Nerve Transfers for Severe Nerve Injury

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KEYWORDS

• Accessory nerve • Brachial plexus injury
• Intercostal nerves • Neurotization • Spinal nerve

Brachial plexus and other severe nerve injuries can have devastating consequences affecting largely a young, productive population. The optimal management, whenever possible, is direct nerve repair, which can be difficult or impossible to achieve in patients who have spinal nerve root avulsion or very proximal injury, and in patients who have a large nerve gap. Delay in presentation for surgery further complicates the situation. Nerve transfer is one strategy with potential for improved outcome. Nerve transfers (also referred to as "neurotization" or "nerve crossing") involve the repair of a distal denervated nerve element using a proximal foreign nerve as the donor of neurons and their axons, which will reinnervate the distal targets. The concept is to sacrifice the function of a lesser-valued donor muscle to revive function in the recipient nerve and muscle that will undergo reinnervation.[1] The first report of neurotization in an attempt to restore injured plexus function was by Tuttle[2] in 1913. Popularized by Oberlin, distal fascicular nerve transfers are showing encouraging and promising results,[3] and are gradually replacing the tediously performed proximal brachial plexus exploration and lengthy graft repair, which have more unpredictable results.

NERVE TRANSFERS: INDICATIONS, PROS, AND CONS

Currently, no absolute guidelines exist for when nerve transfer should be performed, but the authors consider the following to be appropriate conditions in which nerve transfer can be useful:

- Brachial plexus roots avulsion or very proximal intraforaminal injury close to the spinal cord with no, or poor, nerve stump available to lead nerve graft from
- Proximal injury with a long distance to the target muscle (eg, a high [axillary or arm] ulnar nerve lesion)
- Significant vascular and or bony injuries in the region of the brachial plexus; keeping away from of the injured, scarred area may avoid unnecessary damage to vital structures
- Delayed presentation and long interval from injury to surgery; the ideal time for direct nerve repair is up to 6 months after the injury
- Previously failed brachial plexus or proximal nerve repair

The following are some useful criteria for choosing donor nerves for transfer:

- Donor nerve near motor end plate of the target muscle
- Expandable or redundant donor nerve
- Donor nerve with many pure motor (or sensory) axons
- Donor nerve with synergistic action to the target muscle, when possible, to facilitate motor reeducation
- Size matching between the donor and recipient nerves

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The advantages of using a nerve transfer over a nerve graft repair include the following:

- Nerve transfers are usually done with the donor nerve brought closer to the end-organ. The closer the innervation of the target muscle, the shorter the distance the regenerating axons have to travel and subsequently, the better the chance of functional reinnervation.
- It allows improved and earlier reinnervation with potentially improved outcomes.
- Most nerve transfers can be accomplished without the use of an interposition graft. This advantage translates into one microsuture repair site, compared with two, and a correspondingly decreased likelihood of loss of axons (or their misdirection) at the repair sites

When selection is made carefully and functional recovery takes place, nerve transfer seems an ideal option with few downsides. However, it is not a flawless technique. Some of the disadvantages include

- Donor site morbidity and loss of muscle function of the donor nerve, particularly so when the donor nerve or fascicle is sacrificed to a muscle with suboptimal function to begin with. For instance, taking an ulnar nerve fascicle in a patient who has poor (grade 3 or barely grade 4) hand function may significantly downgrade finger flexion and intrinsic hand muscles.
- The muscle whose nerve has been used for transfer will be no longer suitable for muscle transfer. Examples are the latissmus dorsi (thoracodorsal nerve [TDN]), pectoralis major (medial pectoral nerve), and the triceps muscles (triceps muscle branch), all of which can be used to restore elbow flexion.
- The need for central reeducation to have functional recovery[4–6]
- Nerve transfers tend to take the surgeon away from exploring the injury site, the brachial plexus, which carries the potential for surgeons to not even offer an anatomic nerve reconstruction, even in situations when these are perfectly appropriate. An example is to perform a distal triceps fascicle to axillary nerve transfer in a patient who a posterior cord–axillary nerve stretch lesion, which fares well with resection of the intervening neuroma and nerve graft repair.[7]
- With the increasing use of transfers, newly trained peripheral nerve surgeons are less likely to have exposure to the brachial plexus and they will be increasingly unfamiliar with the detailed anatomy and intraoperative electrophysiology assessment of the lesions.

TREATMENT OPTIONS FOR BRACHIAL PLEXUS INJURIES

Generally, the main objectives in treating severe brachial plexus injury are to restore shoulder abduction, external rotation, elbow flexion, and forearm supination.[8] The combination of these movements will allow the patient to hold a food tray, to bring his/her hand up to his/her mouth, and to be able to push doors open while carrying items with the healthy arm. Some experts also advocate attempting restoration of wrist extension and shoulder adduction.[9,10] The following are some of the authors' preferred options for nerve reconstruction.

C5-C6 (Upper Trunk) Palsy

Traumatic complete avulsion of C5 is uncommon; therefore, C5 can often be used for plexoplexal repairs with interposed sural nerve grafts.[8] The information from preoperative imaging (CT post myelogram or high-quality MRI scans), supplemented with intraoperative dissection to the level of the intervertebral foramen and the use of intraoperative electrodiagnostic studies, will aid in the decision making.[11–14] Nonetheless, nerve transfer may be preferred because of its quicker recovery and avoidance of the injury site dissection, which can be tedious and fruitless.[9,15] Distal spinal accessory nerve (SAN) transfer to the suprascapular nerve (**Fig. 1**) and triceps branch transfer to the anterior division of the axillary nerve will restore shoulder abduction.[16,17] Elbow flexion is restored by transferring an ulnar nerve fascicle (selecting a fascicle that predominantly supplies flexor carpi ulnaris muscle) to biceps branch $\pm$ a median nerve fascicle to the brachialis branch of the musculocutaneous nerve.[3,18]

C5, C6, and C7 Palsy

When C7 is involved and the triceps muscle is weak (Medical Research Council [MRC] grade<4), triceps branch-axillary nerve transfer may downgrade the triceps muscle further and therefore, should not be used. The same overall strategy used in C5 and C6 injury can be used. However, to reinnervate the axillary nerve, thoracodorsal nerve (TDN), if intact, can be used. Medial pectoral nerve and intercostal nerves (ICNs) are alternative donors. Furthermore, the triceps muscle, if significantly weak, can be reanimated by transferring ICNs to the triceps fascicle of the radial nerve or directly to the triceps muscle branches (whichever is weaker).[15]

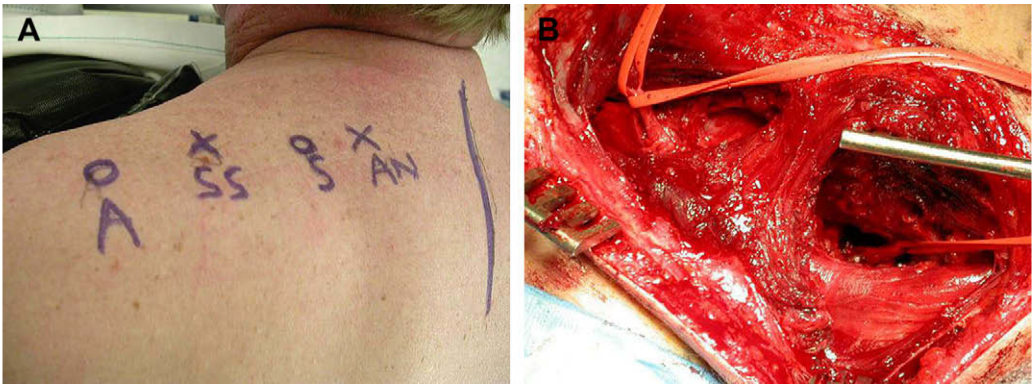

Fig. 1. (*A*) A patient is seen positioned prone with a left superior scapular incision outlined. This positioning allows exposure of both the accessory nerve (AN), which is located midway between the spinous process of the vertebra (vertical line is the midline) and the medial spine of the scapula (S), and the suprascapular (SS) nerve, landmarked halfway between the acromion (A) and the medial spine of the scapula (S). (*B*) The distal accessory nerve deep to the trapezius muscle (encircled by two vessel loops) and, to the right, the suprascapular nerve deep and just proximal to the suprascapular notch after incising the transverse scapular ligament.

Total Plexus (C5-T1) Palsy

Although a pan-plexus injury is the most common situation, avulsion of all C5-T1 roots is rare; the C5 spinal nerve root may be singularly spared, thus allowing it to be used as the source of axons for a plexo-plexal repair to distal elements.[8] Overall, in this dreadful situation, the donor nerve options are limited to extraplexal nerves. Donor nerves include the spinal accessory, phrenic, ICNs, contralateral C7, and the disparately anterior motor divisions of the cervical plexus.[8] The reanimation of hand function is disappointingly poor and no attempt is made to reinnervate the lower plexus elements in adults. Secondary reconstructive procedures are usually needed for functional recovery of the hand.

In this difficult scenario, the author's strategy will depend on the availability of the C5 nerve root. If intact, C5 to upper trunk elements (suprascapular and to axillary nerve) is performed using sural nerve grafts. At times, C5 (if robust) may also be directed by way of a graft to the musculocutaneous nerve. However, elbow flexion is usually restored by performing intercostal-musculocutaneous (ICN-MC) nerve transfers (**Fig. 2**).[19] When C5 is not available for use, accessory-suprascapular nerve transfer is used as means of restoring some useful shoulder abduction, together with ICN-MC nerve transfer.

In addition to the criteria listed earlier for choosing the donor nerve for transfer, personal surgical preference and the experience of the different institutes are believed to play a role in this choice. Examples are the C7 and phrenic nerve transfer, with most of the reports coming from China and Taiwan[20–25] with good results; such reports are rarely reported by North American centers.

COMMON NERVES USED FOR NERVE TRANSFERS

Spinal Accessory Nerve

As an extraplexal nerve, the SAN is rarely injured in patients who have brachial plexus injury. When harvested distal to its initial trapezius motor branches

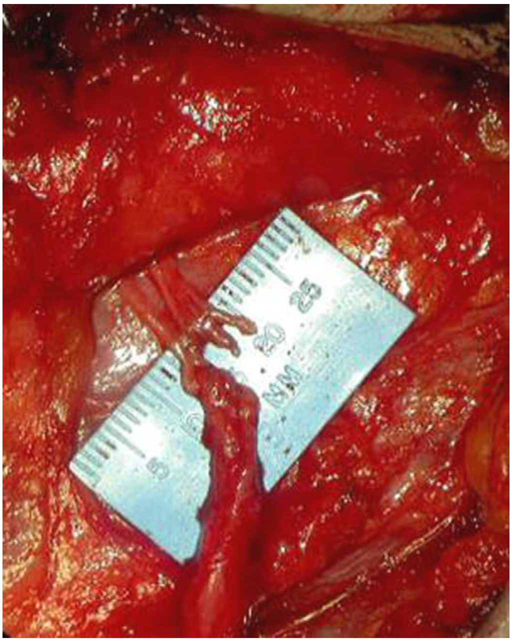

Fig. 2. Three ICNs after extensive mobilization along the chest wall, tunneled behind the right axillary skin fold and ready to be coapted directly (without interposed nerve grafts) to the musculocutaneous nerve.

and transferred to the donor nerves, it provides a good source of motor axons (1500–3000 myelinated axons) to the plexal elements, with and without the use of an interposition graft.[15] The SAN is commonly transferred to suprascapular and musculocutaneous nerves to restore shoulder abduction and elbow flexion, respectively. For restoration of dynamic shoulder function, the suprascapular and axillary nerves have been chosen as targets. Although the former can be repaired directly by end-end suture of the distal accessory nerve, the latter requires an interposed nerve graft.[26]

SAN transfer to the suprascapular nerve to restore shoulder abduction has been associated with mixed results; some investigators reported good functional recovery when SAN was transferred to the suprascapular nerve alone or when combined with axillary nerve reinnervation.[27] Malessy and associates[28] had more pessimistic results, with poor restoration of active glenohumeral abduction; their patients compensate by rotating the scapula laterally (thoracoscapular rotation) to achieve and maintain their shoulder abduction. Suprascapular nerve reanimation alone may restore up to a mean range of 90° of shoulder abduction, and such range of motion has been claimed to be useful by some;[27] however, when combined with axillary nerve reanimation, a more functional recovery, with up to 115°,[17] can be restored.

The other major target for accessory nerve transfer has been the musculocutaneous nerve. The results for elbow flexion in recent series have been good, with MRC grade 3 or better outcomes achieved in 65%,[29] 72%,[30] 72.5%,[31] and 83%[32] of patients. In the analysis of factors predicting outcome, the most important negative predictor was increased duration of time between injury and surgery; the need for a longer graft also negatively influenced results.[9,11] Although a meta-analysis of the literature suggests that when the musculocutaneous nerve is the recipient nerve, it is best to use ICNs as donors,[33] only the series by Waikakul and colleagues[32] directly compared the two extraplexal donors, finding that the accessory nerve achieved superior outcomes for elbow flexion compared with the ICNs.[11]

Traditionally, accessory to suprascapular nerve transfer has been accomplished through an anterior supraclavicular approach; however, more recently, a posterior approach (see **Fig. 1**) has been described, particularly when triceps branch to axillary nerve transfer is considered in combination.[34]

Intercostal Nerves

ICNs are commonly used extraplexal donor nerves. They have a long history of use and have been successfully transferred to the musculocutaneous nerve with satisfactory results.[19] The importance of this transfer becomes especially evident in patients who have severe brachial plexus injury involving C5-T1 roots, where the source of donor nerves is limited. ICNs are mixed motor/sensory nerves, with 500 to 700 myelinated motor axons. When an average of three nerves is used, an adequate number of motor axons will be available for transfer.

Results of ICN-MC nerve transfer vary widely with the various techniques, ranging from no change in biceps function to strong elbow flexion. The differences in the techniques involve

- Site of ICN transection ranging from paravertebral to parasternal
- Number of ICNs used
- The recipient nerve
- Use of interposition graft
- Use of vascularized ICN

Given that few patients are reported and the various permutations used in these techniques, it is difficult to agree on the optimum transfer technique.

Standardized techniques, consisting of the use of three ICNs (third to fifth) to the distal musculocutaneous nerve, without interposed grafts, used by Friedman and colleagues[35] and the Duke University group, led to more consistent results, approaching MRC grade 3 or better function in about 50% of the patients. Their research also provided the first detailed evidence of independent (without synkinetic respiratory movements) use of biceps over the course of time, hinting at cortical plasticity, a concept that has subsequently been directly validated with electrophysiologic and functional brain mapping and imaging studies.[4–6,36] Indeed, it is suggested that whether patients obtain functional use depends on cortical readaptation, with failures construed to lack such adaptation; however, this hypothesis requires validation.[15] In a recent meta-analysis, ICN-MC transfer resulted in 72% of patients recovering to greater than or equal to M3 strength, but only 47% of patients recovering to that strength when an interposition graft was used. Restoration of elbow flexion was superior when compared with accessory-musculocutaneous transfer.[12] In a small group comparison, Okinaga and Nagano[37] did not find any clinical advantage to using vascularized versus nonvascularized ICN transfer.

Unilateral (ICN) transfer does not significantly impair respiratory function. However, most peripheral nerve surgeons generally agree that respiratory dysfunction will occur when the phrenic nerve is simultaneously transferred. This old belief is currently being challenged repeatedly.[38]

Ipsilateral and Contralateral C7 Spinal Nerve Transfer

The C7 spinal nerve, middle trunk, and its anterior and posterior divisions can be used as a donor nerves in cases of partial or complete brachial plexus injury. Ipsilateral and contralateral sides can be used according to the pattern of injury. The C7 nerve root provides a rich source of nerve fibers because it contains up to 23,000 axons. C7 contains between four and six fascicles, continues as the middle trunk, and subsequently divides into anterior and posterior divisions. The anterior division contains laterally disposed fascicles with more motor supply (especially to pectoralis) and medial fascicles with more sensory axons, whereas the posterior division contains motor input for the extensor muscles (mainly triceps). Such an orientation allows a better selection when choosing the recipient nerves. The whole root, or part of it, can be used with minimal or no deficit in the donor side.[21]

In some cases of Erb's palsy, where both C5 and C6 are avulsed, the C7 spinal nerve is intact and available as an intraplexal donor for reinnervating the distal upper trunk or its divisional outflow. Such a transfer can be associated with good outcomes related to the recipient elements,[39] with little risk for loss of function from taking the C7 spinal nerve.[22] However, considerable caution is required if significant lower plexus lesion coexists because the muscles innervated by C7, which normally would be redundantly supplied by the C8 (and T1) spinal nerves, will not be present.

The redundancy of the C7 spinal nerve, allowing for its safe sacrifice, has been verified by investigators who have used the contralateral C7 as a donor for transfer. Other than causing mild loss of triceps function and clinically inconsequential loss of the triceps reflex, the procedure appears to be safe as far as motor loss is concerned. However, sensory abnormalities are common following C7 sacrifice, and may be permanent in 5% of cases.[40] Moreover, neuropathic pain may be evoked temporarily in a few patients,[41] and a rare case may have permanent motor deficits in wrist extension.[42] Selective use of anterior or posterior portions of the contralateral C7, aided by intraoperative electrophysiologic tests, may make the procedure safer and further add to the specificity of the reinnervated element to which it is transferred.[21,23]

The best results in the use of contralateral C7 for total avulsion were claimed by Waikakul and colleagues[32] who noted that, in 98 adolescent and adult patients, when the median nerve was the recipient, good sensory function was achieved in about half of the adolescents and some also experienced forearm muscle recovery. In a most carefully reported 3-year follow-up, Songchareon and colleagues[26] reported median nerve motor recovery to an MRC grade 3 or 4 in about 20% of patients, whereas another 20% had an MRC grade 2 outcome in wrist flexion. Outcome in the sensory domain was better, especially in adolescents, with half of these patients having useful sensory restoration in the median nerve distribution. In Terzis and colleagues'[39] adult brachial plexus series, the average grade achieved in various recipients was less than MRC 3. Others have used the C7 strictly to transfer, by way of vascularized ulnar nerve graft, to the lateral cord contribution to the median nerve and report a 100% success rate with good sensory recovery.

Contralateral C7 nerve transfer has been used recently in 12 infants and children, with promising results.[43] A more selective approach of choosing the motor rootlets through a posterior approach has recently been described, with promising results.[10,39]

One of the main criticisms of this transfer technique remains the long graft (and hence regeneration) distance, but the possibility of a prespinal retropharyngeal route of graft placement has been suggested.[44] Nevertheless, the technique remains limited, given the modest results in motor recovery. The synchronous movement of the healthy side required to facilitate the desired action can be frustrating, with patients needing to make a fist on the healthy side to initiate the action on the involved side. This facilitatory action may take up to 3 years to improve but rarely will it go away completely.[28] Although most of the reports suggest minimal or no deficit in the donor side, even a minor deficit in the only normal arm can be of considerable clinical and psychologic consequence. Perhaps a targeted approach to obtain median nerve distribution sensory recovery is warranted, although similar outcomes may be possible with a less cumbersome transfer from the lower ICNs to the sensory (lateral cord) contribution to the median nerve.[45] The authors, therefore, rarely, if ever, perform contralateral C7 transfers.

Medial Pectoral Nerves

The pectoralis major muscle has dual input from the medial and lateral pectoral nerves, arising from the medial and lateral cords, respectively.

Because C5 and C6 avulsion interrupts the lateral cord supply, the muscle remains innervated (and strong) as long as a significant injury to the C7 and C8 elements does not occur. Although popularized recently for upper plexus injuries, the medial pectoral nerve as a donor for transfer has been considered previously and used infrequently, as reviewed by Narakas[46] for adults and Gilbert[47] for obstetric palsy.

Brandt and Mackinnon[48] directed the medial pectoral nerve to the musculocutaneous nerve, with the additional innovation of turning the distal lateral antebrachial cutaneous nerve (the cutaneous derivative of the musculocutaneous) into the biceps muscle to try to avoid loss of motor axons into the cutaneous distribution. A resurgence of interest in this transfer has been associated with reports of useful outcomes (defined as MRC grade 3 or better) in elbow flexion in approximately 84% of patients.[49] Excellent results in obstetric palsy, too, have been claimed, with success in 68% of cases.[50] However, the results of various series vary, and Samardzic and associates[29] have noted that medial pectoral transfers were associated with significantly improved outcomes in elbow flexion as compared with ICN and accessory nerve transfers. This group has also been one of the few to demonstrate remarkably good results in transfer to the axillary nerve, reporting useful results in more than 80% of patients.[49]

With the increasing interest in the medial pectoral nerve as a donor, the anatomy of the pectoral nerve complex has been more clearly defined.[51] The traditional concept of separate lateral and medial pectoral nerves innervating the pectoralis minor and major muscles as discrete nerves has been replaced with the knowledge that as these nerves run toward the pectoralis minor and major muscles, they exhibit considerable branching and intermingling. Not infrequently, a plexus will form where branches from the medial and lateral pectoral nerves, destined for the pectoralis major, merge together and then final branches will ramify toward the muscle. Because only one, or at times two, of these terminal branches to the pectoralis need be taken (and distally) for the transfer, the practical implication is that some pectoralis major supply can be preserved and a direct repair without intervening graft can be performed to the musculocutaneous nerve in the distal axilla. Significant caution needs to be exercised if substantial injury involving C7 and C8 exists; in this case, pectoralis major will be weak preoperatively and this finding is a contraindication to considering a medial pectoral transfer. A similar sophisticated appreciation of the nerve supply of the biceps and brachialis muscles[52] has propelled further surgical evolution in transfers so that the biceps and brachialis are discretely reinnervated by transfer procedures.[18]

Phrenic Nerve

The phrenic nerve is the motor nerve to the diaphragm, originating mainly from the fourth cervical root, but both C3 and C5 contribute to and augment the nerve. For a complete phrenic nerve paralysis to take place, both C4 and C5 have to be injured. This scenario is, fortunately, not common because the C4, like C5, nerve root is strongly bound with fibrous tissue to the chute-like structure of the transverse process. In 100 consecutive cases of brachial plexus injury, Chen and others[53] have found an incidence of 13% severely and 7% partially injured phrenic nerves. When healthy, unlike the cervical plexus, which contains a variable and small aliquot of motor fibers, the phrenic nerve contains many pure motor axons that allow the possibility of entire or partial transfer with success.

Box 1 compares the advantages and disadvantages of using the phrenic nerve as a donor for transfers. In 12 patients, a 75% success rate with phrenic transfer to musculocutaneous, suprascapular, or axillary nerves was reported.[54] In particular, the transfer to the musculocutaneous nerve has been an excellent tactic, with 11/12 patients achieving better than antigravity (MRC

Box 1
Advantages and disadvantages of phrenic nerve transfer

Advantages

Predominance of motor axons

Proximity to major nerves, namely the suprascapular and musculocutaneous nerves, which may allow a direct coaptation, sometimes, with no intervening graft

Technical ease of finding and dissecting

Disadvantages

The potential for significant respiratory function decline, at least temporarily, and the poor handling of respiratory infections, particularly in the pediatric age group or in adults with poor cardiorespiratory functions

The short length of nerve available from the usual supraclavicular approach, with a graft usually needed

The need for considerable neural plasticity because the patient will need to take a deep breath when he/she tries to flex his/her elbow; although this situation may improve over 2 to 3 years, it can be a frustrating task for patients grade 3) and 58% MRC grade 4 function.[55] An important issue when the phrenic nerve is sacrificed is the resulting respiratory function compromise, which has been measured to be an average of about a 10% decrease in vital capacity.[55] Although not clinically important in most situations, this degree of loss in respiratory reserve will produce symptoms in higher-demand situations and may be severely detrimental to infants and children who develop respiratory infections. This possibility essentially precludes the use of the phrenic nerve as a donor in infants who are undergoing nerve reconstruction for obstetric palsy. Moreover, it also implies that the ICNs should not be used as donors for transfer when the phrenic nerve function is absent preoperatively or when the phrenic is transferred.

Xu and associates[23] compared vascularized and nonvascularized phrenic nerve transfer in 15 patients and found no statistically significant difference. This lack of difference was attributed to the small diameter of the nerve (2 mm) and its well-vascularized bed. It is not completely understood, but Luedemann and collaborators[55] found a statistically significant drop in vital capacity when using the right phrenic nerve compared with the left. This difference was not clinically significant, but the investigators cautioned against using the right side if the maximal inspiratory pressure is decreased preoperatively. It was not clear why patients who have phrenic nerve transfer fare well regarding the respiratory function, but it has been attributed in part to the presence of accessory phrenic nerve. However, Xu and colleagues[25] showed that patients will recover vital capacity within 1 year following section of the phrenic nerve near its attachment to the diaphragm done thoracosopically, a technique that rules out the role of accessory phrenic nerve supply. Transferring both phrenic and ICNs is not preferred because the patient is deprived of two important nerves that supply the diaphragm and the accessory respiratory muscles, respectively. This principle has been challenged recently in 15 patients who had both nerves transferred; some also had the spinal accessory and cervical plexus motor branches used as donors, thus denervating many accessory respiratory muscles. Although the patients' diaphragmatic and lung function showed a measurable impact, their ventilation and exercise performance were not affected.[38]

Ulnar Nerve Fascicle Transfer (Oberlin Transfer)

In 1994, Oberlin and associates[3] reported the use of an ulnar nerve fascicle for transfer to the biceps muscle branch. Since Oberlin's first description of this technique, transferring an ulnar nerve fascicle has become a commonly used nerve transfer for biceps muscle reanimation. The ulnar nerve receives its input from C8 and T1, with occasional contribution from C7. These roots are usually preserved in patients who have upper plexus injury. The ulnar nerve is anatomically close to the biceps muscle and its branch; this anatomic fact allows a direct coaptation of the two nerves (**Fig. 3**). The nerve is exposed in the medial arm and commonly found in a groove between the biceps and triceps muscles. Once identified and isolated using a nerve stimulator, the common epineurium of the ulnar nerve is opened under magnification, and the fascicle, with predominant innervation to the flexor carpi ulnaris muscle, is isolated and used for transfer to the biceps branch. Intraoperative stimulation using a disposable variable

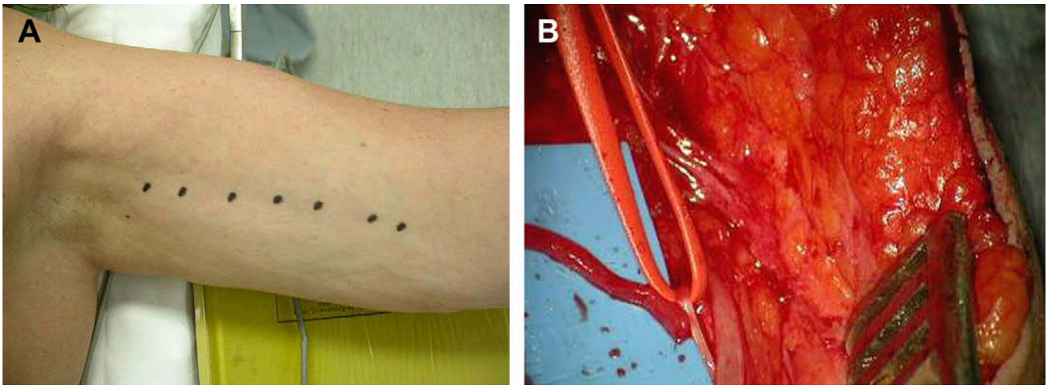

Fig. 3. (*A*) The incision (*dotted line*) at the medial arm between biceps and triceps muscles for the exposure of ulnar and musculocutaneous nerves. (*B*) An ulnar nerve fascicle (electrically verified as predominantly supplying flexor carpi ulnaris muscle) isolated (vessel loop) and ready to be coapted to the biceps branch (*overlying the blue background*) of musculocutaneous nerve.

stimulating device (Xomed, Medtronics Corporation) is usually sufficient for the identification of an appropriate fascicle.

Leechavengvongs and colleagues[56] reported 32 patients with mean time to surgery of 6 months and follow-up of 18 months, with 93% of patients recovering elbow flexion to MRC grade 4, and no patient showing ulnar nerve–associated hand function deterioration.

More impressive results have been those reported by Sungpet,[57] who used a single ulnar nerve fascicle directed to biceps and obtained an MRC grade 3 or better outcome in 34/36 patients. Noted, too, in his article, was that time to reinnervation began as early as 3.3 months and that hand function and ulnar assessment using a series of tests and functional tools was not compromised in long-term follow-up. The key aspect of the procedure is to reinnervate the biceps branch close to its motor entry into the muscle.

A recent report indicates that elbow flexion function will be further augmented (especially in delayed surgery cases) by concomitantly reinnervating the brachialis muscle by way of a graft from the medial pectoral nerve.[58] A similar promising result has been reported in obstetric brachial plexus palsy.

Partial Median Nerve Fascicle Transfer

The same concept of transferring a fascicle from the ulnar nerve can be applied to the median nerve by choosing a fascicle innervating predominantly flexor carpi radialis or palmaris longus muscles. The median nerve receives contributions from upper and lower plexus elements and therefore can be partially involved in patients who have upper plexus palsies; however, it may not always be suitable for fascicle transfer because it may produce more deficits in the distribution of the median nerve. Sungpet and colleagues[59] reported using a single median nerve fascicle, which predominantly innervated either the flexor carpi radialis or palmaris longus muscle, and transferring it to the biceps motor branch of the musculocutaneous nerve. They observed MRC grade 4 elbow flexion in four out of five patients and MRC grade 3 recovery in one patient. No donor nerve morbidity occurred. In a report by Ferraresi and associates,[60] elbow flexion was restored by using median nerve fascicle to main musculocutaneous nerve in only 4 of 43 patients, so the authors caution against a nondiscrete transfer. Mackinnon[61] used median nerve fascicle to brachialis branch and ulnar nerve fascicle to biceps branch (so-called "double fascicular transfer") to augment elbow flexion. The investigator's rationale was explained by the fact that brachialis is the main elbow flexor and biceps is primarily a supinator with flexion being a secondary function, thus making reanimating the brachialis an important component of reconstruction of elbow flexion. The authors' preferred technique is to use the Oberlin transfer alone in most cases, but to consider a double fascicular transfer in delayed (>6 months postinjury) cases. They also caution against using these transfers in cases where the patient's preoperative ulnar or median nerve is compromised.

Triceps Muscle Branch to Axillary Nerve

The triceps muscle, with its three heads, offers the possibility of using one of the three nerve branches as a good donor nerve to the nearby axillary nerve. When the triceps is of normal power, the nerve supply of one of its heads can be transferred without any demonstrable loss in its strength. Leechavengvongs and associates[17] described transferring the long head of the triceps branch to the anterior division of the axillary nerve (**Fig. 4**) in seven patients, combined with accessory-suprascapular nerves, with excellent outcome in shoulder abduction. Colbert and Mackinnon[34] have recently reported a posterior approach, in which both transfers were performed in a prone position (see **Fig. 1**).

Although no firm agreement exists as to the importance of each of the triceps heads, it seems that muscle weakness is a rare occurrence, regardless of the chosen branch, providing the muscle is of normal power. The branch to the medial head is easy to find between the lateral and the long heads, and has enough length for coaptation to the axillary nerve. The branch to the long head of the triceps is closer to the axillary nerve, but division of the teres major muscle is almost always required to obtain adequate length.[47] The author's choice of the anterior division of the axillary nerve versus the axillary nerve proper depends on each patient's individual anatomy. Care should be exercised not to use this technique in patients who have triceps weakness or C7 injury because it may affect the quality of the donor nerve and, most importantly, will worsen the triceps muscle strength.

Distal Anterior Interosseous Branch Transfer-Deep Motor Branch of Ulnar Nerve

Proximal ulnar nerve injuries with loss of intrinsic hand muscles are a devastating event with severe functional loss. Primary or grafted repair of high ulnar nerve injury is typically associated with inadequate or no recovery of hand intrinsic muscle function.[62] In high ulnar nerve injury, the long distance between the cell body and the

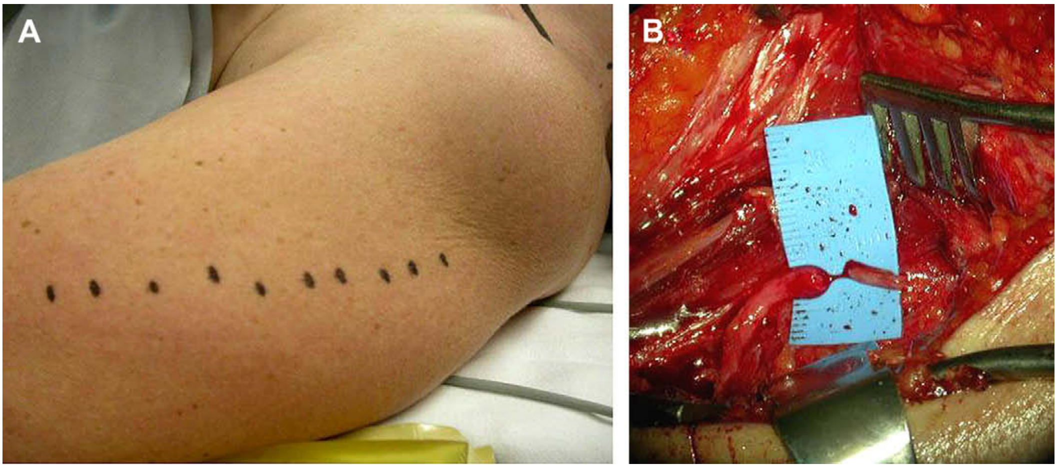

Fig. 4. (*A*) A posterior arm incision marked between the atrophic deltoid muscle and the long head of triceps allows for simultaneous exposure of both triceps branches of the radial nerve and distal axillary nerve. (*B*) Anterior division of the axillary nerve is ready to be coapted to the long head of triceps branch. Note the slight difference in diameter of the two nerve stumps.

target muscle prevents a timely reinnervation of target muscles. Nerve transfer presents a good treatment option for high ulnar nerve injury because it avoids the long distance the regenerating axons have to travel. The pronator quadratus muscle branch (of the distal anterior interosseous nerve) offers a suitable donor nerve for the deep motor branch of the ulnar nerve because it is purely motor (900 axons), is close to the deep motor branch of the ulnar nerve (1200 axons), and is a good size match (**Fig. 5**). Loss of pronator quadratus muscle is usually not clinically noticeable.[63] Novak and Mackinnon[63] reported eight patients who had ulnar nerve injury proximal to the elbow; all patients demonstrated reinnervation of ulnar intrinsic hand muscles, with improved lateral pinch and grip strength. No functional deficit in pronation was reported. Battiston and Lanzetta[62] reported seven patients who had double median to ulnar nerve transfer in which the distal anterior interosseous branch was transferred to the deep motor branch of the ulnar nerve and the palmar cutaneous branch of the median nerve was transferred to the sensory branch of the ulnar nerve. Six of the seven patients recovered to grade M4 or better. All patients recovered protective sensation, and five had full sensory recovery.

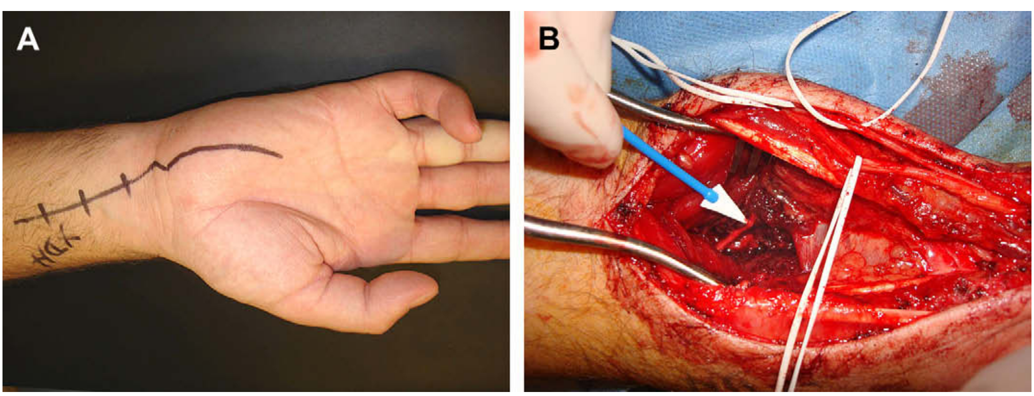

Fig. 5. (*A*) A patient who has a severe and nonrecovering high right ulnar nerve injury (note claw deformity of little finger) is prepared for an incision to expose the deep motor branch of the ulnar nerve and distal anterior interosseous nerve. (*B*) The motor branch of the ulnar nerve is extensively neurolyzed (topmost vessel loops) so that it can be sectioned proximally. It will then be brought in approximation to the deeply located distal anterior interosseous nerve branch to the pronator quadratus muscle (*arrow*).

Thoracodorsal Nerve

The TDN is a pure motor nerve supplying the latissmus dorsi muscle; it receives input from C6 to C8. The mean surgical available length for transfer is 12.3 cm with a range of 8.5 to 19 cm, with diameter ranges from 2.1 to 3 mm. The number of myelinated axons ranges from 1530 to 2470. All these criteria make the nerve an excellent motor nerve donor. Transfer of the TDN to the musculocutaneous and to the axillary nerves has been achieved successfully.[64,65] The available length of the TDN allows its coaptation to those nerves without the need of an interposition graft. However, in patients who have C7, middle trunk, or posterior cord injury, the TDN may be significantly affected. Clinical examination of the latissmus dorsi muscle, electromyographic testing, and intraoperative stimulation will allow an accurate assessment before selecting TDN as a donor nerve. Using TDN will lead to latissmus dorsi muscle weakness and subsequently, arm adduction, an action that can be helpful in children age group as they use it to hold objects under their armpits. Notably, it also takes away the option of using this muscle for transfer to augment elbow flexion.

Use of Nerve Transfer for Restoration of Sensation

Nerve transfer to restore sensation is much less commonly used than motor nerve transfer. However, the same principles apply. The sensory nerve transfer can be a useful procedure when restoring protective sensation is the goal.[66] Examples of sensory nerve transfer include

Palmar cutaneous branch of the median nerve to the ulnar nerve sensory branch

Deep peroneal nerve at the ankle level to the medial plantar nerve

Saphenous nerve to the posterior tibial nerve

Digital nerves of the little (radial side) or ring fingers to the thumb or index fingers

Intercostal (sensory) nerves to the lateral cord (which is primarily sensory) head to the median nerve

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