Review Article

Nerve Transfers for the Upper Extremity: New Horizons in Nerve Reconstruction

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Abstract

Nerve transfers are key components of the surgeon's armamentarium in brachial plexus and complex nerve reconstruction. Advantages of nerve transfers are that nerve regeneration distances are shortened, pure motor or sensory nerve fascicles can be selected as donors, and nerve grafts are generally not required. Similar to the principle of tendon transfers, expendable donor nerves are transferred to denervated nerves with the goal of functional recovery. Transfers may be subdivided into intraplexal, extraplexal, and distal types; each has a unique role in the reconstructive process. A thorough diagnostic workup and intraoperative assessment help guide the surgeon in their use. Nerve transfers have made a positive impact on the outcomes of nerve surgery and are essential tools in complex nerve reconstruction.

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Although not a new concept, nerve transfers have become an increasingly important technique in the strategic algorithm for nerve reconstruction. Pioneers such as Flouren introduced the rooster plexus model in 1820, Balance described the spinal accessory nerve (SAN) transfer to the facial nerve in 1903, Vulpius described use of the medial pectoral nerve in 1920, and Seddon, the transfer of intercostal nerves (ICNs) in 1963.[1]

The definition of nerve transfer is the surgical coaptation of a healthy nerve donor to a denervated nerve. The principle is similar to that of tendon transfers in that a necessary distal function is recovered by sacrificing another function that is less essential to the patient. Synonyms for nerve transfer are nerve-to-nerve neurotization, heterotopic nerve suture, and nerve crossing. The term neurotization should be reserved to describe the direct implantation of a divided donor nerve into muscle, which has shown promise in an animal model.[1,2]

Indications and Contraindications

A variety of indications exists for nerve transfer, primarily when the proximal nerve end is nonfunctional or nerve reconstruction would require an excessively long nerve graft. Nerve transfer may expedite reinnervation when traditional nerve grafting would exceed the expected viability of motor end plates and muscle (approximately 12 to 18 months).[3] Nerve transfer may also be indicated in patients in whom the zone of injury is very broad, with dense scarring. Nerve transfer outside the zone of injury is more surgically efficient and outcomes, more predictable.[4]

In the upper extremity, nerve transfer is most commonly used for reconstruction of brachial plexus injury. Other indications include complex injuries to peripheral nerves, especially when associated with fractures and dislocations, lacerations, injuries from projectiles, neoplasia, or, occasionally, neuralgic amyotrophy (Parsonage-Turner syndrome).

Contraindications for nerve transfer include the presence of a superior reconstructive option, excessive time between injury and reinnervation (ie, >18 months), or donor nerve motor strength of less than Medical Research Council grade M4.

Advantages of Nerve Transfer

Nerve transfer has the distinct advantage over primary nerve repair and long nerve grafting of shortening the length that the nerve must regenerate by bringing the donor nerve closer to the target organ.[3,5] With nerve transfer, pure motor fascicles with maximal axonal counts are directed to a recipient nerve. Optimally, nerves are directly transferred to the recipient nerve without an interposed nerve graft. As opposed to tendon transfer, when nerve transfer is successful, recovered function is similar to the original muscle function because synchronous physiologic motion may be achieved. With quicker nerve recovery, more rapid motor reeducation is also possible.

Nomenclature

Intraplexal versus extraplexal: Intraplexal refers to nerve transfers in which the donor nerve originates in the brachial plexus, including the terminal peripheral nerve branches above the elbow. Examples include the medial pectoral or thoracodorsal nerve to the axillary nerve, a fascicle of the ulnar nerve to the biceps motor branch, a fascicle of the median nerve to the brachialis motor branch, and triceps branches of the radial nerve to the axillary nerve and its branches. Extraplexal refers to donor nerves that originate outside the plexus. Examples include the SAN to the suprascapular nerve (SSN) and the ICN or phrenic nerve to the musculocutaneous nerve (MCN).

Distal transfer: Nerve transfer that is at or distal to the elbow.

Single versus dual transfer: Single transfer refers to the use of one nerve transfer to achieve one action. An example of a single transfer is an ulnar nerve fascicle to the biceps motor branch to achieve elbow flexion. Dual transfer refers to the use of two nerve transfers to achieve one action. An example is an ulnar nerve fascicle to the biceps motor branch and a median nerve fascicle to the brachialis motor branch to achieve elbow flexion.

Direct nerve transfer: A direct nerve transfer connects the donor nerve to the recipient nerve without an interposed graft. If a tensionless nerve coaptation is not possible, an interposition nerve graft must be used.

Motor versus sensory transfer: Transfers with the goal of recovering motor or sensory function. Transfers performed to restore sensory function have the added benefit of decreasing neuropathic pain.[6]

End-to-end, end-to-side, reverse end-to-side: End-to-end nerve transfer refers to direct coaptation of the end of the donor nerve to the proximal end of the recipient nerve (Figure 1). End-to-side nerve transfer describes coaptation of the proximal end of the recipient nerve to an epineural window in the side of an intact and functioning donor nerve. Reverse end-to-side is when the end of a freshly divided donor nerve is coapted to an epineural window in the side of an intact but functionally compromised recipient nerve.[7] End-to-end transfer is preferable for all transfers; reverse end-to-side transfers have not been demonstrated to improve motor outcomes in humans but do show experimental promise.[7,8] End-to-side transfers have demonstrated efficacy in sensory nerves.[3,6]

The most common upper extremity deficits that benefit from nerve transfer are elbow flexion and shoulder stabilization, abduction, and external rotation. Other indications include scapular stabilization for winging, elbow extension, wrist extension, finger and thumb extension, finger flexion, and intrinsic hand function. Tables 1 to 3 describe intraplexal, extraplexal, and distal motor transfers. Sensory deficits of the thumb, index, ring and small finger and ulnar border of the hand are treated by nerve transfers listed in Table 4.

Intraplexal donors include the following: ulnar nerve fascicle, median nerve fascicle, medial pectoral nerve, thoracodorsal nerve, triceps branches of the radial nerve, brachialis branch of the MCN, and pectoral fascicle from the middle trunk of C7.

Extraplexal donors include the following: SAN, ICNs, phrenic nerve, and contralateral C7 nerve root.

Distal transfer donors include the following: distal anterior interosseous nerve (AIN), radial nerve branch to the extensor carpi radialis brevis, supinator branches of the posterior interosseous nerve (PIN), and radial nerve branch to the brachioradialis.

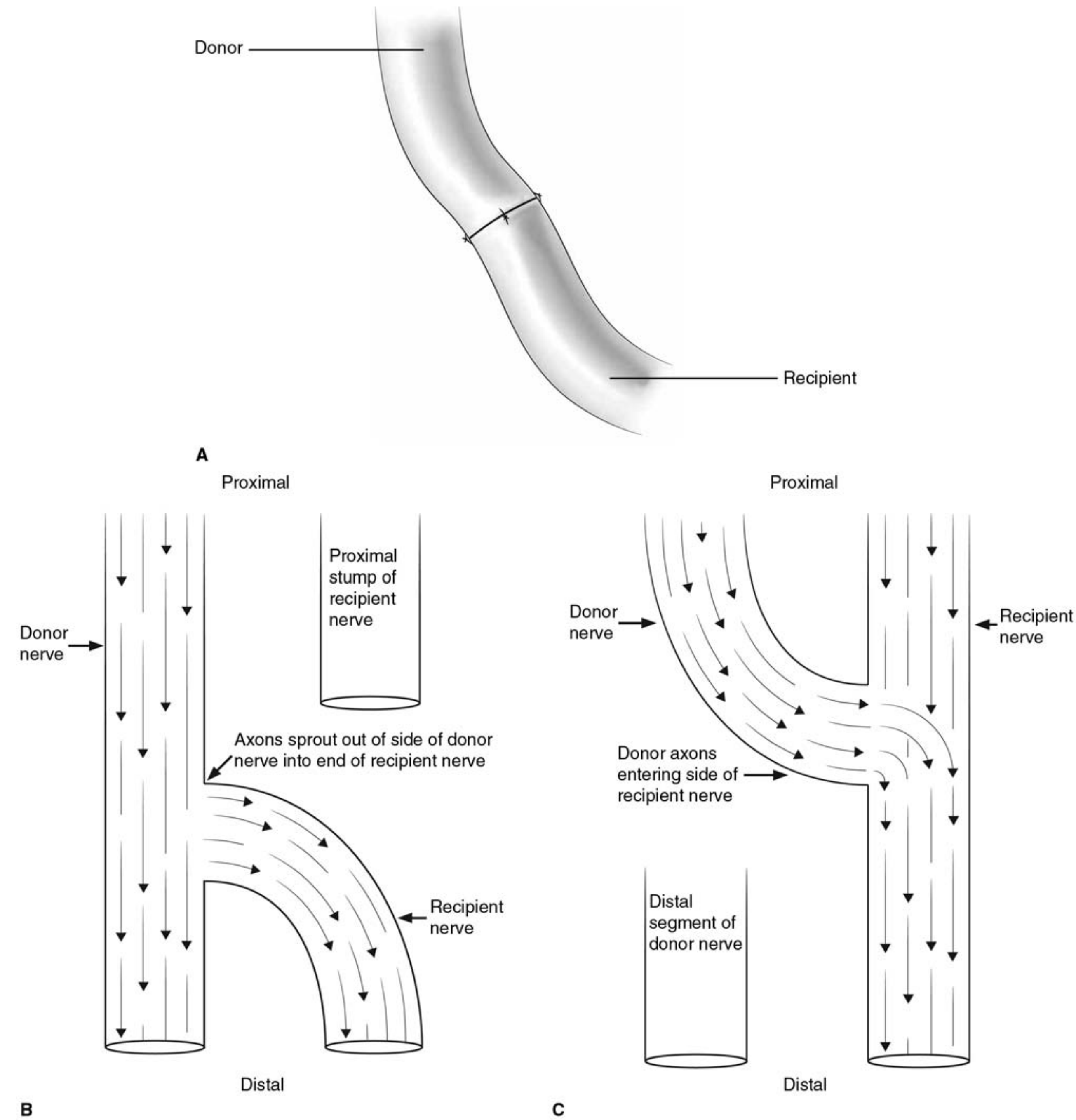
Common Transfers and Outcomes

Intraplexal Transfers

Ulnar Nerve Fascicle to Biceps Motor Branch

Transfer of the ulnar nerve fascicle to the biceps motor branch, described by Oberlin et al[9] in 1994, critically altered the approach to modern

Figure 1



Illustrations of the types of nerve transfer. **A,** End-to-end. **B,** End-to-side. **C,** Reverse end-to-side.

nerve transfers. In this transfer, one or two fascicles of the ulnar nerve are transferred directly to the motor branch of the biceps. In our practice, fascicles are identified intraoperatively by electrically stimulating an individual fascicle (Checkpoint Surgical Stimulator; Checkpoint Surgical, Cleveland, OH) and observing the distal muscular contraction. A fascicle to the flexor carpi ulnaris is chosen, which is usually in the lateral or central part of the nerve;[10] any fascicles that give no response are presumed to be sensory, and those that cause flexor digitorum profundus stimulation are avoided. Evidence suggests that any of the fasci-

Table 1

Common Intraplexal Motor Transfers

Motor Deficit	Recipient Nerve or Nerves	Donor Nerve or Nerves	Comment
Elbow flexion	Musculocutaneous nerve: biceps and brachialis branches dual transfer	Ulnar nerve fascicle and median nerve fascicle	Primary choice, if possible, in upper nerve root brachial plexus injury (C5-6, C5-7)
	Musculocutaneous nerve	Medial pectoral nerve	Secondary choice
	Musculocutaneous nerve	Thoracodorsal nerve	Secondary choice
Shoulder stabilization/abduction/external rotation	Suprascapular nerve and axillary nerve dual transfer	Spinal accessory nerve and triceps branches	Primary choice, if possible, combination intraplexal and extraplexal
Shoulder stabilization/abduction	Axillary nerve	Medial pectoral nerve	Secondary choice
	Axillary nerve	Thoracodorsal nerve	Secondary choice
Scapular stabilization/anti-winging	Long thoracic nerve	Thoracodorsal nerve	Primary choice if possible
	Long thoracic nerve	Pectoral fascicle from middle trunk from C7	Secondary choice
Thumb and index finger flexion	Posterior fascicle of the median nerve in the arm which corresponds to the anterior interosseous nerve	Brachialis branch of musculocutaneous nerve or extensor carpi radialis brevis supinator branches of radial nerve	For lower trunk plexus injury or high median nerve injury. Coupled with tenodesis of the four flexor digitorum profundus tendons in the forearm
Elbow extension	Triceps branch of radial nerve	Ulnar nerve fascicle to flexor carpi ulnaris or median nerve fascicle to flexor digitorum superficialis	—

Table 2

Common Extraplexal Motor Transfers

Motor Deficit	Recipient Nerve or Nerves	Donor Nerve or Nerves	Comment
Elbow flexion	Musculocutaneous nerve	Intercostal nerves	Primary choice if intraplexal nerve transfers not possible
	Musculocutaneous nerve	Spinal accessory nerve	Secondary choice
	Musculocutaneous nerve	Phrenic nerve	Infrequently performed given decreased exercise tolerance
Shoulder stabilization/abduction/external rotation	Suprascapular nerve	Spinal accessory nerve	Primary choice as part of dual nerve transfer with triceps branches to axillary nerve
	Suprascapular nerve	Intercostal nerves	Secondary choice
Shoulder stabilization/abduction	Axillary nerve	Intercostal nerves	Secondary choice if triceps branch is not available
Scapular stabilization/anti-winging	Long thoracic nerve	Intercostal nerves	Secondary choice if thoracodorsal nerve is not available
Elbow extension	Triceps branch of radial nerve	Intercostal nerves	—
Elbow flexion, hand function	Musculocutaneous nerve, median nerve	Contralateral C7	For five-root avulsion in a young patient, less commonly performed

cles of the ulnar nerve at the level of the proximal arm can be used for transfer without the loss of ulnar nerve function.[11]

After 10 years of experience, Teboul et al[12] reported their outcomes in 32 patients with upper nerve root brachial plexus injuries (C5-6, C5-7). There were no deficits in the donor ulnar nerve; 24 of 32 patients achieved strength grade M3 or higher. A Steindler flexorplasty

Table 3

Common Distal Motor Transfers

Motor Deficit	Recipient Nerve or Nerves	Donor Nerve or Nerves	Comments
Intrinsic hand	Ulnar nerve motor branch	Distal anterior interosseous nerve	For high ulnar nerve lesions
Thumb, finger extension	Posterior interosseous nerve branches of radial nerve	Nerve to supinator	For C7-T1 plexus injuries
Wrist, finger extension	Radial nerve branch to extensor carpi radialis brevis and posterior interosseous nerve	Median nerve fascicles to flexor digitorum superficialis and median nerve fascicles to flexor carpi radialis	Dual transfer
Thumb, finger flexion	Anterior interosseous nerve	Radial nerve branch to the brachioradialis	Indicated for lower trunk plexus injury or high median nerve injury. Coupled with tenodesis of the four flexor digitorum profundus tendons in the forearm

Table 4

Common Sensory Transfers

Sensibility Deficit	Recipient Nerve or Nerves	Donor Nerve or Nerves	Comments
Radial hand	Lateral cord contribution to the median nerve	Intercostal sensory nerve branches	Proximal transfer
Thumb and index finger	Common digital nerve to first web space, radial digital nerve to thumb	Superficial radial nerve	—
	Digital nerves of the ulnar aspect of the thumb and radial aspect of the index finger	Digital branches of superficial radial nerve	Very distal transfer
	Common digital nerve to first web space, radial digital nerve to thumb	Common digital nerve to third web space	—
	Common digital nerve to first web space, radial digital nerve to thumb	Common digital nerve to fourth web space	—
	Common digital nerve to first web space, radial digital nerve to thumb	Dorsal branch of the ulnar nerve	—
Ring and small fingers	Ulnar nerve	Lateral antebrachial cutaneous nerve	C7-T1 injuries
	Common digital nerve to fourth web space, ulnar digital nerve to small finger	Common digital nerve to third web space	—
Ulnar border of hand	Dorsal branch of the ulnar nerve	Lateral antebrachial cutaneous nerve	—
	Dorsal branch of the ulnar nerve	Median nerve at distal forearm (end to side)	—

was performed as a secondary procedure in 10 patients with strength grade M3 or lower. Overall, including all patients with and without Steindler flexorplasty, 30 of 32 patients achieved a good (M4) or a fair (M3) result. Leechavengvongs and colleagues reported 30 of 32 patients with M4 strength[13] and, in a different series, 13 of 15 patients with M4 strength, without using the complementary Steindler flexorplasty.[13,14]

Figure 2

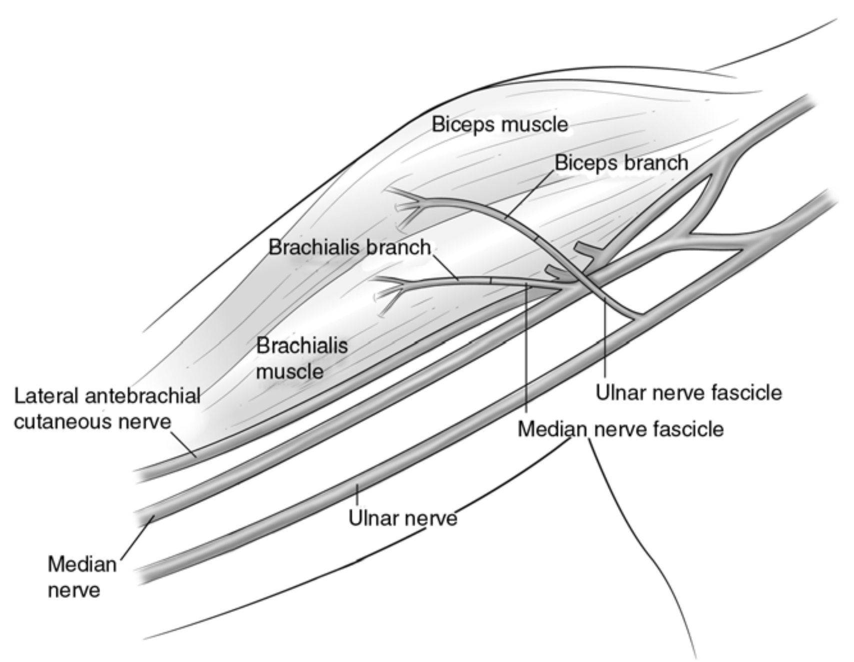


Illustration of dual transfer to regain elbow flexion. Transfer of an ulnar nerve fascicle to the biceps motor branch, plus transfer of a median nerve fascicle to the brachialis motor branch.

Medial Pectoral or Thoracodorsal Nerve to Musculocutaneous Nerve

Brandt and Mackinnon[15] reported on five cases in which biceps/brachialis reinnervation was performed by using one or more medial pectoral nerve branches, which lie in close proximity to the MCN. Novak et al[16] examined the feasibility and success of the thoracodorsal transfer to the MCN; in five of six cases, the patients recovered M4 or M5 strength of elbow flexion.

Dual Transfer: Ulnar Nerve Fascicle to Biceps Transfer and Median Nerve Fascicle to Brachialis

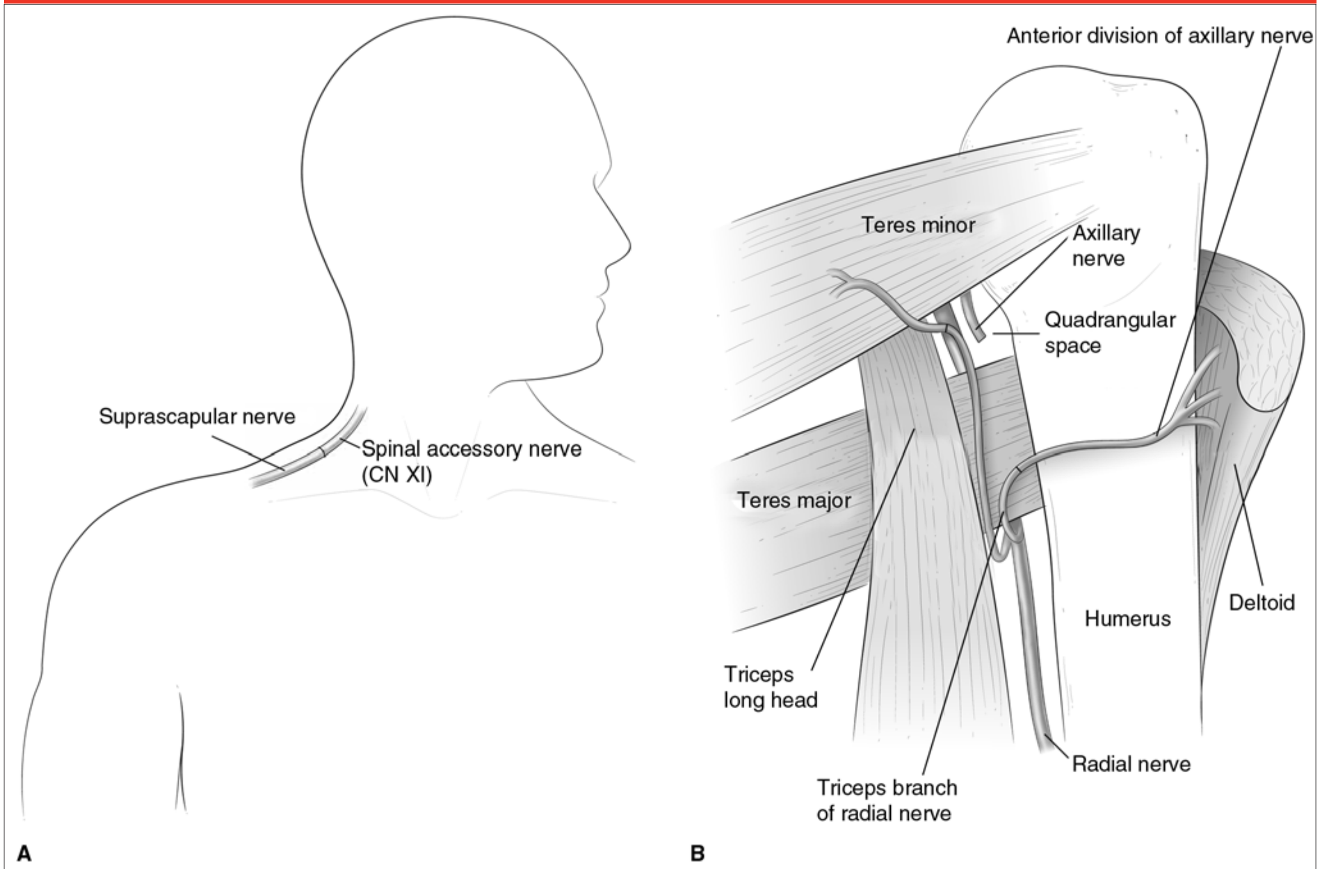
Given the initial 80% success rate with the single nerve transfer for elbow flexion, Ray et al,[10] Mackinnon et al,[17] and Liverneaux et al[18] proposed a dual transfer to regain elbow flexion. The first part of the dual transfer is transfer of an ulnar nerve fascicle to the biceps motor branch, as described above. This is followed by transfer of a median nerve fascicle (generally, the branch to the flexor carpi radialis or flexor digitorum superficialis) to the brachialis motor branch (Figure 2). In practice, either ulnar or median nerve fascicles may be transferred to either the biceps or brachialis branches, depending on the patient's anatomy. Liverneaux et al[18] reported on 10 patients, all with grade M4 elbow flexion strength. Ray et al[10] reported on 29 patients: 23 had strength of grade 4 or better, and 4 had grade 3. There were no donor deficits.

Mackinnon et al[17] and Liverneaux et al[18] make a strong argument for dual transfer for elbow flexion, especially compared with previous published results of single transfer. Carlsen et al[19] reported that, with the numbers tested, there was no difference between single and dual transfers. However, these authors still use the dual nerve transfer in practice. Garg et al[4] performed a systematic review comparing the outcomes of nerve transfers for elbow function with autogenous nerve grafting from C5 or C6; they found that 83% of nerve transfers achieved elbow flexion strength of grade M4 or higher, and that 96% achieved grade M3 or higher. By comparison, for nerve graft outcomes, 56% achieved grade M4 or higher and 82% achieved grade M3 or higher. The authors concluded that, compared with traditional nerve grafting for restoration of elbow function, nerve transfers led to improved outcomes.[4]

Triceps Branch to Axillary Nerve

Regarding shoulder function, a key transfer is the triceps branch of the radial nerve to the axillary nerve.[20,21] The nerve branches to the long, medial, or lateral head of the triceps are transferred to branches of the axillary nerve. Because of the critical importance of external rotation, Bertelli and Ghizoni[21] recommend transfer to both the anterior branch and the teres minor branch. Transfer of the triceps branch to the axillary nerve may be combined with SSN reinnervation,[21,22] thereby making the procedure a dual nerve transfer for both shoulder abduction and external rotation (Figure 3). In seven patients who had dual transfers of SAN to SSN and of the triceps branch to the axillary nerve, Leechavengvongs et al[20] reported all patients as having grade M4 deltoid function with 124° of abduction. In 10 patients with C5-6 brachial plexus injury, Bertelli and Ghizoni[21] reported that, with dual shoulder nerve transfers, 3 patients had grade M4 abduction, 7 had grade M3 shoulder abduction (average, 92°), 2 had grade M4 external rotation, and 5 had grade M3 external rotation; average external rotation was 93° from full internal rotation. In their systematic re-

Figure 3



Illustrations of dual nerve transfer for shoulder stabilization, abduction, and external rotation. Transfer of the spinal accessory nerve to the suprascapular nerve (**A**), plus transfer of triceps branches to the anterior division of the axillary nerve and teres minor branch (**B**). CN XI = cranial nerve XI

view, Garg et al[4] found that 74% of patients with dual nerve transfers had shoulder abduction strength of grade M4 or higher, compared with 35% of patients with single nerve transfer and 46% of patients with nerve grafts. They concluded that dual nerve transfers are associated with improved outcomes for shoulder abduction.

Thoracodorsal Nerve to Long Thoracic Nerve

Raksakulkiat et al[23] have shown the feasibility and value of reinnervating the serratus anterior muscle using the thoracodorsal nerve in five patients with C5-6 root avulsion. Postoperatively, two patients had no scapular winging, and three had decreased scapular winging. These patients also had transfers of the SAN to SSN and of the triceps branch to the axillary nerve. Average shoulder external rotation from the fully internally rotated resting position improved to 124°. The authors concluded that reinnervating the serratus anterior muscle is beneficial for shoulder function.[24] This finding may be particularly important in managing patients with C5-7 injuries and consequent complete denervation of the serratus anterior; reinnervation should be considered critical to restoration of shoulder function.

Extraplexal Transfers

Spinal Accessory Nerve to Suprascapular Nerve

The SAN (ie, cranial nerve XI) innervates the sternocleidomastoid and trapezius muscles. Transferring the distal fascicles of the SAN to the SSN is part of a key nerve transfer set for regaining shoulder function. In this transfer, the inferior branch of the SAN is divided distally and directly transferred to the SSN. Superior branches to the trapezius are left intact, which preserves strong trapezius function. It is best to transfer without a nerve graft; interposed nerve grafting worsens results.[22,25]

Figure 4

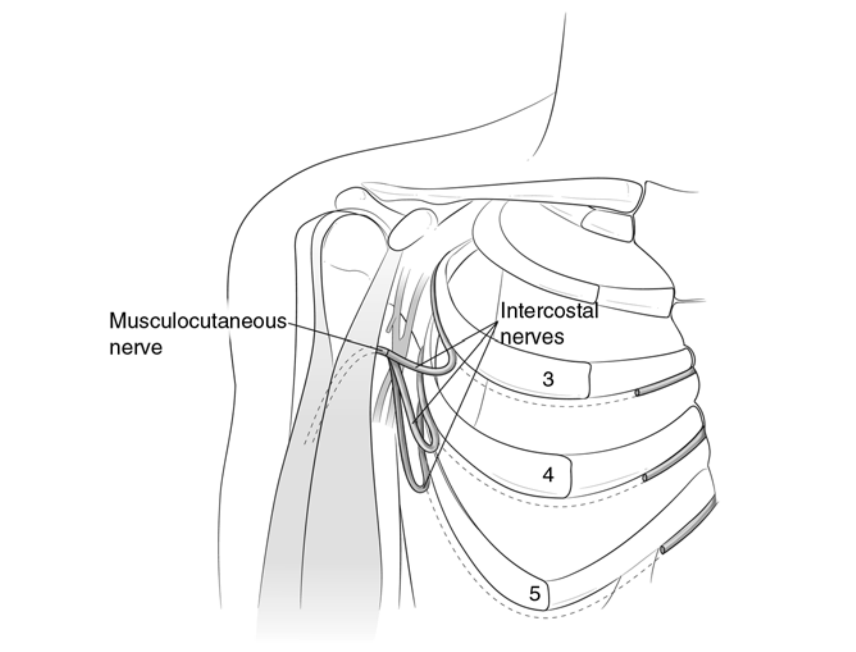


Illustration of transfer of intercostal nerves to the musculocutaneous nerve.

Segmental injury of the SSN can occur; patients with upper trunk or C5 root injuries can also have a distal injury to the SSN at the suprascapular notch, especially those who have sustained scapular fractures, scapulothoracic dissociation, and clavicle dislocations. In these situations, Bertelli and Ghizoni[26] proposed to dissect both the SAN and SSN via a distal oblique supraclavicular incision, prolonged up to the scapular notch, so that the SSN can be decompressed and the nerve inspected for continuity. As discussed, dual transfers for shoulder function lead to improved results over isolated transfers to the axillary nerve.[4,22,25,26] However, poor recovery of external rotation continues to affect outcomes, especially with more extensive injury patterns. Bertelli and Ghizoni[26] showed that no patient with a five-level plexus palsy recovered external rotation. Suzuki et al[27] reported results in 12 patients with a mix of injuries at the C5-6, C5-7, and C5-8 levels, with mean outcomes of 77° abduction and 17° external rotation. With less severe, isolated C5-6 injury, patients have better results.[21]

Intercostal Nerve

ICNs are among the most useful and dependable extraplexal donors. Used most frequently in cases of five-level (C5-T1) plexus palsy, up to seven ICNs can be transferred to regain some control of the upper extremity. ICNs are most frequently used for restoration of elbow flexion, but other recipients include the axillary nerve, long thoracic nerve, and SSN (Figure 4). A systematic review by Merrell et al[22] showed that 72% of patients achieved elbow flexion recovery of grade M3 or better when direct transfer of ICNs to MCNs was performed; only 47% achieved grade M3 or better when interposed nerve grafts were used. Given the original function of the ICNs, it is not considered a synergistic transfer; retraining takes dedicated patient effort and considerable time (12 to 24 months). The sensory branches of the ICNs may also be used for recovery of limited hand sensation and relief of neuropathic pain.[28] Kovachevich et al[29] reported a 15% complication rate with ICN transfers, the most common being pleural tears. They stated that the current literature shows minimal effect of ICN harvest on pulmonary function. Giddins et al[30] reported no pulmonary dysfunction after intercostal harvest, even with concomitant phrenic nerve palsy. ICNs may also be used as the motor nerve for free-functioning muscle transfers.[31]

Phrenic Nerve to Musculocutaneous Nerve

The phrenic nerve is most commonly used as a donor to regain elbow flexion when other donor nerves are not available. Exposure of the phrenic nerve is rapid, but it must be lengthened by a nerve graft to reach the MCN or the median nerve. Endoscopic harvest has been described to lengthen the donor phrenic nerve to allow for direct transfer to the MCN or median nerve.[32] Gu and Ma[33] reported on results of this technique in 65 patients; 85% achieved a strength grade of M3 or higher, and 50% achieved a grade of M4 or M5. Pulmonary function tests showed decreased pulmonary capacities within 1 year of surgery, improving toward 2 years. Disadvantages of this transfer are that, in young, active patients, the donor defect may permanently affect aerobic performance. Also, considerable retraining is required. Because of this, the phrenic nerve transfer has diminished in popularity in the last several years.

Contralateral C7

The contralateral C7 nerve root or its posterior division may be prolonged with a nerve graft and

Figure 5

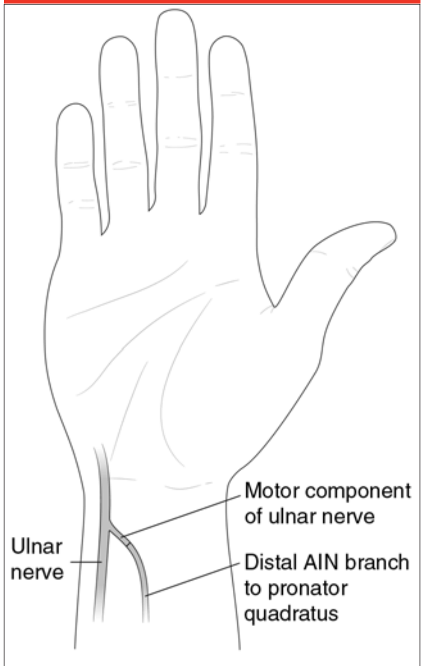


Illustration of transfer of the distal anterior interosseous nerve (AIN) to the ulnar motor nerve.

crossed over the chest to the injured side, to be used as a donor nerve when there is a paucity of other nerve donors. The best results have been reported in young patients with complete five-level (C5-T1) root avulsions. In this transfer, the ipsilateral full-length vascularized ulnar nerve graft is raised on a pedicle based on the superior ulnar collateral artery and is reversed to cross the chest to the contralateral brachial plexus. Usually several fascicles of C7 are isolated, identified as fascicles to the shoulder, then divided and coapted to the ulnar nerve. Usual targets include the median nerve and/or the MCN. Hierner and Berger[34] reported on 10 cases—6 to the MCN, 4 to the median nerve. All 10 patients had temporary donor sensory deficits but no donor motor deficits. All six of the MCN transfer patients had M3 or M4 elbow flexion return, but two required a "start" command—that is, contracting the contralateral latissimus dorsi muscle to flex the elbow. These authors reported no functional median nerve recovery in the four median nerve patients.

Liu et al[35] reported on two cases with severe donor C7 motor and sensory deficits. Full functional recovery was documented at 6 months. However, objective qualitative and quantitative differences in the motor and sensory deficits in the donor limbs were still present at 1.5 to 2 years. Songcharoen et al[36] reported on 21 patients with transfer of the contralateral C7 to the median nerve; 6 patients (29%) obtained grade M3 recovery of the wrist and finger flexors, and 4 (19%) achieved grade M2. Ten of the 21 patients (48%) achieved British Medical Research Council grade S3, and 7 (33%) had grade S2 recovery in the median nerve distribution. Average time to recovery was 34 months. Three of 6 patients aged <18 years had grade M3 finger flexion; 3% of the original 111 patient cohort had motor deficits in the donor extremity, with permanent wrist extension weakness in one patient. Sammer at al[37] recommended against the use of this procedure, given its poor outcomes and risk of permanent donor site morbidity. Enthusiasm for this transfer has waned in recent years.

Distal Transfers

Brachialis Motor Branch to the Anterior Interosseous Nerve, Coupled With Tenodesis of the Flexor Digitorum Profundus

For patients with the rare C8-T1 or lower trunk plexus injury, and potentially for patients with a high median nerve injury, the brachialis motor branch of the MCN can be transferred to the posterior third of the median nerve in the arm to restore median motor function.[3,38] The posterior third of the median nerve was identified by Zheng et al[38] to represent the AIN fascicles. This transfer must be coupled with side-to-side flexor digitorum profundus tenodesis to transmit forces from the median-innervated index and middle fingers to the ulnar-innervated ring and small fingers. Zheng et al[38] reported that five of six patients had recovery of digital flexion at 18-month follow-up. Grip strength averaged 66 lb.

Distal Anterior Interosseous Nerve to Ulnar Nerve Motor Branch

For patients with high ulnar nerve lesions, the AIN branch to the pronator quadratus can be transferred to the motor branch of the ulnar nerve[39,40] (Figure 5). In a series of eight patients, all had reinnervation of their intrinsic muscles at 18 months. Pinch increased from 2.2 lb preoperatively to 13.8 lb postoperatively. Grip strength increased from 8.8 lb to 61.2 lb.[39]

Supinator Branches to Posterior Interosseous Nerve

In the uncommon C7-T1 palsies of the brachial plexus, shoulder and elbow function is preserved, but digital function is absent. Supinator muscle function is preserved because innervation arises from the C6 nerve root. Sacrifice of the supinator motor branches does not eliminate supination because biceps muscle function is preserved in C7-T1 palsies. Bertelli et al[41] performed a cadaver feasibility study and showed that one or two branches of the PIN to the supinator can be transferred to the PIN branches that innervate the extensor pollicis longus and the extensor digitorum communis muscles (Figure 6). These authors later reported that four of four patients had full metacarpophalangeal joint extension after this transfer.[42] Dong et al[43] also reported good results with this transfer.

Figure 6

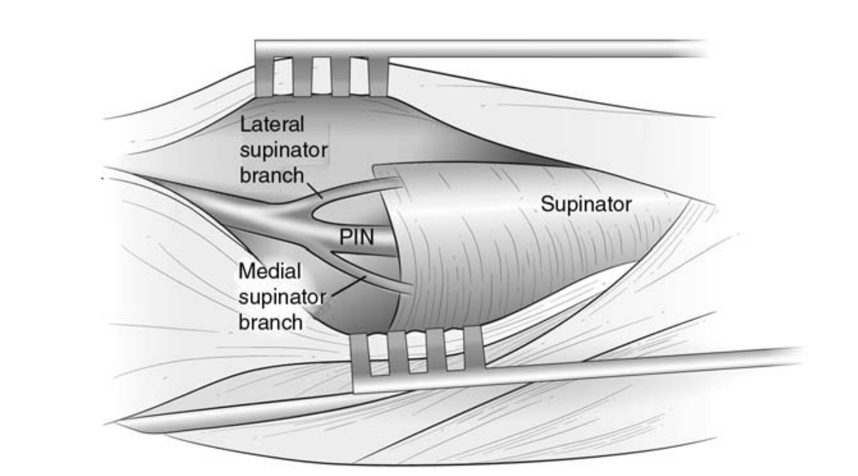


Illustration of transfer of supinator branches to the posterior interosseous nerve (PIN). (Adapted with permission from Bertelli JA, Ghizoni MF: Transfer of supinator motor branches to the posterior interosseous nerve in C7-T1 brachial plexus palsy. *J Neurosurg* 2010;113[1]:129-132.)

Figure 7

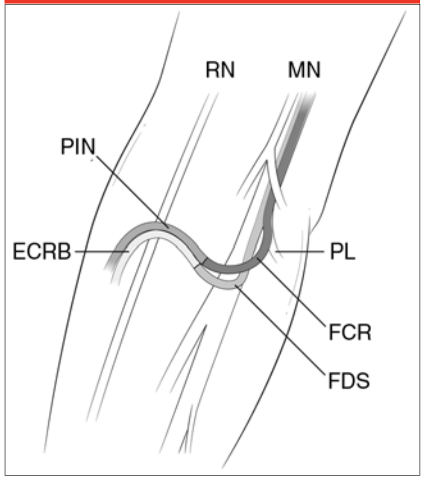


Illustration of transfer of median nerve branches to the posterior interosseous nerve (PIN) and extensor carpi radialis brevis (ECRB) branches. FCR = flexor carpi radialis, FDS = flexor digitorum superficialis, MN = median nerve, PL = palmaris longus, RN = radial nerve. (Adapted with permission from Ray WZ, Mackinnon SE: Clinical outcomes following median to radial nerve transfers. *J Hand Surg Am* 2011;36[2]:201-208.)

Median Nerve Branches to Radial Nerve Branches

This procedure is a dual transfer set in which median nerve branches to the flexor digitorum superficialis are transferred to the radial nerve branch to the extensor carpi radialis brevis, and median nerve branches to the flexor carpi radialis are transferred to the PIN.[44,45] Ray and Mackinnon[46] reported that 18 of 19 patients had good to excellent wrist extension; 9 patients also had pronator teres to extensor carpi radialis brevis tendon transfer. Twelve of 19 patients had good to excellent finger and thumb extension (grade M4 or M4+), 2 of 19 had fair recovery (M3), and 5 of 19 had poor recovery (M0 to M2) (Figure 7). A comparative functional study of nerve transfers versus tendon transfers for restoration of PIN function has not been performed.

Sensory Transfers

Sensory transfers are employed to regain essential zones of sensibility and to decrease neuropathic pain.[6] Bertelli and Ghizoni[47] reported on very distal superficial radial nerve transfers to the digital nerves of the ulnar aspect of the thumb and radial aspect of the index finger in eight patients with high median nerve lesions. Protective or better sensation was recovered in all patients. Ducic et al[48] presented two successful cases of radial sensory nerve transfers to the thumb and index finger. In C7-T1 injuries, the lateral antebrachial cutaneous nerve can be transferred to the ulnar nerve in the arm to regain distal sensory function.

Authors' Preferred Nerve Transfers and Reconstructive Strategies

Nerve transfers are part of our armamentarium for nerve reconstruction, along with nerve grafting and secondary procedures. When we evaluate a patient with brachial plexus injury, the physical examination, imaging studies, and electrodiagnostic studies help us define whether viable roots are present to use for reinnervation. We routinely employ intraoperative electrodiagnostic studies and histopathologic frozen-tissue examination to further evaluate potential donor root viability. Each reconstructive strategy is individualized.

Our main goals for reinnervation are (1) elbow flexion, (2) shoulder abduction and external rotation, (3) scapular stabilization, (4) elbow extension, (5) sensory reinnervation for control of neuropathic pain, and (6) restoration of distal (below-elbow) function. For elbow flexion, we prefer the double fascicular transfer of ulnar and median fascicles to biceps and brachialis. We perform double nerve transfers whenever possible for shoulder recovery—generally, transfer of the SAN to the SSN and of the triceps, medial pectoral, thoracodorsal, or ICN to the axillary nerve. Whenever possible, reinnervation of the teres minor branch of the axillary nerve is performed to improve external rotation. If there is an intact C5 nerve root, the target will often be the axillary nerve or the posterior cord, lengthened by sural nerve grafts.

ICNs are our extraplexal source of choice, especially in five-level plexus injuries. Common intercostal targets are the MCN, axillary nerve, and long thoracic nerve. Intercostal sensory nerves are often transferred to the lateral cord contribution of the median nerve for pain relief and protective sensibility. "Crossing the elbow" for hand and wrist reanimation with nerve reconstruction is relatively ineffective in adult total plexus palsies; if there is insufficient nerve regeneration 2 years after nerve reconstruction, we generally employ a combination of tendon transfers, joint fusions, and free-functioning muscle transfers to improve the position and function of the wrist and hand. The phrenic nerve and contralateral C7 are not common donor sources in our practice.

Summary

Nerve transfers are a vital part of the global strategy for the surgical treatment of brachial plexus and complex nerve injuries. All of the various types of transfers may be used for a variety of indications, including intraplexal, extraplexal, and distal, and for recovery of motor and sensory function. Knowledge of and the ability to perform these transfers is paramount to the success of these complex reconstructions.

References

Evidence-based Medicine: Levels of evidence are described in the table of contents. In this article, references 2, 4, 7, 8, 19, and 22 are level III studies. References 6, 9-18, 20, 21, and 23-48 are level IV studies. References 1, 3, and 5 are level V expert opinion.

References printed in **bold type** are those published in the past 5 years.

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