

## REVIEW ARTICLE

# Heterotopic Nerve Transfers: Recent Trends With Expanding Indication

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There has been increasing enthusiasm for heterotopic nerve transfers for brachial plexus palsy as well as peripheral mononeural dysfunction. The concept of nerve transfer surgery is not new; the first publications on the topic date back to the early 1900s. A wide variety of potential donor nerves are available including the intercostal nerves, the spinal accessory nerve, the phrenic nerve, the ipsilateral medial pectoral nerve, partial ulnar nerve, partial median nerve, thoracodorsal nerve, radial nerve to the triceps, and the ipsilateral C7 or the contralateral C7 nerve roots. Treatment strategies include avoidance of interposed nerve grafting, isolated motor recipient nerve, early transfer, neurorrhaphy close to target motor end plates, and similar diameter between donor nerve and recipient nerves. (J Hand Surg 2007; 32A:397–408. Copyright © 2007 by the American Society for Surgery of the Hand.)

**Key words:** Nerve transfer, brachial plexus, nerve graft, neurorrhaphy.

In recent years, there has been increasing enthusiasm for heterotopic nerve transfers for a variety of challenging peripheral nerve problems. The general indications for these procedures include:

1. Proximal level upper extremity nerve injuries.
2. Nerve lesions with a poor record of motor recovery due to the distance from injury level to target motor end plates or a very large gap requiring a nerve graft of greater than 10 cm.
3. Nonreconstructible upper extremity nerve injuries because of nerve root avulsion, absent proximal nerve segment, or certain idiopathic or undefined neuropathies.

Perhaps, in some instances, nerve transfers have the potential for overuse. The selection of a nerve transfer should always be weighed against other treatment alternatives. This especially applies to orthotopic nerve graft reconstruction, which in some situations may have an equal or even better likelihood of long-term success, albeit technically more difficult to perform. Moreover, virtually all nerve transfer procedures carry the risk of donor nerve impairment, which should be carefully considered. Some patients with peripheral nerve injury may have the option of tendon or muscle transfers. In these patients, if the donor muscle is potentially paralyzed as a result of nerve transfer, future reconstructive

options for the patient might be unnecessarily narrowed. Depending on the donor nerve under consideration, one should carefully evaluate the risk-to-benefit ratio of nerve transfer versus tendon transfer.

### History

Although enthusiasm for heterotopic nerve transfer procedures has blossomed in the past two decades, this concept dates back to the early part of the 20th century. Klivington<sup>1</sup> published in 1907 in the *British Medical Journal* an article on nerve crossover to innervate the neurogenic bladder from spinal cord injury. The earliest reports that we could identify for nerve transfer as applied to brachial plexus paralysis was by Tuttle in 1913.<sup>2</sup> He used anterior branches of the cervical plexus and also suggested the use of the spinal accessory nerve. In 1920, Vulpus and Stoffel<sup>3</sup> reported using branches of the medial and lateral pectoral nerves for nerve transfer to the musculocutaneous and axillary nerves. Foerster<sup>4</sup> used the technique of nerve transfer to repair brachial plexus injuries during and after the First World War. He described a number of strategies including the use of the subscapular, medial pectoral, thoracodorsal, and long thoracic nerves to reinnervate the musculocutaneous nerve. In addition to the use of nerve transfers to reanimate the upper limb, this technique was considered early on for the treatment of paraplegia. In

1934, Chiasserini<sup>5</sup> described the use of intercostal nerves proximal to the level of spinal cord transection to reanimate the lower limb and trunk muscles by transfer to the lumbosacral plexus.

During and after the Second World War, Yeoman and Seddon<sup>6</sup> popularized the use of intercostal nerves, extended by free nerve grafts to the musculocutaneous nerve with a modest record of success. Tsuyama (Tsuyama and Hara, presented at the SICOT 12th Congress, Tel Aviv, 1972) and other Japanese surgeons<sup>7-9</sup> later modified this technique by isolating the intercostal motor branch and providing a direct coaptation to the biceps motor branch, with improved results.

The present-day era of selective nerve transfers for brachial plexus reconstruction was ushered in by the work of Lurje<sup>10</sup> in 1948. He advocated the use of the thoracodorsal, long thoracic and part of the radial nerve for re-innervation of the axillary, suprascapular and musculocutaneous nerves. By the late 1970s and early 1980s, the technique of heterotopic nerve transfer for brachial plexus reconstruction appeared to be gaining increasing acceptance, due to the contributions of pioneers from all parts of the world including Narakas, Dolenc, Samii, Allieu, Brunelli, Gilbert, Tsuyama, Nagano, Gu, Chuang, Songcharoen, Kline, Mackinnon, Millesi, and others.<sup>7,11-23</sup>

For the purposes of this discussion, the authors would like to initially focus attention on the brachial plexus and the many different options and indications for reanimation by nerve transfer. Before concluding, however, we will touch on the role of nerve transfer for peripheral mononeural reconstruction, the role of sensory nerve transfer, and a few more unusual applications.

## Treatment Strategies for Nerve Transfer in Brachial Plexus Palsy

It is not surprising that the most common indication for a nerve transfer procedure is an early brachial plexus injury. There are several reasons for this.

Often, at least a portion of a brachial plexus injury involves a nerve root avulsion or intraforaminal nerve root rupture, thus denying a proximal source of motor axons for nerve graft reconstruction.

The extreme proximal location of these injuries at the supraclavicular level can result in an injury that is far removed from the distal motor end-plates. Thus any technique to decrease the regeneration distance between viable proximal motor axons and the distal motor end-plate will hasten the speed of reinnervation and in most cases the quality of the clinical result.

If recovery of a specific motor function is the highest priority (ie, elbow flexion, shoulder external rotation), then coapting known functioning motor axons to a pure motor recipient nerve is more likely to result in the desired function compared with coapting a mixed motor-sensory nerve to a mixed motor-sensory recipient nerve.

The use of a nerve transfer may require only a single neurotomy site as opposed to use of a nerve graft, which requires two neurotomy sites. Thus coaptation site barriers to axon regrowth is halved.

Most brachial plexus injuries involve the upper two or three roots, a combination of upper or middle trunks, or the entire plexus. From a practical perspective, the goals for upper limb reconstruction are recovery of elbow flexion, shoulder external rotation, shoulder abduction, elbow extension, and wrist extension—generally in that order. Thus, the highest priority recipient motor nerves in patients with the typical upper brachial plexus or total plexus injury are the musculocutaneous nerve or its biceps and/or brachialis motor branches, the suprascapular nerve, the axillary nerve, and the radial nerve or one or more of the radial nerve's triceps branches—also in that order. In patients undergoing a free microvascular transfer to obtain a desired function, the transferred muscle's motor nerve would of course be the desired recipient nerve.

A wide variety of potential donor nerves has been used with success about the brachial plexus. Donor nerve selection seems limited only by human anatomy and human ingenuity. In general, the selection of the ideal donor nerve should include consideration of the following principles<sup>24,25</sup>:

- If motor function is the desired goal, then the donor nerve should be as purely motor in function as possible.
- The functional loss resulting from transfer of the donor nerve should be relatively inconsequential and certainly much less than the expected function in the recipient nerve.
- The donor nerve should be of sufficient mobilized length to permit a direct coaptation to the recipient nerve. Ideally, this mobilized length should place the recipient nerve as close as possible to the muscle motor end-plates.
- The diameter of the donor and recipient nerves should be similar.
- The normal function of the donor nerve should be somewhat synergistic with the recipient nerve function.



**Figure 1.** Chest wall and arm incisions for intercostal nerves harvest.

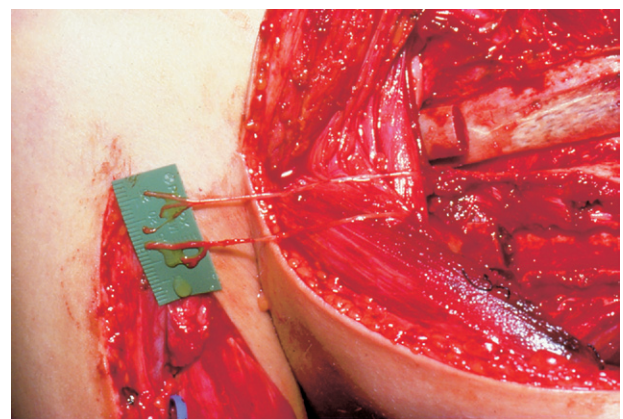
### Donor Nerves

**Intercostal nerves.** Intercostal nerves are probably the most common donor nerves for brachial plexus reconstruction.<sup>26–28</sup> This is due in part to their long history of use. The intercostal nerves are also frequently selected because of the scant loss of function resulting from sacrificing two to four intercostal nerves, the fact that the motor component of the intercostal nerve can be accurately isolated, and the relatively long length of intercostal nerve that can be mobilized from the anterior chest wall (Figs. 1, 2). The intercostal nerves also are extraplexal in origin and thus are usually functioning and available in spite of extensive brachial plexus injuries. The motor portion of the intercostal nerve contains 500–700 myelinated motor fibers.<sup>26</sup> It is now well recognized that a direct coaptation of the isolated motor portion of the intercostal nerves to the isolated recipient muscle nerve, as in the technique of Tsuyama (Tsuyama and Hara, presented at the SICOT 12th Congress, Tel Aviv, 1972), provides a superior result to the use of an interposition nerve graft to a mixed motor-sensory nerve (ie, the musculocutaneous nerve) as in Seddon's technique.<sup>28</sup> Intercostal nerves have been transferred to a variety of nerves including the axillary nerve, radial nerve, long thoracic nerve, and the motor nerve to a free microneurovascular muscle transfer. The most common application, though, is for reanimation of elbow flexion by neurotization of the biceps motor nerve or biceps and brachialis fascicular bundles of the musculocutaneous nerve.<sup>6–9,11,24–28</sup> Moreover, the sensory portion of the intercostal nerves may be useful for restoring

protective sensibility in the upper limb when coapted to the lateral cord contribution to the median nerve.

**Spinal accessory nerve.** The next most frequently utilized donor nerve, after the intercostals, is likely the spinal accessory nerve.<sup>13,14,24–26,29,30</sup> It, too, is extraplexal in origin and thus is usually functioning after extensive brachial plexus injury. It also fulfills the principle of being essentially a pure motor nerve and contains approximately 2,000 myelinated motor fibers.<sup>26</sup> It is functionally important in that it provides the principal innervation of the trapezius muscle. In approximately 75% of individuals, the spinal accessory nerve is the sole source of innervation of the trapezius, and in 25% of people the upper trapezius is innervated by motor branches from the cervical plexus (nerve roots C2 and C3).<sup>31</sup> If the spinal accessory nerve is to be used as a nerve transfer, it is important to use only the distal portion to ensure at least partial innervation to the trapezius. The spinal accessory nerve lies close to the upper trunk of the brachial plexus, and particularly its suprascapular nerve branch. Thus, it is well positioned to permit a direct coaptation to the mobilized suprascapular nerve without the use of a nerve graft. It is also frequently used as a donor nerve for a free microneurovascular muscle transfer and may be useful as a source of motor axons to the musculocutaneous nerve.<sup>29</sup>

**Phrenic nerve.** Since the phrenic nerve was first clinically utilized by Gu,<sup>32</sup> it has been increasingly adopted by other surgeons. Although it principally arises from the roots of the cervical plexus (C3, C4, and C5), it may suffer injury in proximal brachial plexus lesions. Thus, it is not always available as a source of motor axons. When uninjured, it contains a



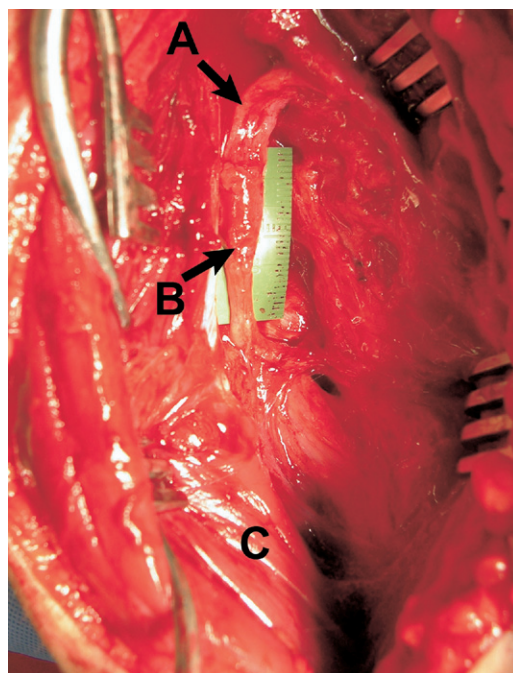
**Figure 2.** Harvest of intercostal nerves for transfer to the biceps branch of the musculocutaneous nerve.



relatively large number of motor axons.<sup>32</sup> The phrenic nerve, however, has two drawbacks. First, only a short length of nerve is available through the usual supraclavicular incision used for brachial plexus exposure. Therefore, most of the time that it is used for nerve transfer purposes, it must be prolonged with a nerve graft. Some authors have described extending the length of available phrenic nerve by an intrathoracic harvest of the nerve.<sup>33</sup> In some patients, especially those who are overweight, even this technique is inadequate in providing enough nerve length. The second drawback to the use of the phrenic nerve is that its harvest usually results in decline of pulmonary function,<sup>34</sup> at least temporarily; and more significantly affecting the right hemithorax.<sup>35</sup> This is a problem chiefly in infants susceptible to recurrent upper respiratory tract infections and in adults with impaired cardiac or pulmonary function. Most authors do not recommend the use of the phrenic nerve in these patients.<sup>24</sup>

**Medial pectoral nerve.**<sup>36–39</sup> In patients with preserved function of the C8 and T1 nerve roots and lower trunk, the function of the medial pectoral nerve is usually well preserved, providing innervation to the pectoralis minor and sternal head of the pectoralis major muscles. It is essentially a pure motor nerve and is reasonably well positioned to permit direct coaptation to the fascicular bundles of the musculocutaneous nerve, which innervate the biceps and brachialis muscles.<sup>36</sup> It is also relatively easy to isolate compared with multiple intercostal nerves. The functional loss is minimal, unless there is a plan to use a pectoralis major/minor tendon transfer to augment or restore elbow flexion strength.

**Partial ulnar nerve (flexor carpi ulnaris fascicles).** Perhaps the most recent, widely used nerve transfer to provide reanimation of the biceps muscle is the partial ulnar nerve transfer<sup>40–44</sup> (ie, the fascicles within the ulnar nerve that chiefly innervate the flexor carpi ulnaris muscle, as described by Oberlin<sup>40</sup>). Because the ulnar nerve is innervated by the lowest roots of the brachial plexus, it is frequently uninjured in palsies involving the upper plexus only. Based on multiple reports, little donor site morbidity occurs with transecting about 20% of the ulnar nerve, provided it involves those fascicles innervating the flexor carpi ulnaris muscle.<sup>40–44</sup> When carried out adjacent to the biceps motor branch of the musculocutaneous nerve, a direct coaptation to the transected fascicular group can be accomplished (Fig. 3). One potential drawback to the use of the procedure is that



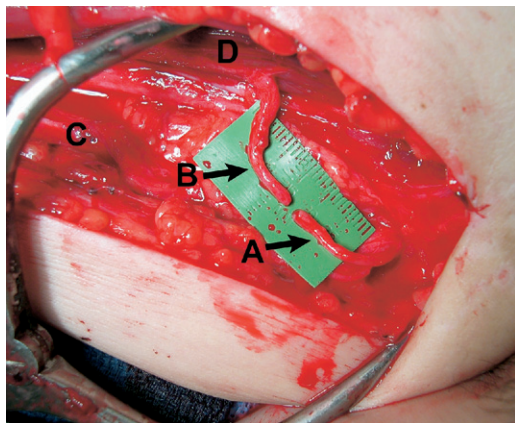
**Figure 3.** Radial nerve to triceps motor branch transfer as described by Leechavengvongs et al (*J Hand Surg* 2003;28A: 633–638): A, axillary nerve; B, radial nerve motor branch to the long head of triceps; C, triceps muscle.

transection of the flexor carpi ulnaris fascicles within the ulnar nerve may sufficiently weaken the flexor carpi ulnaris muscle such that a late-stage flexor/pronator muscle group advancement to augment the strength of elbow flexion would not be possible.

**Partial median nerve.** A conceptually similar approach to that of Oberlin, using a portion of the median nerve, has found various devotees.<sup>45–48</sup> However, the median nerve does share part of its origin with the upper plexus roots and thus often is at least partially dysfunctional. Thus, the risks of producing an unacceptable amount of donor site deficit by partial transection of the median nerve exceeds the risks of a similar technique using the ulnar nerve.<sup>48</sup> Sungpet et al<sup>47</sup> described using a single median nerve fascicle, which chiefly innervated either the flexor carpi radialis or palmaris longus, and transferring it to the biceps motor branch of the musculocutaneous nerve. They reported good results with recovery of elbow flexion exceeding M3+ in 4 of 5 patients. Nath and Mackinnon have also advocated the use of partial median nerve transfer to either the biceps or brachialis motor nerve branches of the musculocutaneous nerve in conjunction with using the flexor carpi ulnaris fascicles of the ulnar nerve to biceps or brachialis.<sup>46</sup>

Thoracodorsal nerve. Transfer of the thoracodorsal nerve to the musculocutaneous nerve to restore elbow flexion has been successfully utilized by several authors.<sup>10,49</sup> It has also been utilized for transfer to the axillary nerve.<sup>26,46</sup> The use of this nerve is attractive because it is readily identifiable and usually can be mobilized to provide an ample length of proximal nerve segment. However, in patients with C7, middle trunk, or posterior cord injury, the thoracodorsal nerve may be significantly affected and thus provide a diminished number of motor axons. Thus, prior to selecting it as a donor in such patients, the strength of the latissimus dorsi muscle upon direct nerve stimulation should be confirmed. Moreover, one should consider that the use of the thoracodorsal nerve for transfer to the musculocutaneous nerve will preclude later stage use of the latissimus dorsi as a tendon transfer to provide shoulder external rotation or elbow flexions or extension.

Radial nerve to triceps motor branches. The branches from the radial nerve to either the long or lateral head of the triceps muscle are well positioned for direct coaptation to the axillary nerve and have been successfully used by several authors (Fig. 4)<sup>10,24,50–53</sup> This transfer is best utilized in patients with brachial plexus injuries confined to the C5 and C6 nerve roots or upper trunk. If C7 or the middle trunk is involved, it is important to confirm by direct stimulation the functionality of the selected triceps branch prior to transecting it. In most patients, the branch to the long head of triceps is preferable to that of the lateral head because it is more proximal and is easier to coapt to



**Figure 4.** Flexor carpi ulnaris fascicles of ulnar nerve transfer to biceps motor branch of musculocutaneous nerve as described by Oberlin et al (*J Hand Surg* 1994;19A:232–237): A, ulnar nerve fascicles to the flexor carpi ulnaris; B, biceps motor branch from the musculocutaneous nerve; C, ulnar nerve; D, biceps muscle.

the axillary nerve as it exits the quadrilateral space.<sup>52</sup> Additionally, normally the triceps long head is a less effective elbow extensor than the lateral head and thus can be denervated with less elbow extension strength loss.<sup>53</sup> The chief drawback to the use of a triceps motor branch is some degree of weakening of the triceps, which may be of significance in overall limb function.

Ipsilateral C7 nerve root. Either whole or part of the ipsilateral C7 nerve root (middle trunk) may warrant consideration as a plexo-plexal nerve transfer,<sup>54</sup> but if uninjured, its use may result in a significant loss of remaining function in the injured limb. It is best used for nerve transfer in the upper trunk when the C5 and C6 nerve roots are avulsed and the middle trunk is ruptured distal to an intact C7 nerve root. When completely intact, it is probably safest to leave the middle trunk undisturbed and instead select branches from the posterior cord (ie, thoracodorsal and triceps motor branches) and/or extraplexal nerves (ie, spinal accessory nerve or intercostal nerves) as possible donor nerves.

Contralateral C7. Since Gu et al<sup>55</sup> introduced the concept of using either a complete or partial contralateral C7 nerve root transfer, this procedure has been increasingly adopted. Anatomic studies have suggested that the posterior portion of the C7 nerve root contains the heaviest concentration of motor axons,<sup>56</sup> but the anterolateral portion of the nerve root contains a sufficient concentration of motor axons for nerve transfer purposes with a lesser risk of donor limb motor deficit.<sup>57</sup> There is differing opinion regarding which portion of C7 is the preferred fraction to use for partial contralateral transfer. Several reports have confirmed the relative paucity of donor limb deficits,<sup>55–59</sup> although significant donor limb motor and sensory losses have rarely been seen.<sup>24,56,60</sup> Thus selection of contralateral C7 as a donor nerve should not be lightly regarded. Although this procedure seems to be gaining popularity, long-term studies regarding recovery of function to the injured limb are still relatively lacking.<sup>59,61</sup> The summation of results from blending several series suggest that contralateral C7 transfer is useful for providing protective sensibility to an injured limb, but it is not consistently effective in restoring motor function in most patients.<sup>27,56</sup> In addition to the drawback of requiring surgical trauma to an otherwise uninjured brachial plexus, the chief disadvantage of contralateral C7 transfer is the need for an extremely long nerve graft between it and the recipient nerve.

This distance may be abbreviated by retropharyngeal routing of the nerve graft,<sup>62</sup> but even this results in a very long graft. Thus axon growth across the graft results in a protracted recovery time, which may preclude effective motor function even when contralateral motor axons reach the recipient motor endplates. The recovery time for axon regeneration may be accelerated if a vascularized nerve graft is employed. The other significant disadvantage relates to the ability for patients to translate contralateral motor activation into useful function for day-to-day activities. There appears to be marked differences in the ease of retraining heterotopic motor activity when the donor nerve is ipsilateral rather than contralateral. This point, however, remains controversial.

#### Other Possible Donor Nerves

Other donor nerves have been utilized for nerve transfer in brachial plexus palsy but without broad acceptance. These include anterior branches of the cervical plexus (C2, C3 and C4),<sup>15</sup> the hypoglossal nerve,<sup>63-65</sup> and contralateral thoracodorsal or lateral pectoral nerves.

### Treatment Options

#### Total C5 to T1 Palsy

With total C5 to T1 nerve root avulsion or equivalent injury, nerve transfer options are restricted to extraplexal donor nerves. In such patients, the chief priorities are restoration of elbow flexion, some degree of shoulder control, and, if possible, grasp. For these patients, intercostal nerves 3 and 4 transfer to the biceps motor branch of the musculocutaneous nerve, and transfer of the distal spinal accessory nerve to the suprascapular nerve is an appropriate treatment approach. In addition, some authors have also recommended phrenic nerve transfer (either prolonged by the use of a free nerve graft or as an extended nerve by thoracoscopic harvest of the entire phrenic nerve length) to the axillary nerve. In general, most attempts to neurotize the axillary nerve have met with a checkered record of success. Most surgeons agree that the most useful and predictable recovery of shoulder function is achieved by utilizing the suprascapular nerve as the recipient nerve.<sup>24,26,27</sup>

The reasons recovery of suprascapular nerve function appears superior to that of the axillary nerve is unclear, but it may be related to the fact that nerve transfer to the suprascapular nerve can often be accomplished without an intervening graft, particularly when the distal spinal accessory nerve is employed as the donor.<sup>27</sup> Chuang et al<sup>66</sup> have suggested that trans-

fer to both the suprascapular and axillary nerves maximizes the likelihood of recovery of useful shoulder function.

A more complex approach, but also one that may result in a higher level of function, is the two-stage reconstruction as designed by Doi and others.<sup>67,68</sup> This involves in stage 1 a free microneurovascular gracilis transfer, innervated by the distal spinal accessory nerve for elbow flexion and finger extension, as well as either the C5 nerve root, if available, to the suprascapular nerve, or contralateral C7 transfer to the suprascapular and axillary nerves. In stage 2, 2 months later, a second free microneurovascular gracilis transfer, innervated by the 5th and 6th intercostal motor nerves for finger flexion, and transfer of the 3rd and 4th intercostal motor nerves to the triceps lateral head motor branch is carried out. In addition, at the second stage, the lateral cutaneous branches of the 3rd through 6th intercostal nerves are transferred to the medial cord.

#### C5, C6, C7 (Upper/Middle Trunk) Avulsion or Equivalent Injury

Patients with irreparable injury to the upper 3 nerve roots or upper and middle trunks, but with intact C8 and T1 or lower trunk function, are left with a useful hand but absent elbow flexion and shoulder control and either weak or absent elbow extension and wrist extension. In many such patients, wrist extension may be regained or augmented by late tendon transfer. Thus the priorities for early nerve transfer should be focused on recovery of elbow flexion, shoulder external rotation, shoulder abduction, and elbow extension. To accomplish these goals, one still has the same array of extraplexal donor nerves available as outlined for the total palsy patient. However, in addition, the flexor carpi ulnaris fascicles of the ulnar nerve, the medial pectoral nerve, and perhaps the thoracodorsal nerve (depending on the relative importance of the C7 contribution) may be available. Respecting the principles of nerve transfer as previously outlined, an appropriate strategy for nerve transfer would be:

- Flexor carpi ulnaris fascicles of ulnar nerve (or medial pectoral nerve) to biceps ( $\pm$ brachialis) fascicles of musculocutaneous nerve.
- Distal spinal accessory nerve to suprascapular nerve.
- Thoracodorsal nerve (if functional) to axillary nerve.
- If triceps M3 or less, intercostal nerves 3 and 4 to triceps division of radial nerve or directly to



branch to long or lateral triceps head (whichever is weakest).

#### C5, C6, or Upper Trunk Avulsion or Equivalent Injury

Isolated root avulsion injuries to C5 and C6 are less frequent than those injuries that also include C7 or the lower roots.<sup>18</sup> Moreover, when an isolated C5 and C6 level injury is encountered, it usually does not involve a root avulsion and thus may be a good candidate for an orthotopic nerve graft reconstruction at least to C5, which is rarely avulsed.<sup>19</sup> Nonetheless, isolated injuries to C5 and C6 may require consideration of nerve transfer,<sup>40,44</sup> particularly if seen relatively late or if a very proximal rupture or root avulsion is encountered. In such patients, hand function, wrist extension, and elbow extension are usually well preserved. The chief reconstructive goal in this patient group is restoration of elbow flexion, shoulder external rotation, and shoulder abduction. The approach is similar in principle but simpler to that of the C5, C6, C7 injury patient. Elbow flexion is restored by transfer of the extensor carpi ulnaris fascicles of the ulnar nerve (or medial pectoral nerve) to the biceps ( $\pm$ brachialis) fascicles of the musculocutaneous nerve. The shoulder is reconstructed by transfer of the distal spinal accessory nerve to the suprascapular nerve and transfer of the long or lateral triceps motor branch of the radial nerve to the axillary nerve.

### Results of Nerve Transfer for Brachial Plexus Reconstruction

Merrell et al<sup>26</sup> summarized 1,088 nerve transfers from 27 peer-reviewed series and found:

- Intercostal direct transfers to the biceps motor branch of the musculocutaneous nerve resulted in 72% of patients regaining M3 or greater elbow flexion.
- Intercostal nerve transfer using an intervening graft to the musculocutaneous nerve resulted in only 47% of patients regaining M3 or better elbow flexion.
- Comparing biceps reinnervation by direct transfer of the spinal accessory nerve versus direct transfer of intercostal nerves resulted in M4 elbow flexion in 29% versus 41% of patients.
- When the suprascapular nerve only was the target recipient nerve, shoulder abduction of M3 or more was achieved in 92% of patients. When the axillary nerve only was the target recipient nerve, M3 shoulder abduction was achieved in only 69%.

The literature suggests that with all other aspects being equal, the results of the use of direct transfer of intercostal nerves, the distal spinal accessory nerve, the medial pectoral nerve, flexor carpi ulnaris fascicles of the ulnar nerve or the thoracodorsal nerve to the biceps motor nerve or contributing fascicles within the musculocutaneous nerve are equivalent in terms of recovery of elbow flexion strength of at least M3 level.<sup>26,38,44,49</sup> The chief variables affecting selection of one of these donor nerves over the others should include availability, technical simplicity, and in some cases timing after injury. In these regards, use of the flexor carpi ulnaris fascicles of the ulnar nerve or the medial pectoral nerve probably wins top honors for biceps reanimation.

It is clear that shoulder reanimation is most predictably achieved by direct transfer of the distal spinal accessory nerve to the suprascapular nerve.<sup>24,26,27</sup> It is less clear if nerve transfer to the axillary nerve, in addition to the suprascapular nerve, provides a sufficient degree of improved shoulder function to justify the use of an otherwise potentially useful donor nerve.<sup>30,66</sup>

The role of the phrenic nerve is not well established. It contains an abundant source of motor axons, but in most cases, even with a tedious intrathoracic harvest, it is too short for direct coaptation to most important target nerves. Thus the use of an interposition graft is often necessary, which may diminish the degree of motor recovery. Moreover, one must maintain serious concerns regarding the long-term detriment to pulmonary function with sacrifice of a phrenic nerve, especially in an infant or in adults with cardiopulmonary dysfunction.

Contralateral C7 transfer, in whole or part, has been a controversial procedure for the past decade and remains so today. Clearly, initial concerns about an unacceptable risk of donor deficit have not proved valid. However, reliable functional motor recovery has been disappointing. In the series of Songcharoen et al,<sup>56</sup> only 20% of patients recovered M3 or more for median nerve reconstruction. Most agree contralateral C7 transfer may be more predictable for recovery of sensibility rather than motor function.<sup>27</sup>

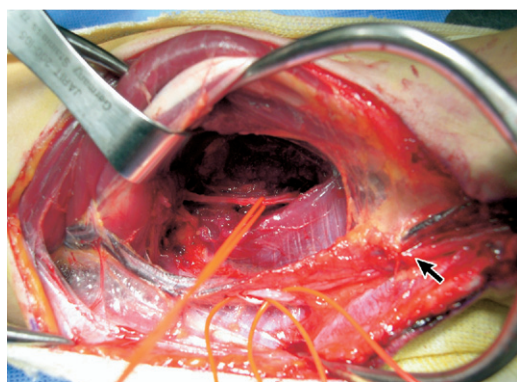
### Use of Nerve Transfer for Mononeural Reconstruction

The concept of nerve transfer can usefully be extended beyond its role for brachial plexus reconstruction to that of reconstruction of specific peripheral nerves that may not be candidates for orthotopic nerve graft repair or may have a very poor prognosis

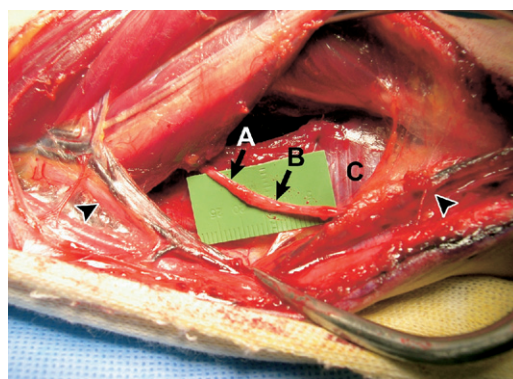
for useful motor recovery with nerve graft repair. In terms of motor nerves, the chief candidates in this regard include high ulnar nerve lesions and long thoracic nerve injuries at the supraclavicular level. At times, the absence of an identifiable proximal nerve segment may dictate consideration of a nerve transfer procedure.

Of all nerve transfers for more distal reconstruction, perhaps the distal anterior interosseous nerve transfer to the deep motor branch of the ulnar nerve or the thenar branch of the median nerve is most useful and well known.<sup>69-71</sup> This is because ulnar nerve repair or graft reconstruction at a level proximal to the elbow has a dismal record for recovery of ulnar-innervated intrinsic motor function.<sup>72</sup> Mobilization of the distal anterior interosseous nerve within the proximal portion of the pronator quadratus muscle results in sufficient nerve length to permit direct coaptation between it and either the deep motor division of the ulnar nerve (Figs. 5, 6)<sup>72-74</sup> or the thenar motor branch of the median nerve,<sup>75,76</sup> provided these target nerves are mobilized proximally by the intrafascicular dissection.

Another nerve transfer that we have found useful is that of intercostal motor nerves (usually third and fourth) to the long thoracic nerve, when the long thoracic nerve is injured proximally within the substance of the scalene muscle mass. Dissection of the long thoracic nerve within the scalene muscle mass is extremely difficult without the risk of iatrogenic injury to the proximal portion of the brachial plexus or phrenic nerve. On the contrary, isolation of the long thoracic nerve on the serratus anterior muscle in the axilla is straightforward, and the nerve lies close to the intercostal nerves.



**Figure 5.** Distal anterior interosseous nerve transfer to the motor branch of the ulnar nerve at the wrist. The anterior interosseous nerve is shown after splitting of the pronator quadratus muscle. The ulnar nerve is identified by the black arrow.



**Figure 6.** Distal anterior interosseous nerve transfer to the motor branch of the ulnar nerve at the wrist: A, distal anterior interosseous nerve; B, motor fascicles of the deep branch of the ulnar nerve; C, pronator quadratus muscle. Arrowheads show the ulnar nerve.

A wide variety of other nerve transfers for mononeural reconstruction, when orthotopic nerve repair is not possible, have been reported. These include:

- Third lumbrical motor nerve to the thenar branch of the median nerve.<sup>77</sup>
- The thoracodorsal nerve to the long thoracic nerve.<sup>78</sup>
- The medial pectoral nerve to the long thoracic nerve.<sup>79</sup>
- The medial pectoral nerve to the spinal accessory nerve.<sup>80</sup>
- The lateral gastrocnemius motor nerve to the deep division of the peroneal nerve.<sup>81</sup>

## Use of Nerve Transfer Procedures for Sensory Reconstruction

The application of nerve transfer to restore sensibility is less widely used than motor nerve transfer.<sup>71</sup> Even with proximal nerve injuries and relatively large nerve gaps, reconstruction by orthotopic nerve grafting can result in some degree of protective sensibility that is perceived as topographically appropriate. The quality of the result can often be further enhanced by a conscientious program of sensory reeducation. Thus, if a viable proximal nerve segment can be identified, nerve graft reconstruction may yield an acceptable result for recovery of sensibility, in contrast with motor recovery. Moreover, sensory nerve transfer rarely, if ever, results in sensibility that topographically matches the recipient nerve zone.<sup>82</sup> Rather, the sensibility is perceived in the topography of the donor nerve. Many patients find this mismatch confusing, which may degrade the functional usefulness of the nerve transfer. Despite this distinct draw-



back, sensory nerve transfer may be indicated in highly selected patients who are not candidates for orthotopic nerve reconstruction. The most common sensory nerve transfers for a total brachial plexus injury are the use of the lateral cutaneous branches of multiple intercostal nerves to the medial cord or the use of the contralateral C7 nerve root, prolonged with a vascularized intervening ulnar nerve graft, to the median nerve. The latter procedure has been reported to result in useful protective sensibility in about 50% of patients.<sup>56</sup>

The more well-known use of sensory nerve transfer has been for nonreconstructible mononeural injuries to the hand<sup>46,71,83,84</sup> or the plantar aspect of the foot.<sup>45,85</sup> Various reports include:

- Ulnar digital nerve to the ring finger (or long finger when functional) to the ulnar digital nerve of the thumb or radial digital nerve of the index finger.
- Transfer of the superficial radial nerve to the radial aspect of the median nerve.
- Transfer of the palmar cutaneous branch of the median nerve to the ulnar-palmar aspect of the ulnar nerve.
- Transfer of the dorsal sensory branch of the ulnar nerve to the median nerve.
- Transfer of the deep peroneal nerve at the ankle level to the medial plantar nerve.
- Transfer of the saphenous nerve to the posterior tibial nerve.

The availability of sensory nerve transfers should be considered whenever one is dealing with an unusual situation where orthotopic nerve grafting cannot be done and where protective sensibility is necessary in the hand or foot. The selection of a specific procedure, however, will depend on so many unique factors that each patient should be individualized regarding donor and recipient nerve.

### Other Applications of Nerve Transfer Procedures

Undoubtedly, the most widely used nerve transfers have involved upper limb reanimation after brachial plexus trauma or nonreconstructible upper limb mononeuropathies. Hypoglossal nerve transfer for facial nerve reanimation is also widely used. However, other creative applications of this procedure have also been reported.

Livshits et al<sup>86</sup> reported reinnervation of neurogenic bladders by transfer of the 11th and 12th intercostal nerves to the second and third sacral nerve roots, with improvement in 8 of 11 patients. Similar

techniques have been reported by Carlsson, Vorstman, and others.<sup>87,88</sup> An interesting application of nerve transfer is that of intercostal nerve coaptation to the phrenic nerve for diaphragm reanimation in patients with high cervical tetraplegia.<sup>89</sup>

Attempts to reanimate the lower trunk and lower extremities by intercostal nerves transfer to the lumbosacral plexus have also been reported by a few authors. These include Chiasserini as early as 1934, and more recently by Zhang et al<sup>90</sup> and Wang et al.<sup>91</sup> In the 2003 study of Zhang et al, they reported that transfer of 2–4 intercostal nerves proximal to the level of spinal cord transaction to the L1, L2 or L3, L4 nerves resulted in the ability of 18 of 23 patients to independently ambulate with crutches. Variations of this approach have also been studied.<sup>92</sup> Brunelli has reported encouraging results using a pedicled ulnar nerve to reanimate the lower extremities.<sup>93</sup>

Whether improved techniques of nerve coaptation and enhancement of the speed and quality of nerve regeneration by pharmacologic or genomics advances will promote wider use of nerve transfers for paraplegic reconstruction is yet to be determined.

In conclusion, nerve transfer procedures have in recent years gained widespread acceptance as an important method to reanimate paralyzed muscles and in some instances restore functional sensibility.

### Summary

The applicability of nerve transfers in upper extremity peripheral nerve reconstruction is ever expanding. The indications include proximal injuries, nerve injuries where useful recovery is unlikely because of the distance to the target motor end-plate, large nerve defects, and nerve root avulsion injuries about the brachial plexus. Specific successful nerve transfer strategies have been developed for the following brachial plexus injuries: C5 to T1 avulsion injury, C5 to C7 avulsion injury, and C5 to C6 avulsion injury. Direct intercostal nerve transfers to the motor branch of the musculocutaneous nerve can result in greater than 70% recovery of M3 elbow flexion. The use of interposed nerve graft material compromises the rate of M3 recovery. Recovery of shoulder abduction is enhanced when the spinal accessory nerve is transferred to the suprascapular nerve rather than the axillary nerve. The most useful nerve transfer in more distal peripheral nerve reconstruction is the anterior interosseous nerve transfer to the ulnar nerve deep motor branch. The technique of nerve transfer to restore extremity sensibility is less popular.

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