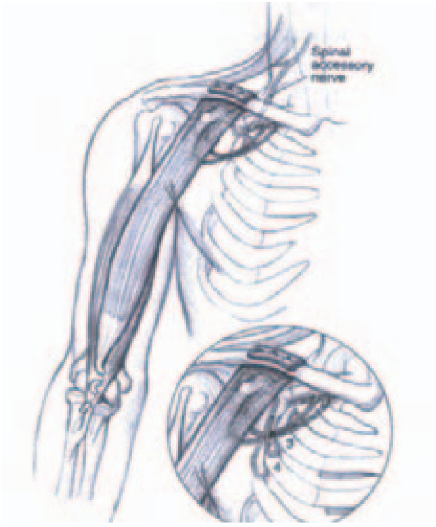


FIGURE 11. Free muscle transfer for restoration of elbow flexion.

FIGURE 12. First stage of "Doi procedure" which provides elbow flexion and finger extension.

results are significantly higher than any other procedures mentioned above for regaining both the functional elbow flexion and prehension capability from the complete brachial plexus root avulsion injuries.

## Other Procedures and Approaches

Reconstructive techniques such as tendon transfers, pedicled muscle transfers, joint fusions and a variety of osteotomies are indicated as secondary procedures for patients who have already had brachial plexus reconstructions to improve particular functions. These procedures are also of great use in patients who present late or those who are not good candidates for brachial plexus reconstruction. Different approaches are available in literature. Recently Millesi (33) published article summarizing five different approaches in management of brachial plexus. Besides above mentioned procedures there are several experimental works about *root implantation* done by Carlstedt (34) and some other authors. Although this technique seems logical and there are encouraging initial results, no clinical application has been done yet. *Dorsal approach with laminectomy* which is used by Kline (35) is supposed to provide better approach to the roots and more precise diagnosis about root avulsion. However there are still 15 % of false negative result reported, and also there is reasonable chance for further root damage. Therefore this approach has not gained popularity. *Extraplexal neurotization* without exploration of plexus brachialis has been popularized from Tsuyama. Although Dr Tsuyama (36) has obtained good results using this approach there are still some opinions that this approach jeopardizes the possibility of muscle regeneration that have direct connection to the spine after the brachial plexus nerve roots are repaired. We prefer integrated concept using all options indicated above which might improve final result. Reconstructive surgeons who manage these challenging injuries should be well versed in all techniques including: neurolysis, nerve grafting, neurotization, free muscle transfer and tendon and muscle transfer and joint fusions. Moreover, a single patient may require several different options to obtain good result and a useful extremity (37,38).

## Postoperative Care

Typical postoperative care involves strict immobilization of the neck, shoulder and elbow to protect the microsurgical repairs. This can be done with cervical collars, halos, and customized shoulder and elbow braces or slings. Immobilization is necessary for typically six to eight weeks at which point passive range of motion of the upper extremity may have begun. Once wound healing is complete, a serial neurological examination to assess recovery is performed every few months. There are multiple hand rehabilitation protocols to help maximize recovery available. The need for secondary reconstruction is determined at twelve to twenty-four months after brachial plexus reconstruction as final outcomes may take a significant time period to assess.

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