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Current Trends in the Management of Adult Brachial Plexus Palsy

Part I: Upper arm type

Abstract

The brachial plexus consists of cervical nerve roots C5, C6, C7, C8, and thoracic nerve root T1. Upper arm type brachial plexus injury (BPI) means C5 and C6 root injury with or without C7 injury. Nerve injury caused by sharp cut or stab injury might be treated with direct repair with or without a nerve graft. However, for most of the BPIs which were caused by high velocity trauma, nerve root avulsion or rupture require nerve transfer (neurotization) to bypass the damaged zone thereby allowing patients to regain critical shoulder and elbow functions faster. In this review article, we present various reconstructive nerve / tendon transfer techniques for the management of adult upper arm type BPI. With the modern advances of microsurgery, the shoulder and elbow functions can be successfully recovered in around 80% to 90% of upper arm type BPI patients.

Introduction

Injuries to major nerves of the upper extremities, especially the brachial plexus, have devastating consequences owing to the resultant motor, sensory, and autonomic function loss associated with such injuries.¹⁻⁵ Unfortunately, such injuries are occurring with increasing frequency, owing to high-velocity civilian injuries (motor vehicle and motorbike accidents) and, more recently, war related injuries seen in war veterans. Patients suffering from upper arm type brachial plexus injury (BPI) present with loss of motor function in shoulder elevation / abduction / external rotation, and elbow flexion. The other major clinical problems are pain and loss of adequate sensory function.⁵⁻⁷ Microsurgical repair of injured nerves has achieved significant advancement, but the functional recovery is still suboptimal.^{2,4} Direct microsurgical repair of injured nerves, especially in sharp cut and stab injury, represent the best repair strategy when feasible. However, even with such repairs, return of useful function cannot be guaranteed, especially in avulsion root injuries or for denervated targets that are farthest from the

injury sites.^{4,5,8,9} Hence, regenerative distance and time to reinnervation represent some of the key determinants of functional outcomes after injuries to brachial plexus nerve trunks.^{4, 5, 9-13} Nerve transfers (neurotization) represent a relatively novel approach to restore useful upper limb function after severe proximal nerve injuries in BPI. Nerve transfer technique reduces the distance to reinnervate target organs by delivering expendable motor and/or sensory axons close to the denervated end organs.^{1-4, 9-12, 14-21}

History of BPI and reconstruction

Brachial plexus injuries have been reported directly or indirectly for the last 2800 years. The first mention of a BPI in the literature occurs in Homer's "*The Iliad*" around 800BC.^{2,22} The attempts to reconstruct the BPI by direct suturing the ruptured nerve stumps, or free interposition sural nerve grafting had gained its popularity after the development of microsurgical techniques and equipments.^{23,24,25,26} However, the results of direct nerve repair or free nerve grafting for BPI did not obtained satisfactory clinical results, which altered the trends of BPI reconstruction toward the technique of nerve transfers.^{1-5, 9-21, 24, 27} French physiologist Marie Jean Pierre Flourens was the first to theorize that an injured nerve could be bypassed by suturing the superior end of one nerve with the inferior end of the other nerve in 1824.^{28,29} But the first brachial plexus reconstruction by using the nerve transfer technique was reported on a 20 year old female injured by a Nazi bomb blast. The surgery was performed prior the advent of microsurgical instruments / equipment, by a Russian surgeon, Alexander Lurje, in 1948.³⁰ Our improved understanding of nerve pathophysiology, anatomy, repair, and reconstruction has led to advances in the treatment options for upper arm type BPI in the past 30 years.

Physical examinations and diagnostic tools for upper arm type BPI

The mechanism of most BPIs is a traction injury, in which the head is forcefully distracted from the ipsilateral shoulder. This manner of traction force typically results in pre-ganglionic root avulsion or post-ganglionic rupture of the upper trunk (C5-C6) and middle trunk (C7), while sparing the lower trunk (C8 and T1).⁹

The typical findings in physical examination for upper arm type BPI are the loss of elbow flexion and shoulder elevation / abduction / external rotation in C5 and C6 roots injury. The physical examination of individual muscle function reveal that paralysis of the biceps, brachialis, deltoid, and the rotator cuff are seen commonly, ^{12, 16, 17} while the additional loss of wrist dorsiflexion or finger extension implies that the C7 root is also damaged with possibly concomitant incomplete lower trunk (C8, T1) injury. ^{9,14,15,16} These physical findings can be reasonably explained by understanding the anatomy of brachial plexus (Figure 1).

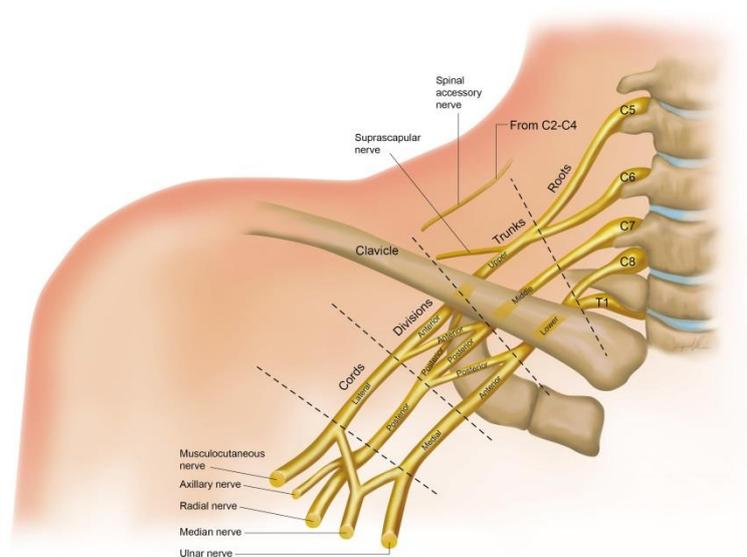


Figure 1:
Anatomical diagram of the brachial plexus. The spinal accessory nerve originating from C2-C4 is also shown.

In addition to physical examination, the diagnosis of upper arm type BPI is confirmed by serial needle electromyography (EMG) and nerve conduction velocity (NCV) studies, CT myelograms, and magnetic resonance myelography (MRM). ^{5, 9, 12}

These diagnostic tools are required to be performed prior to brachial plexus exploration. Typically, the first EMG and NCV are performed 6 weeks following trauma, and the second EMG / NCV studies are performed 3 to 4 months after injury if indicated. If no progress is identified on the EMG / NCV or during physical examination, then a CT myelogram or MRM is obtained and plexus exploration is performed.

Philosophy and concepts of upper arm type BPI reconstruction

Many studies document nerve regeneration following injury; however the clinical results regarding recovery remain elusive.^{1, 2, 4} As we understand that once the nerve begins to regenerate, it moves at around 1-1.5 mm daily.^{2, 12, 31} The motor endplates with which the nerve communicates will eventually cease to function in 12-18 months. If a proximal plexus injury occurs, then the regenerated nerve may not reach the motor endplate in time to be effective. Therefore, using the nerve transfer technique of harvesting nerve fascicles from uninjured nerve and transferring to the injured nerve (close-target neurotization) may facilitate the salvage of critical motor endplates and their corresponding muscles.^{1-4,8,10,12,14} This nerve re-routing essentially converts a proximal nerve injury into a distal nerve injury closer to the motor endplate and denervated muscle. By this neurotization method, the proximal nerve stump can reach the target muscle before motor endplate degradation.

Post-ganglionic root sharp-cut and rupture injuries are amenable to primary nerve repair and nerve grafting, whereas pre-ganglionic avulsion lesion injuries require nerve transfers.^{9,10,21,23,24,32,33} Although intra-plexus nerve transfers (such as ulnar nerve or median nerve transfer to musculocutaneous nerve, and radial nerve transfer to axillary nerve) remain the best options for pre-ganglionic root avulsion injuries, some injuries which avulse or rupture more than 80% of the plexus roots are not good candidates for nerve transfer due to the partial loss of the motor nerves in the lower trunk.^{2-5,12,16,17,31} In these situations (such as complete C5,6,7 injury with incomplete C8,T1 injury), extra-plexus nerve transfers (by using neurotization from the spinal accessory nerve, phrenic nerve, intercostal nerve, or contralateral C7 root) are the methods of choice for BPI reconstruction.^{2,4,9,10,12,13,15,24,27,34-36} Re-implanting avulsed spinal roots directly into the spinal cord for the reconstruction of pre-ganglionic avulsion BPI has been reported from the United Kingdom with acceptable clinical outcomes.^{37,38} However, this nerve root re-implantation technique has not been popularly used in the field of brachial plexus reconstruction.

Factors influencing the outcomes of nerve transfers

The outcomes of nerve transfers for BPI patients depend on four factors which may influence the clinical results. The first factor is **patient selection**. Studies have shown that younger patients recover from nerve transfer faster and ultimately have better outcomes than older patients. Typically patients under 40 years of age have the best functional outcomes following nerve transfer.^{12, 18, 39} In addition to age, some other factors such as tobacco use, body mass index (BMI), patient's compliance, and social-economical status also influence the surgical outcomes of BPI patients.^{2-5, 9, 10, 18, 21, 40, 41} The use of tobacco and obesity tend to result in less satisfactory outcomes than in patients who do not smoke, or patients who have a normal BMI. It is critical that the patient adheres to an occupational therapy and physical therapy program both before and after surgery. An adequate scheduled rehabilitation program may prevent joint stiffness before nerve surgery, and may also allow early joint passive range of motion during the interval between a nerve transfer procedure and target muscle power recovery.

The second factor is **the timing of reconstruction**. Many studies have shown that nerve transfers performed within 6 months post-injury yield results superior to transfers performed after 6 months post-injury.^{1-5, 9, 12, 15, 18, 21, 27, 31, 39, 42} When the interval between injury and nerve reconstruction surgery is more than 9 to 12 months after trauma, then the surgical options are either tendon transfer or free functioning muscle transfer, instead of nerve transfers.^{5, 12, 43, 44}

The third factor is **the extent of initial nerve trauma**. We are aware that many nerve transfer methods such as Oberlin I nerve transfer (fascicle of ulnar nerve transfer to musculocutaneous nerve), and Somsak's method (branch of radial nerve transfer to axillary nerve) have quite satisfactory outcomes in C5 and C6 roots injury. However, when injury involves not just the C5 and C6 roots, but also the C7 root or partial damage of lower trunk, the intra-plexus nerve transfers are not optimal surgical procedures for BPI reconstruction.^{2-5, 12, 16, 17, 31} Surgeons may need to apply the techniques of extra-plexus nerve transfers (such as phrenic nerve, spinal accessory nerve, intercostal nerve, or contralateral C7 root) for BPI reconstruction.^{2, 4, 9, 10, 12, 13, 15, 24, 27, 34-36} The outcomes of extra-plexus nerve transfers are not as satisfactory as intra-plexus nerve transfers, especially for elbow

flexion.^{4,15,21,39,45} Therefore, the extent of initial nerve trauma plays an important role in determining the surgical outcomes in BPI.

The fourth factor is **the priority of functional reconstruction**. The two most important functions which need to be restored in upper arm type BPI are elbow flexion and shoulder abduction / elevation / external rotation.^{1-4,12,14,16,31,46} Elbow flexion is critical to human interaction with the environment, and its restoration is the principal goal of BPI reconstruction. This is particularly true in C5-C6 injuries where the musculocutaneous nerve (MCN) has been compromised. The MCN innervates the biceps and brachialis which are the elbow flexors. Restoration of elbow flexion can significantly improve the activities of daily living for the BPI patient.^{1-5,9,10,12,14-21} Restoration of shoulder stabilization and elevation / abduction / external rotation are the second most important priorities in primary reconstruction of BPI.^{4,9,10,12,14,15,31,39,42,46} In addition to suprascapular nerve (innervation of the supra- and infra-spinatus muscles of rotator cuff), the axillary nerve (innervation of the deltoid muscle) is also compromised in C5-C6 injuries.^{14,15,47} Nerve transfers to both the suprascapular nerve and axillary nerve may restore the function of rotator cuff muscles and deltoid muscle which may abduct / elevate / externally rotate, and stabilize the shoulder, providing a solid platform for both elbow and hand functions.^{10,12,14,15,16,46,47}

Nerve repair, nerve grafting, and nerve transfer options for elbow flexion in upper arm type BPI

Nerve repair is indicated for the treatment of open wounds with clean transaction of a part of the brachial plexus, if the proximal and distal stumps can be clearly identified.^{1,2,4,5,8,9,48} Direct coaptation of the proximal and distal stumps of the disrupted musculocutaneous nerve, the lateral cord, or the C5-C6 upper trunk by microsurgical techniques may obtain the most predictable and reliable clinical outcomes.^{3,5,9,12,23,25,26,48}

Nerve grafting is indicated in cases with loss of continuity, either caused by sharp or traction injury at the level of the post-ganglionic level, trunk level, or cord level. Since it remains doubtful whether useful regeneration can occur in a reasonable time, the neuroma should be resected. After the proximal and distal stumps have

been properly prepared after neuroma resection, a direct nerve coaptation suture is usually impossible, due to fibrosis and shrinkage of nerve stumps after trauma. If the nerve defect is short, then the continuity can be restored by an interposition nerve graft. The most commonly used free nerve graft is sural nerves harvested from the legs. The length of sural nerve is up to 30 cm long.

Knowledge of the cross-sectional intraneural topography should be adequately applied to achieve proper anatomical coaptation between proximal and distal nerve fibers. In upper arm type BPI, if the defect is between C5 and C6 roots proximally and in the upper trunk level distally, the sural nerve graft coaptation suture with C5 should be connected to the distal stump with the part of the cross-sectional surface that forms the posterior division; whereas the sural nerve graft coaptation with C6 proximally should be connected with anterior division of the cross-sectional surface distally.^{3,9,24,25,32,33,48} However, in cases with longer nerve defects, the anatomical cross-sectional coaptation suture with sural nerve graft seems to be impractical. Because there is not enough autologous donor nerve available to restore continuity to all parts of the plexus, and nerve fiber exchange within long segments loss of the brachial plexus is high, there is a high possibility of nerve fiber loss after nerve grafting surgeries due to the deviation of regenerating axons. Therefore, it is more practical and has been proven to be more successful to connect proximal stumps directly with distal nerves, instead of a connection with ill-defined distal stumps at trunk or division levels. For instance, if there is a long nerve defect between C5 and C6 and the posterior and lateral cords in upper arm type BPI, the ideal method is to use sural nerve graft connecting the proximal C6 stump directly to the musculocutaneous nerve of the lateral cord distally. Then the regenerating nerve fibers go directly to the musculocutaneous nerve and provide motor innervation to the biceps and brachialis muscles.^{4, 9,12,15,25,32,33,48} Nerve grafting provides good results for elbow flexion in 70-75% of cases with upper arm type BPI.^{3, 15, 23,25,33,48}

There are several nerve / tendon transfer options for the reconstruction of elbow flexion in upper arm type BPI. The donor nerves applied for BPI neurotization include: ulnar nerve (UN), median nerve (MN), intercostal nerve (ICN), spinal accessory nerve (SAN), phrenic nerve (PN), and medial pectorial nerve (MPN). The recipient nerve is the musculocutaneous nerve (MCN). The following six

techniques are most commonly used methods.

- (1) **Oberlin I method:** The current most commonly used nerve transfer technique for elbow flexion in upper arm type BPI is the Oberlin I transfer which was first described by Christophe Oberlin of Paris in 1994. He described the transfer of one or two nerve fascicles from the ulnar nerve (UN) directly coapted to the biceps motor branch of the MCN (Figure 2A-C).¹⁹

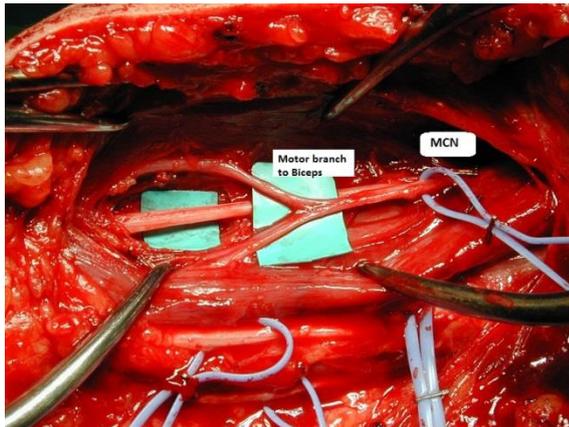


Figure 2A: Oberlin I neurotization. The motor branches to biceps (in this patients, two branches were found) were identified. MCN: Musculocutaneous nerve

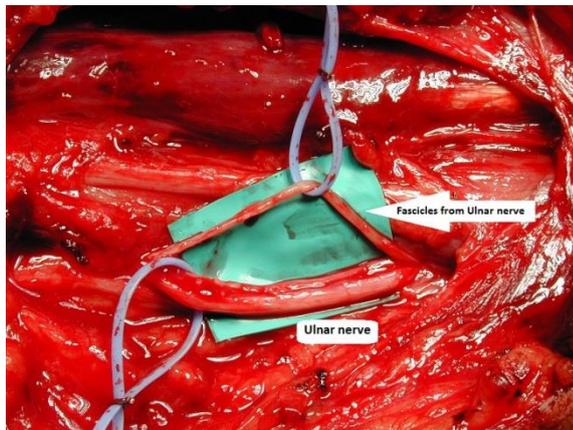


Figure 2B: Two motor fascicles from ulnar nerve (UN) were identified.

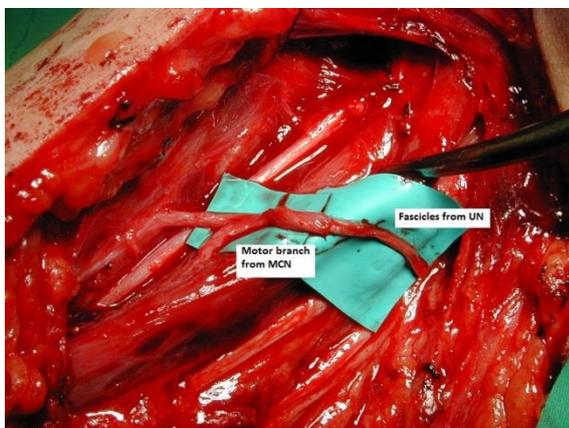


Figure 2C: The motor fascicles from UN were transferred to the motor branches from MCN to biceps by 9-0 Nylon coaptation suture.

This transfer restores elbow flexion following loss of the MCN, a branch of lateral cord. In 2004, he reported that 20 of 32 patients who underwent this procedure and recovered active motion against gravity and resistance (M4).²⁰ This procedure was validated by Leechavengvongs in Thailand who reported his experience with 26 of 32 patients (81.3%) who had regained M4 elbow flexion following the Oberlin I transfer.⁴⁹ In both studies none of the patients displayed any sequelae from sacrificing an UN fascicle as a donor.^{20,49} The technique to choose adequate donor nerve fascicles of UN is very important. By using a nerve stimulator intra-operatively, surgeons should choose the fascicles that innervate extrinsic muscles (such as flexor carpi ulnaris) for transfer. This selective nerve fascicle dissection can prevent a mistake in harvesting the fascicles of UN that supply the intrinsic muscles and cause donor site deficiency (such as claw hand deformity).^{2-4,12,14,16,17,19,20,48-50}

(2) **Mackinnon's method (Oberlin II method):** Although the Oberlin I method is a common and practical technique for reconstructing elbow flexion in upper arm type BPI, some patients in the French and Thai studies unfortunately required further muscle origin transfers (Steindler flexorplasty) to improve elbow flexion. Surgeons found that when the brachialis muscle was also re-innervated in addition to biceps, the patient achieved better elbow flexion than biceps re-innervation alone.^{12,17,20,49,50} In search of a procedure which could eliminate the need for additional muscle transfer, Susan MacKinnon in St. Louis along with Christophe Oberlin in Paris described the Oberlin II (double) nerve transfers in 2003.^{12,17,50,51} In this reconstruction, one fascicle from UN was transferred to MCN, while one fascicle from MN was transferred to the motor branch to the brachialis muscle. (Figure 3A-C)

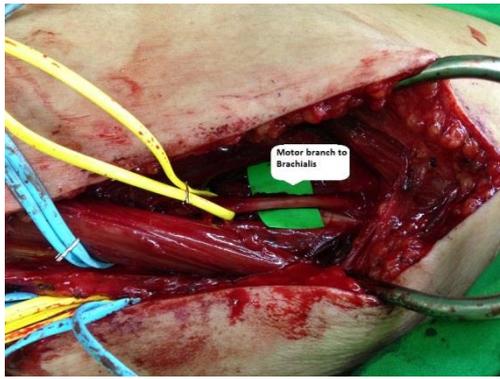


Figure 3A: Mackinnon's method (Oberlin II). The motor branch to brachialis muscle was identified.

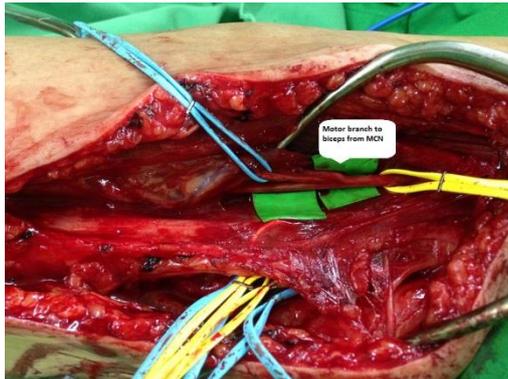


Figure 3B: The motor branch from MCN to biceps was also identified.

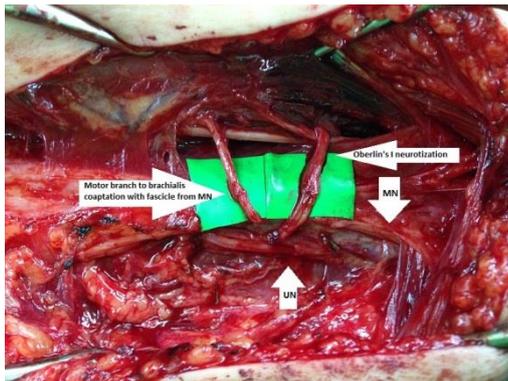


Figure 3C: The motor fascicle from MN was transferred to the motor branch to brachialis muscle, and the motor fascicle from UN was simultaneously transferred to the motor branch from MCN to biceps by 9-0 Nylon coaptation suture.

The additional re-innervation of the brachialis, a strong elbow flexor, has improved outcomes following loss of MCN. In 2005, Oberlin reported 15 of 15 patients (100%) recovering M4 elbow flexion, and Mackinnon reported 6 of 6 (100%) recovering M4 strength. No patient from either study showed any sign of motor or sensory loss.^{2, 50, 51} the addition of the MN coaptation has markedly increased the success rate of elbow flexion without sacrificing the donor nerve (MN and UN) function in hands.

(3) Intercostal nerves (ICNs) transfer to MCN: The ICN contains approximately 3,000 to 4,000 myelinated fibers, with each ICN carrying a different number of motor and sensory fibers.^{1, 48} The 3rd and 4th ICNs contain a significant number of motor fibers. ICN transfer was introduced

by Yeoman and Seddon, but sparked by Japanese doctors Tsuyama, Hara, and Nagano.^{10, 12,36,39,45} It has been widely used for BPI neurotization, especially for reinnervation of the MCN.^{9, 45, 48} The surgical approach for harvesting ICNs is extended from the usual supra- and infra-clavicular incisions at the anterior border of the axilla onto the infra-areolar (male) or inframammary fold (female) to gain access to the ICNs. Direct suture of 2 or 3 ICNs to MCN without nerve graft is the key to achieving good results. (Figure 4A, 4B)

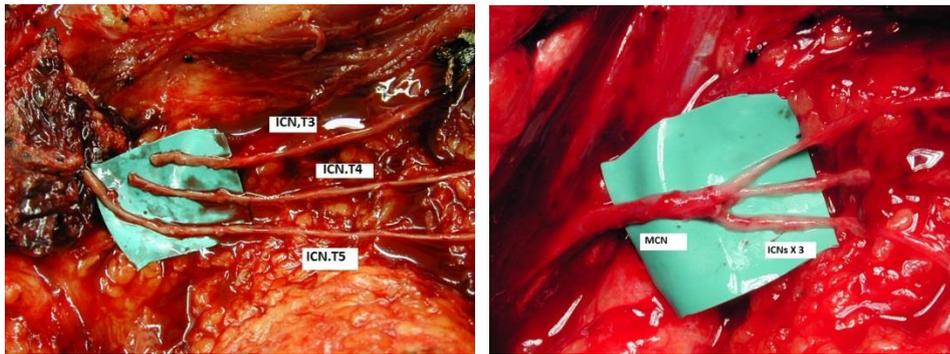


Figure 4A (left): Three intercostal nerves (ICNs) were identified from the 3rd, 4th, and 5th intercostal spaces with thoracic spinal roots (T3, T4, T5) harvested for transfer.

Figure 4B (right): Three ICNs were transferred to the MCN by using 10-0 Nylon coaptation suture.

The techniques of ICNs direct coaptation suture with the MCN should be emphasized in two aspects. The first aspect is the tension-free nerve coaptation suture to ensure proper nerve regeneration after trauma. The second aspect is the concomitant reconstruction of motor and sensory function of the MCN by accurate location of the motor and sensory components of MCN and ICNs. The MCN is the terminal branch of lateral cord. The motor component of the MCN is located in the central and upper zones of cross-section cut, while the sensory component of the MCN is located in the peripheral and lower zones of the MCN. Therefore, we recommend transfer of 2 or 3 ICNs to the MCN by using motor nerves of ICNs direct coaptation suture with central and upper portions of the MCN cut-surface. And then, the superficial lateral sensory branches of ICNs should be sutured onto the peripheral and lower portions of the

MCN cut-surface.¹⁰ The M3 elbow flexion is usually achieved 12 to 18 months after surgery. The continuous improvement of M3 to M4 elbow flexion depends on the intensity of rehabilitation and the compliance of patients. An adequate physical therapy program may allow patients to achieve M4 elbow flexion in 3 years after surgery. During the first 2 years after the operation, biceps function synchronizes with the respiratory cycle. In the 3rd postoperative year, voluntary biceps control is usually obtained, but involuntary elbow contraction while coughing and sneezing still persists. Sensory recovery of the MCN territory is also attained. During the first 1 to 2 years, sensation is perceived only in the chest. Later, some sensations are recovered on the radial surface of the forearm 2 to 3 years after surgery. The reported successful rate (\geq M3 elbow flexion) of ICNs neurotization on MCN is ranged from 36% to 65%. Due to the complexity of harvesting ICNs which is a time consuming procedure, most surgeons prefer Oberlin's or Mackinnon's methods for reconstructing elbow function instead of ICNs, in upper arm type BPI.^{9,12,45}

(4) SAN-sural nerve graft-MCN, or PN-sural nerve graft-MCN: The use of the spinal accessory nerve (SAN) or phrenic nerve (PN) transfer, by a free sural nerve graft bridging interposition, and neurotization of the MCN had been reported to have acceptable muscle power recovery of elbow flexion (range from 50% to 80% \geq M3 elbow flexion).^{1,3,10,12,15,18,27,34,48,52} A prospective randomized comparison study was conducted to investigate the elbow power recovery by SAN-nerve graft-MCN and by ICNs-MCN respectively. Their results showed that for the SAN-nerve graft-MCN technique, the successful rate (\geq M3 elbow flexion) was 83%, while the ICNs neurotization on MCN had only 64% successful rate.⁵² There are two advantages of using the SAN and PN as motor neurotizers for elbow flexion. First, the SAN and PN contain more motor myelinated fibers than 3 ICNs. Second, the functional relationship between shoulder abduction / respiration and elbow flexion leads to easier postoperative rehabilitation.³⁴ However, the SAN-sural nerve graft-MCN and PN-sural nerve graft-MCN methods are purely for motor recovery of

elbow. No sensory recovery was achieved by these 2 techniques. The disadvantages of using the SAN transfer are the need for harvesting sural nerve graft by an additional incision, and the sacrifice of a potential neurotizer for a dysfunctional supra-scapular nerve (for shoulder function). The disadvantages of the PN transfer are similar to the SAN, with additional drawbacks of immediate postoperative respiration distress, and long term complications of decreased vital capacity of lung function. In recent years, most surgeons prefer to employ Oberlin's or Mackinnon's methods to reconstruct elbow flexion in upper arm type BPI, instead of using the SAN or PN as an elbow neurotizer.^{3,9,10,12,14,16,17,20,21,51}

(5) Medial pectoral N (MPN) to MCN transfer. The direct coaptation suture of **the** MPN with the MCN is an intra-plexus neurotization method.^{3,12,18,53} The reported data showed that 80% patients achieved \geq M3 elbow flexion, while 60% of patients gained MRC grade 4 motor recovery of elbow flexion.⁴ With the additional C5 or C6 nerve direct repair, the surgical results of elbow flexion might even reach 100%.⁴ The disadvantages of using the MPN as neurotizer are the short length of the donor nerve (MPN), and the long distance between the MPN and MCN which makes its reach to the motor branch of the MCN difficult.⁵³

(6) Latissimus dorsi (LD) flap / Gracilis free functioning muscle transfer (FFMT) to elbow (biceps insertion). These two methods are reserved as salvage procedures for upper arm type BPI reconstruction. In upper arm type C5-C6 injury BPI, when the above mentioned neurotizations failed, the LD flap anterior transfer to biceps tendon insertion (so-called **bipolar transfer**) is an alternative salvage procedure for restoring elbow flexion. The successful rate of this LD pedicle functioning muscle transfer is acceptable (80% \geq M3 elbow flexion).⁵ However, in C5-6-7 complete injury, the thoracodorsal nerve supplying the motor function of LD muscle is mostly damaged. Therefore, the gracilis FFMT should be employed for reconstructing elbow flexion.^{5,12,40,41} The proximal gracilis is sutured onto the distal clavicle or coracoid process, while the distal gracilis tendon is sutured onto the biceps insertion site. The motor nerve (obturator nerve) of this FFMT may be

microsurgically sutured with ICNs or SAN as neurotizers. With adequate planning of microsurgery and proper postoperative rehabilitation, the elbow flexion after gracilis FFMT may be recovered around 75% to 80% \geq M3 elbow flexion.^{5,40,41}

Nerve / tendon transfers options for shoulder abduction / elevation / external rotation in upper arm type BPI

There are several nerve / tendon transfer options for the reconstruction of shoulder abduction / elevation / external rotation in upper arm type BPI. The donor nerves applied for BPI shoulder function neurotization include: spinal accessory nerve (SAN), triceps branch of radial nerve (TbRN), medial pectoral nerve (MPN), phrenic nerve (PN), and intercostal nerve (ICN). The recipient nerves are the suprascapular nerve (SSN) and axillary nerve (AXN). The following six techniques are most commonly used methods.

- (1) Spinal accessory nerve (SAN) to suprascapular nerve (SSN) transfer.** The SAN to SSN transfer is an older yet reliable option for restoration of shoulder abduction and glenohumeral stability.^{3,9,31,42,46,48} The SAN is the XI cranial nerve which serves to innervate the trapezius muscle distally in its course. Originally this transfer required a large supraclavicular Millesi incision for assess, however recent advances in technique have permitted much smaller and more aesthetic incisions.^{2,23,24} This transfer has been successful largely due to its consistent anatomy, and close proximity to the donor nerve which avoids the need for an interpositional nerve graft.² **(Figure 5A, 5B).** Songcharoen and Spinner reported a good outcome in 74% of their 577 SAN-SSN transfers.³ Terzis and Kostas also reported their good and excellent clinical shoulder recovery outcomes in 79% of their 118 patients receiving SAN-SSN transfers.⁴²

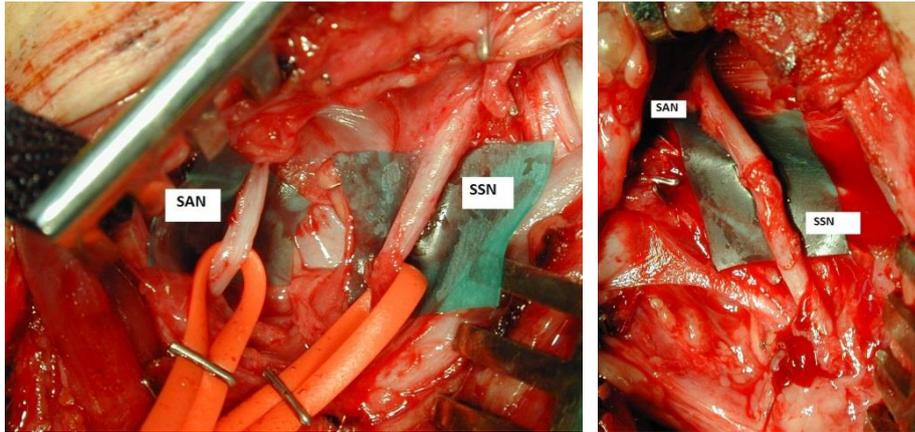


Figure 5A (left): Spinal accessory nerve (SAN) and suprascapular nerve (SSN) were indentified through the anterior supra-clavicular approach.

Figure 5B (right): Neurotization was performed by SAN to SSN transfer, with 9-0 Nylon coaptation suture.

(2) Triceps branch of Radial nerve (TbRN) to axillary nerve (AXN)

transfer. Transferring the radial nerve to the AXN was originally described in 1948 by Alexander Lurje from Russia.^{2,30} However, his initial description was through an anterior approach which was difficult for surgical dissection, and also had the drawback of requiring an interpositional nerve graft. This transfer was essentially abandoned for other transfer options in 2003 when Leechavengvongs from Thailand described the posterior approach.^{2,12,47} The Lerdsin group (Leechavengvongs et al. in Thailand) performed a single longitudinal incision to approach the anterior branch (mostly motor fibers) of the AXN in the quadrilateral space. Subsequently the radial nerve is dissected in the triangular interval just distal to the teres major. The motor nerve to the long head of the triceps is identified and dissected at this point. The TbRN was then coapted by suture to the anterior branch of the AXN directly for restoring the motor function of deltoid muscle. **(Figure 6A, 6B, 6C)** The posterior approach was revolutionary because of the ease of dissection, no interpositional graft is required, and it places the donor nerve close to the motor endplate of the recipient.⁴⁷ This type of nerve transfer may improve the shoulder stability and elevation / abduction because this method is performed in addition to the SAN to SSN

transfer.^{2,9,12,15,16,46,47} Leechavengvongs reported that 7 of 7 patients achieved deltoid function against gravity with a mean of 124 degrees of shoulder abduction. There was no shoulder subluxation or loss of triceps function in their series.⁴⁷ Bertelli et al. also reported their combined SAN-SSN and TbRN-AXN methods for upper arm type BPI reconstruction in which all patients achieved active shoulder abduction / elevation and external rotation. Abduction recovery averaged 92 degrees and external rotation averaged 93 degrees in their patients.¹⁴ In addition to the posterior approach, Bertelli et al. also described a new approach for TbRN transfer to AXN by an anterior approach (axillary access) with excellent shoulder recovery (3 in 3 patients achieved M4 deltoid function and shoulder abduction).⁵⁴ The advantage of this method is the ease of dissection through the anterior approach in one surgical position. The combined SAN-SSN and TbRN-AXN method is currently the most popular technique for shoulder reconstruction in patients with C5-C6 injured upper arm type BPI.

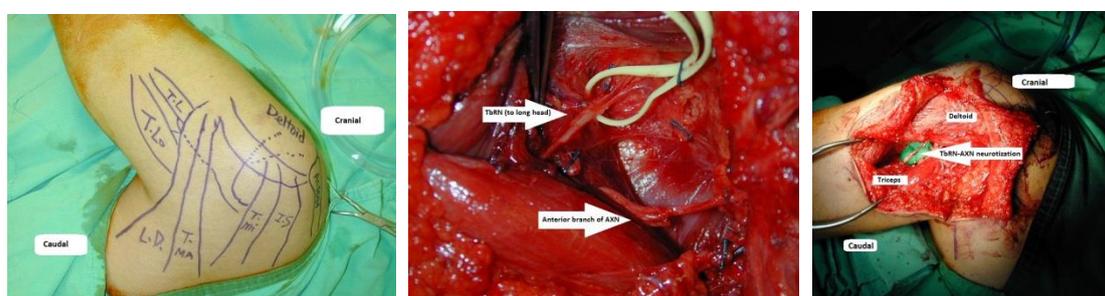


Figure 6A (left): Skin marks for Triceps branch of radial nerve (TbRN) to axillary nerve (AXN) transfer surgery. IS (infra-spinatus muscle); Tmi (Teres minor), TMA (Teres major), LD (Latissimus dorsi), TL (Triceps long head), TLo (Triceps lower head)

Figure 6B (centre): TbRN (to the long head of triceps) and anterior branch of AXN can be easily identified in the quadrilateral space.

Figure 6C (right): Neurotization with TbRN transfer to anterior motor branch of AXN was performed by using 9-0 Nylon coaptation suture.

(3) Intercostal nerves (ICNs) to axillary nerve (AXN) transfer.

Recently many surgeons have recommended simultaneous nerve transfer to both the SSN and AXN for achieving better shoulder function.

^{2,9,12,15,16,46,47} Although the SAN to SSN combined with the TbRN to AXN

double neurotization had been reported to have satisfactory results in shoulder recovery, this model of double neurotization could not be applied in C5 through C7 root avulsion injuries. In C5,C6 combined with C7 damaged BPI, the TbRN could not be used as a neurotizer because the main component of the radial nerve comes from the C7 root. There are some donor nerves that can be used for transferring to the AXN, such as PN, SAN, and MPN.^{10,18,53} However, the clinical results of PN-AXN, SAN-AXN and MPN-AXN neurotization procedures were unsatisfactory.^{10,18,53,55} The Lerdsin group in Thailand developed a method which uses the posterior approach to dissect the 4th and 5th ICNs which are then transferred to the anterior branch of the AXN. The patient is put in supine position with a sandbag underneath the affected upper limb. A curved incision was made along the 5th rib. To ensure an adequate length of the ICNs, the 4th and 5th ICNs were dissected as far posteriorly as possible. Just anterior to the mid-axillary line, the sensory branches of the ICNs were identified and cut to enhance the mobility of the ICNs. Then the shoulder was rolled anteriorly. A second incision was made along the posterior border of deltoid muscle, and the quadrilateral space was explored. The anterior branch of the AXN was identified, and a subcutaneous tunnel was made between the first and the second incisions. The 4th and 5th ICNs were passed through the subcutaneous tunnel and the direct coaptation sutured with the anterior branch of the AXN. Good shoulder function with M4 deltoid recovery was obtained in both of their 2 patients.⁵⁵ Because this is a combined procedures with the SAN-SSN and Oberlin procedures, care must be taken to ensure adequate length of ICNs transfer to the AXN which allows fully passive shoulder abduction motion without tension on the nerve coaptation site.

- (4) **Phrenic nerve (PN) to suprascapular nerve (SSN) transfer.** PN transfer to the SSN could be performed as a direct neurotization method for shoulder reconstruction without interpositional nerve graft. It has been frequently used by many surgeons in Asia, but rarely been used in the Occidental countries because of concern regarding decreased pulmonary capacity after the sacrifice of PN.¹⁰ Based on Gu's study, the

pulmonary capacity decreased because of limited excursion and elevation of the diaphragm for 1 year, but then recovered to normal value by 2 years postoperatively.³⁴ Chuang also frequently used the PN as neurotizer for adult patients without significant respiratory problems.¹⁰ PN transfer to the SSN has similar satisfactory results (around 70% \geq M3 shoulder abduction) as SAN-SSN transfer, because the PN has abundant motor fibers. However, patients with smoking, poor pulmonary function, associated chest trauma, and morbid obesity are not ideal candidates for PN harvesting.

- (5) Nerve transfer to serratus anterior muscle using the thoracodorsal nerve for winged scapula.** Serratus anterior muscle is one of the major scapula stabilizers that is critical in maintaining proper scapulohumeral rhythm during glenohumeral movement, particular in shoulder and arm elevation. Patients with serratus anterior palsy in BPI may present with pain, weakness, limitation of shoulder elevation, and scapular winging with medial translation of the scapula, rotation of the inferior angle toward the midline, and prominence of the vertebral border. This winging becomes more prominent as the patient attempts to push forward against resistance. The Lerdsin group in Thailand found that 7 of 15 patients in their series who received SAN-SSN, TbRN-AXN, and Oberlin's method for C5-C6 BPI, were observed to have winging of the scapula, paralysis of the serratus anterior muscle, and painful disability when elevating their shoulder.¹⁶ Subsequently, the Lerdsin group developed their method of reconstruction for serratus anterior by transferring the thoracodorsal nerve to the long thoracic nerve.⁵⁶ They performed a 12 cm longitudinal incision along the posterior aspect of the axilla which was around the anterior border of the latissimus dorsi muscle. Retraction of the latissimus dorsi allowed exposure of the thoracodorsal and long thoracic nerves. Two thoracodorsal nerve branches (medial and lateral branch) were identified, and the branch with stronger muscle contraction during nerve stimulation was chosen as the neurotizer. The long thoracic nerve was exposed along the chest wall and divided as proximal as possible to ensure that the majority of the

serratus anterior muscle could be innervated. This proximal dissection of long thoracic nerve also provided enough length of nerve for coaptation suture without tension. All patients in their series obtained good shoulder functional recovery without any donor site complication from harvesting one branch of the thoracodorsal nerve.⁵⁶ This additional neurotization procedure (thoracodorsal nerve transfer to long thoracic nerve) may offer better shoulder function than the combined SAN-SSN and TbRN-AXN techniques. This method is especially beneficial in patients who place high demands on their shoulders.

(6) Trapezius muscle transfer to shoulder girdle muscles. Persistent shoulder paralysis after BPI is a difficult and challenging problem to treat. Although various methods of neurotizations have been described in the literature, some BPI patients still suffer from shoulder dysfunction either after nerve transfer reconstruction failure or delayed / neglected treatment. The resulting shoulder muscle weakness leads to a “hand-on-belly” internally rotated position that limits positioning of the hand anterior to the coronal plane with elbow flexion, and painful glenohumeral subluxation. In these instances, upper trapezius transfer has been attempted to restore shoulder abduction with variable results reported^{43,44} A combined procedure with latissimus dorsi muscle transfer to the greater tuberosity to reconstruct the rotator cuff, and trapezius transfer to deltoid muscle had been performed for simultaneous reconstruction of shoulder abduction / elevation and external rotation, but the outcomes could achieved only around 75 degrees of shoulder abduction^{5,23,25,43,44} **(Figure 7A, 7B)**. A novel technique of transferring middle and lower segments of the trapezius muscle, extended with a tendon allograft, to restore the external rotation of shoulder function was reported with good satisfactory results.⁴⁴

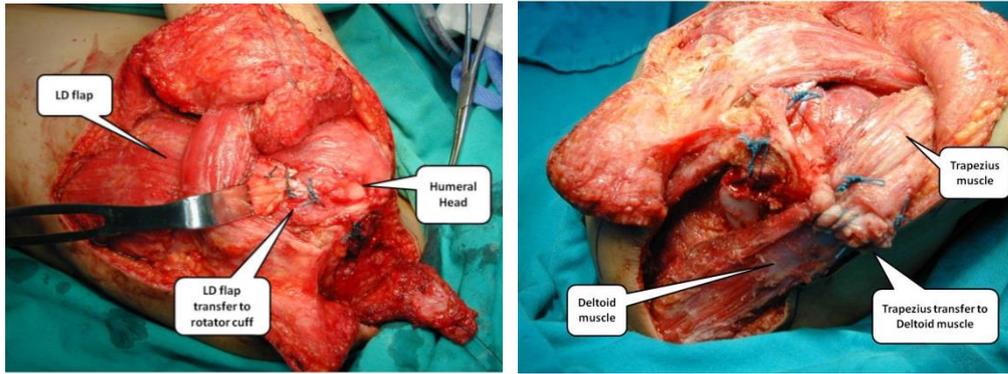


Figure 7A (left): Delay shoulder reconstruction by LD (latissimus dorsi) transfer to anchor at greater tuberosity of humeral head that served as the rotator cuff function.

Figure 7B (right): Trapezius to Deltoid muscle transferred was performed, in combination with the LD-rotator cuff transfer for reconstructing the shoulder abduction / elevation, and external rotation.

Reconstructions for wrist / hand extension function in upper arm type (C5, C6 with C7 injuries) BPI

In upper arm type BPI, many C7 injuries are found in combination with C5 and C6 ruptures. Patients are usually presenting with loss of shoulder abduction / elevation function and elbow flexion, together with loss of wrist and finger dorsiflexion. The reconstructions for this type of injury may include direct repair, nerve graft, and neurotization as well. However, although the reported results of good shoulder and elbow function could be obtained after various neurotization methods, the results of C7 functional recovery were not satisfactory. This is because many of the C7 innervated muscles are located at the forearm level (except the triceps muscles which are located in the arm level), and hence the re-innervation occurs quite slowly before reaching the target neuromuscular junctions. The functional needs of the hand after C7 injury (radial nerve palsy) are (1) wrist extension, (2) finger and thumb extension, and (3) thumb proximal stability.⁵ For wrist extension, The PT (pronator teres) muscle can be transferred to the ECRB (extensor carpi radialis brevis) musculo-tendonious junction, if the motor function of PT is recovered after BPI reconstruction. For finger extension, the traditional procedure uses the FCU (flexor carpi ulnaris) transfer to the EDC (extensor digitorum communis) tendons, and PL (palmaris longus) transfer to

EPL (extensor pollicis longus) tendon. This full FCU transfer often results in a slight radial deviation of the hand at the wrist. If the patient has significant radial deviation at the wrist, the insertion of the ECRL (extensor carpi radialis longus) should be transferred to the ECU (extensor carpi ulnaris), or the FCU tendon transfer should not be done. Fingers and thumb extension can also be reconstructed by transferring the FDS (flexor digitorum superficialis) tendons of the long and ring finger. The ring FDS is attached to the EDC, similar to the FCU transfer, and the long FDS is attached to the EPL. The other alternative method is transferring the PL to EPL, and transferring the FCR (flexor carpi radialis) to the EDC. For the proximal stability of the thumb, the EPB (extensor pollicis brevis) is mobilized from the 1st dorsal compartment and tenodesed to the PL. However, when PL has been used for thumb extension reconstruction, an alternative method is using the split FCR, tenodesing it to both APL (abductor pollicis longus) and EPL tendons.

Surgical Treatment for Pain

Adequate pain management is mandatory for BPI patient's quality of life. The disability of upper limb and intractable pain usually results in limitation of social activities and employment. Pain occurs frequently after injury, starting usually within weeks of the trauma event and then, becomes chronic. Sometimes, but not always, the pain may be relieved by medications, including NSAIDs (Non-steroid anti-inflammatory drugs), narcotics and anticonvulsants. However, many BPI patients suffering from intractable pain which could not be effectively relieved by pain killers, should be considered as candidates for surgery. The surgical treatment for pain relief may be performed by the method of DREZ (Dorsal root entry zone) rhizotomy. The authors performed thermocoagulation (rhizotomy) at the DREZ for intractable pain after BPI in 60 cases.^{5,7} Forty cases were under regular follow-up for 5 to 18 years. In the early postoperative stage, the pain relief was excellent or good in 32 cases (80%). The pain relief rate dropped to 60% at 5 years follow-up, and only 50% of patients had excellent or good pain-relief outcomes in 10 years follow-up.^{5,7} There is still more work to be done in treating pain in BPI patients.

Rehabilitation and objective assessment of the motor recovery after surgery for BPI

Adequate scheduled rehabilitation is the key to satisfactory clinical outcomes after BPI surgery. The postoperative custom made protecting brace should be tailored, and each patient's rehabilitation program has to be unique for each injury. The physical therapy with a passive range of motion and slow-pulse electrical stimulation should be started immediately after proper surgical wound healing. Home electrical stimulation was provided for all of the patients with a portable slow pulse stimulation device that the patient was instructed to use for 4 to 6 hours per day for a minimum of 2 years, or until antigravity motor function (M3) occurred.^{5,13} Significant recovery after neurotizations can take more than 9 to 18 months for functional improvement. The rehabilitation programs also include hand grip-power training (for elbow neurotization), trapezius muscle training (for SAN-SSN), respiration training (for ICN-AXN, and PN-SSN), and repeated elbow extension training (for TbRN-AXN) as well. These physical therapy maneuvers may enhance timely motor recovery.

The Medical Research Council (MRC) grading system, which ranges from graft M0 (no contraction) to M5 (normal), is a quick and easy tool to evaluate muscle strength recovery after BPI surgery. However, the simplified MRC grading system may result in the underestimation of muscle strength improvement. The authors have developed an objective assessment method, which employs the use of HHD (Hand-held dynamometer) for more detailed and scientific evaluations for the functional outcomes of BPI patients during the rehabilitation program after surgery.^{57,58} This HHD evaluation method has been reported to have excellent reliability for measuring the muscle strength recovery after neurotization procedures for BPI ⁵⁷**(Figure 8)**. Based on the objective assessment data by HHD evaluations, neurotization in C5-C6 BPI patients had significant better elbow, shoulder, and hand grip functions than C5-6-7 BPI patients, which were not detected by simplified MRC grading.⁵⁸

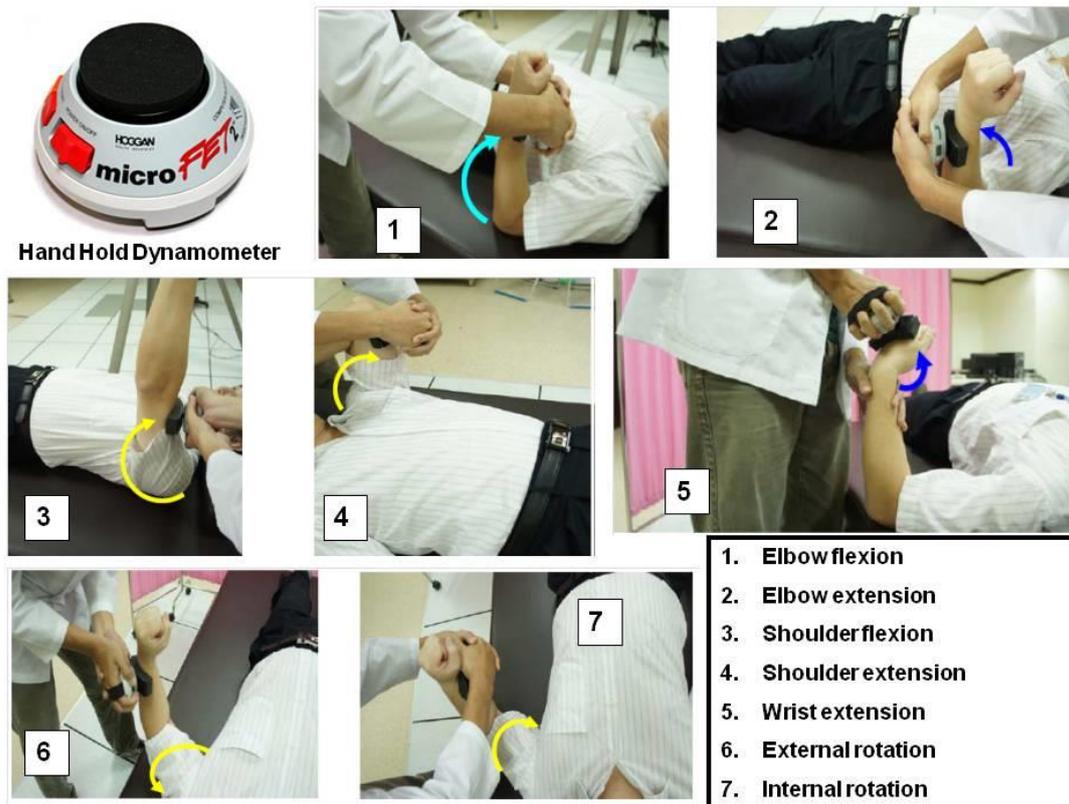


Figure 8: The clinical evaluation of shoulder and elbow muscle power recovery in BPI patients by using the Hand Hold Dynamometer (HHD).

Summary

- (1) The current trends in surgical treatments for upper arm type BPI is close-target neurotization by either intra-plexus neurotization or extra-plexus neurotization methods. The goals are to achieve effective elbow flexion, shoulder abduction / elevation, and shoulder external rotation.
- (2) Primary exploration of the injury site is still needed for better understanding of the extent of trauma, and for the possibility of identifying available proximal nerve root stumps for repairing / grafting.
- (3) The double neurotization technique for elbow flexion (Mackinnon's method or the Oberlin II method) may obtain faster and more effective muscle power recovery for elbow flexion than the Oberlin I, ICNs-MCN, and SAN-sural nerve graft -MCN methods.

- (4) Shoulder function may be reconstructed by either single neurotization (such as SAN-SSN or PN-SSN), double neurotization (such as SAN-SSN and TbRN-AXN, or SAN-SSN and ICNs-AXN), or triple neurotization (such as SAN-SSN, TbRN-AXN, and thoracodorsal nerve to long thoracic nerve transfer). The complexity of shoulder functional recovery suggests that a greater number of neurotization procedures have better shoulder outcomes than with just a single neurotization method.
- (5) Combined neurotization procedures for simultaneous elbow and shoulder reconstruction, such as triple nerve transfers (SAN-SSN, TbRN-AXN, Oberlin I or II method) is the current trend of BPI surgery. This “bundled” transfer when performed prior to 6 months following injury in patients under 40 years of age has achieved excellent results.
- (6) Muscle / tendon transfers may be reserved for BPI salvage procedures, or for C7 deficit functional reconstruction.
- (7) Effective pain relief and well-scheduled rehabilitation programs improve the quality of life in BPI patients. Objective assessments of the muscle strength postoperatively by HHD may allow better awareness of the real situation in the BPI patient’s recovery.

References

1. Narakas AO. Neurotization in the treatment for brachial plexus injuries. In: Gelberman RH. Editor. Operative nerve repair and reconstruction. Philadelphia: JB Lippincott; 1991. p. 1329-58
2. Schessler MJ, McClellan WT. The role of nerve transfers for C5-C6 brachial plexus injury in adults. West Virginia State Medical Journal 2010; 106(1): 12-17.
3. Soncharoen P, Wongtrakul S, Spinner R. Brachial plexus injuries in the adult. Nerve transfers: The Siriraj hospital experience. Hand Clinic 2005; Feb:21(1): 83-9.

4. Sulaiman OAR, Kim DD, Burkett C, Kline DG. Nerve transfer surgery for adult brachial plexus injury: A 10-year experience at Louisiana State University. *Neurosurgery* 2009; Oct: 65(4): 55-62.
5. Tu YK, Chung KC. Surgical procedures for recovery of hand function. Practical management of pediatric and adult brachial plexus palsies. In: Chung KC, Yang LJS, McGillicuddy JE, editors. Saunders Elsevier; 2012. p 271-300.
6. Bertelli JA, Ghizoni MF. Pain after avulsion injuries and complete palsy of the brachial plexus: The possible role of nonavulsed roots in pain generation. *Neurosurgery* 2008; May: 62(5): 1104-14.
7. Chen HJ, Tu YK. Long term follow up results of dorsal root entry zone lesions for intractable pain after brachial plexus avulsion injuries. *Acta Neurochir* 2006; 99: 73-75.
8. Furey MJ, Midha R, Xu QG, Belkas J, Gordon T. Prolonged target deprivation reduces the capacity of injured motoneurons to regenerate. *Neurosurgery* 2007; 60: 723-33.
9. Terzis JK, Kostopoulos VK. The surgical treatment of brachial plexus injuries in adults. *Plast Reconstr Surg* 2007; 119: 73-92.
10. Chuang DCC. Nerve transfers in adult brachial plexus injuries: my method. *Hand Clin* 2005; 21: 71-82.
11. Sammer DM, Kircher MF, Bishop AT, Spinner RJ, Shin AY. Hemi-contralateral C7 transfer in traumatic brachial plexus injuries: outcome and complications. *J Bone Joint Surg Am* 2012;94:131-137.
12. Shin AY, Spinner RJ, Steinmann SP, Bishop AT. Adult traumatic brachial plexus injuries. *J Am Acad Orthop Surg* 2005; 13(6): 382-396.
13. Tu YK, Tsai YJ, Chang CH, Su FC, Hsiao CK, Tan JSW. Surgical treatment for total root avulsion type brachial plexus injuries by neurotization: A prospective comparison study between total and hemicontralateral C7 nerve root transfer. *Microsurgery* 2014;34: 91-101..
14. Bertelli JA, Florianopolis SC. Ghizoni MF. Reconstruction of C5 and C6

- brachial plexus avulsion injury by multiple nerve transfers: spinal accessory to suprascapular, ulnar fascicles to biceps branch, and triceps long or lateral head branch to axillary nerve. *J Hand Surg* 2004; 29(A):131–139.
15. Garg R, Merrell GA, Hillstrom HJ, Wolfe SW. Comparison of nerve transfers and nerve grafting for traumatic upper plexus palsy: a systematic review and analysis. *J Bone Joint Surg Am.* 2011; 93(9):819–829.
 16. Leechavengvongs S, Witoonchart K, Uerpaiojkit C, Thuvasethakul P, Malungpaishrope K. Combined Nerve Transfers for C5 and C6 Brachial Plexus Avulsion Injury. *J Hand Surg.* 2006; 31(A):183–189.
 17. Mackinnon SE, Colbert SH. Nerve transfers in the hand and upper extremity surgery. *Tech Hand Upp Extrem Surg.* 2008; 12(1):20–33.
 18. Merrell GA, Barrie KA, Katz DL, Wolfe SW. Results of nerve transfer techniques for restoration of shoulder and elbow function in the context of a meta-analysis of the English literature. *J Hand Surg* 2001; 26(A): 303-14.
 19. Oberlin C, Beal D, Leechavengvongs S, Salon A, Dauge MC, Sarcy JJ. Nerve transfer to biceps muscle using a part of ulnar nerve for C5-C6 avulsion of the brachial plexus: anatomical study and report of 4 cases. *J Hand Surg* 1994; 19(A): 232-237
 20. Teboul F, Kakkar R, Ameer N, Beaulieu JY, Oberlin C. Transfer of fascicles from the ulnar nerve to the nerve to biceps in the treatment of upper brachial plexus palsy. *J Bone Joint Surg Am* 2004; 86(7): 1485-90.
 21. Tung TH, Mackinnon SE. Nerve Transfers: Indications, Techniques, and Outcomes. *J Hand Surg.* 2010; 35(A):332–341.
 22. Aydn A, et al. Three-thousand-year-old written reference to a description of what might be the earliest brachial plexus injuries in the Iliad of Homer. *Plast Reconstr Surg* 2004: Oct; 114(5):1352-3.
 23. Millesi H. Surgical management of brachial plexus injuries. *J Hand Surg* 1977; 2 (A): 367-79.
 24. Millesi H. Brachial plexus injuries: nerve grafting. *Clin Orthop* 1988;237:36-42

25. Narakas AO. Brachial plexus surgery. *Orthop Clin North Am* 1981;12:303-323
26. Sedel L. Repair of severe traction lesions of the brachial plexus. *Clin Orthop* 1988;237: 62-6
27. Narakas AO, Hentz VR. Neurotization in Brachial plexus injuries: Indication and results. *Clin Orthop* 1988;237:43-56
28. Kennedy, Robert. On the restoration of coordinated movements after nerve-crossing, with interchange of function of the cerebral cortical centers. *Philosophical transactions of the Royal Society of London. Series B. Containing papers of a Biological Character.* 1901; 194: 127-182.
29. Langley JN, Anderson HK. The union of different kinds of nerve fibers. *J Physiol* 1904 Aug; 31(5):365-91.
30. Lurje A. Concerning surgical treatment of traumatic injury of the upper division of the brachial plexus. *Annals of Surgery* 1948 Feb; 127(2):317-26.
31. Weber R, MacKinnon S. Nerve transfers in the upper extremity. *J Hand Surg* 2004;4(A):200-13.
32. Bertelli JA, Ghizoni MF. Results of grafting the anterior and posterior divisions of the upper trunk in complete palsies of the brachial plexus. *J Hand Surg* 2008; 33(A):1529-1540.
33. Ochiai N, Nagano A, Sugioka H, Hara T. Nerve grafting in brachial plexus injury. Results of free grafts in 90 patients. *J Bone Joint Surg* 1996; 78(B): 754-8.
34. Gu YD, Ma MK. Use of the phrenic nerve for brachial plexus reconstruction. *Clin Orthop* 1996;323:119-121.
35. Gu YD, Zhang GM, Chen DS, Yan JG, Cheng XM, Chen L. Seventh cervical root transfer from the contralateral healthy side for treatment of brachial plexus root avulsion. *J Hand Surg* 1992; 17(B):518-521.
36. Nagano A, Ochiai N, Okinaga S. Restoration of elbow flexion in root lesions of brachial plexus injuries. *J Hand Surg* 1992; 17(A):815-21.
37. Htut M, Misra VP, Anand P, Birch R, Carlstedt T. Motor recovery and the breathing arm after brachial plexus surgical repairs, including

- re-implantation of avulsed spinal roots into the spinal cord. *J Hand Surg* 2007; 32(E): 170-8
38. Carlstedt T, Grane T, Hallin RG, et al. Return of function after spinal cord implantation of avulsed spinal nerve roots. *Lancet* 1995, 18346; 1323-5.
39. Dvali L, MacKinnon S. Nerve repair, grafting, and nerve transfer. *Clin Plast Surg* 2003; 30(2):203-21.
40. Doi K, Muramatsu K, Hattori Y, et al. Restoration of prehension with the double free muscle technique following complete avulsion of the brachial plexus. *J Bone Joint Surg* 2000; 82(A): 652-666.
41. Doi K. Palliative surgery: free muscle transfers. In: *Brachial plexus injuries*. ed. by Alain Gilbert, Martin Dunitz, London, 2001; pp 137-147.
42. Terzis JK, Kostas I. Suprascapular nerve reconstruction in 118 cases of adult posttraumatic brachial plexus. *Plast Reconstr Surg* 2006; 117(2): 613-29.
43. Aziz W, Singer RM, Wolff TW. Transfer of the trapezius for flail shoulder after brachial plexus injury. *J Bone Joint Surg* 1990; 72(B): 701-4.
44. Elhassan B, Bishop AT, Shin AY. Trapezius transfer to restore external rotation in a patient with a brachial plexus injury. *J Bone Joint Surg* 2009; 91(A): 939-44
45. Coulet B, Boretto JG, Lazerges C, Chammas M. A comparison of intercostals and partial ulnar nerve transfers in restoring elbow flexion following upper brachial plexus injury (C5-C6±C7). *J Hand Surg* 2010; 35(A): 1297-1303.
46. Terzis JK, Kostas I, Soucacos PN. Restoration of shoulder function with nerve transfers in traumatic brachial plexus palsy patients. *Microsurgery* 2006; 26: 316-24.
47. Leechavengvongs S, Witoonchart K, Uerpaiojkit C, Thuvasethakul P. nerve transfer to deltoid muscle using the nerve to the long head of the triceps, Part II: A report of 7 cases. *J Hand Surg*. 2003; 28(A): 633-38.
48. Songcharoen P. Management of brachial plexus injury in adults. *Scand J Surg*. 2008; 97:371-323.
49. Leechavengvongs S, Witoonchart K, Uerpaiojkit C. Nerve transfer to biceps

- muscle using a part of the ulnar nerve in brachial plexus injury (upper arm type): a report of 32 cases. *J Hand Surg.* 1998; 23(A):711-6.
50. Liverneaux PA, Diaz LC, Beaulieu JY, Durand S, Oberlin C. Preliminary results of double nerve transfer to restore elbow flexion in upper type brachial plexus palsies. *Plast Reconstr Surg* 2006; 117:915-9.
51. Mackinnon SE, Novak CB, et al. Results of reinnervation of the biceps and brachialis muscles with a double fascicular transfer for elbow flexion. *J Hand Surg* 2005; 30(A): 978-85.
52. Waikakul S, Wongtragul S, Vanadurongwan V. restoration of elbow flexion in brachial plexus avulsion injury: Comparing spinal accessory nerve transfer with intercostal nerve transfer. *J Hand Surg* 1999; 24(A): 571-7
53. Samardzic M, Grujicic D, Rasulic L, Bacetic D. Transfer of the medial pectorial nerve: myth or reality? *Neurosurgery* 2002; 50:1277-82.
54. Bertelli JA, Kechele PR, Santos MA, Duarte H, Ghizoni MF. Axillary nerve repair by triceps motor branch transfer through an axillary access: anatomical basis and clinical results. *J Neurosurg.* 2007; 107:370-377.
55. Malungpaishorpe K, Leechavengvongs S, Uerpaiojkit C, Witoonchart K, et al. Nerve transfer to deltoid muscle using the intercostal nerves through the posterior approach: an anatomical study and tow cases report. *J Hand Surg* 2007; 32(A): 218-24.
56. Uerpaiojkit C, Leechavengvongs S, Witoonchart K, Malungpaishorpe K, Raksakulkiat R. Nerve transfer to serratus anterior muscle using the thoracodorsal nerve for winged scapula in C5 and C6 brachial plexus root avulsions. *J Hand Surg.* 2009; 34(A): 74-78.
57. Tsai YJ, Tu YK, Hsiao CK, Su FC. Within-session reliability and smallest real difference of muscle strength following nerve transfers in patients with brachial plexus injuries. *J Hand Surg.* 2015; 40(A): 1196-1201.
58. Tsai YJ, Su FC, Hsiao CK, Tu YK. Comparison of objective muscle strength in C5-C6 and C5-6-7 brachial plexus injury patients after double nerve transfer. *Microsurgery* 2014; 35: 107-114.