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Considerations in the Selection of Donor Nerves for Nerve Transfer for Reanimation of Elbow and Shoulder in Traumatic Brachial Plexus Injuries

Dafang ZHANG*, Vigneswaran VARADHARAJAN†, Praveen BHARDWAJ†, Hari VENKATRAMANI†, S. Raja SABAPATHY†

*Department of Orthopaedic Surgery, Brigham and Women's Hospital, Boston, Massachusetts
†Department of Plastic, Hand and Reconstructive Microsurgery, Ganga Medical Center and Hospitals Pvt. Ltd., Coimbatore, Tamil Nadu, India

The advent of nerve transfers has revolutionised the treatment of brachial plexus and peripheral nerve injuries of the upper extremity. Nerve transfers offer faster reinnervation of a denervated muscle by taking advantage of a donor nerve, branch or fascicle close to the recipient muscle. A number of considerations in respect of donor selection for nerve transfers underlie their success. In this review article, we discuss the principles of donor selection for nerve transfers, the different options available and our considerations in choosing a suitable transfer in reanimating the elbow and the shoulder. We feel this will help nerve surgeons navigate the controversies in the selection of donor nerves and make appropriate treatment decisions for their patients.

Level of Evidence: V (Therapeutic)

Keywords: *Brachial plexus injury, Donor, Fascicle, Nerve, Nerve transfer*

INTRODUCTION

Adult traumatic brachial plexus injuries are rare but devastating neurological injuries. They have been reported in approximately 1%–54% of polytrauma patients, depending on the geographic region.[1,2] These are typically high-energy injuries, predominantly affecting young males in the working years of life.[2] As a consequence, over and above the upper extremity dysfunction, they are costly both to the individual patient and to society.[3]

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Correspondence to: S. Raja Sabapathy
Ganga Medical Center and Hospitals Pvt. Ltd.
313, Mettupalayam Road, Coimbatore 641043, Tamil Nadu, India
Tel: +91 422-248-5000
Fax: +91 422-243-6444
E-mail: rajahand@gmail.com

Suture repair of the brachial plexus was initially described for obstetric brachial plexus injury in 1903 by Kennedy.[4] Primary nerve repair in the brachial plexus is now rarely performed because of the difficulty of coapting healthy nerve ends without tension. Microsurgical nerve grafting in the brachial plexus remains a mainstay of treatment and allows bridging of healthy nerve ends proximal and distal to the zone of injury.[5] A disadvantage of nerve grafting is that the nerve coaptation is performed at a distance from the recipient muscle, which can result in a long period to muscle reinnervation. Moreover, in some cases, e.g., root avulsions, healthy proximal nerve ends are unavailable and nerve grafting is not an option.

Although microsurgical nerve transfers had been performed previously,[6,7] the technique gained popularity after its description in 1994 by Oberlin et al.[8] These authors reported four cases of upper trunk brachial plexus injury in which a normal fascicle of the ulnar nerve was transferred to the motor branch of the musculocutaneous nerve to the biceps, with recovery of elbow flexion and no appreciable donor deficits. Since then, the arsenal of nerve transfers has expanded, and nerve transfers have shifted the paradigm of management of brachial plexus injuries and other peripheral nerve injuries.[9] A nerve transfer offers the advantages of microsurgery away from the zone of injury and places the nerve coaptation in close proximity to the recipient muscle, resulting in a shorter period to reinnervation. They also provide a more selective motor source of innervation to the target muscle. Appropriate and judicious selection of donor nerves, branches or fascicles is crucial to successful outcomes.

Nerve transfers can be partial or terminal. Partial nerve transfers, such as the Oberlin nerve transfer described earlier, harvest a fascicle or branch of a donor nerve without causing an appreciable distal deficit, whereas terminal nerve transfers, such as the spinal accessory to suprascapular nerve transfer, harvest the entire donor nerve, resulting in the paralysis of the muscle supplied by the donor nerve beyond the point of the transfer. Consequently, partial nerve transfers offer a distinct advantage over terminal nerve transfers. However, up until this point in time, they have been limited in number.

PRINCIPLES OF DONOR SELECTION

When selecting a donor nerve for nerve transfer, the donor must be expendable with minimal donor deficits following harvest. Donor nerve can be expendable by virtue of anatomical redundancies, as occurs when multiple nerve branches innervate one muscle, or several muscles performing the same function. When selecting an intraneural fascicle for a partial nerve transfer, the intraneural topography (Fig. 1) of the nerve needs to be considered in order to harvest an expendable fascicle.[10-12]

The chosen donor nerve must be of adequate size for a successful outcome. Histomorphometric studies of the axon counts of donor and recipient nerves help achieve appropriate donor selection.[12] Although it is desirable to minimise axon count discrepancy,[13] there is evidence to suggest that normal muscle activity can be achieved with approximately 30% of the normal motor neuron innervation.[14] In many cases of brachial plexus injuries, the donor nerve itself may be affected by the injury. Consequently, it is convention that the muscle of the donor nerve must have at least Medical Research Council (MRC) scale grading of 4 out of 5 strength of the muscle whose motor nerve is being used as a donor.[15] Higher pre-operative compound motor action potentials in the donor muscles on pre-operative nerve conduction studies have been associated with greater strength recovery following the Oberlin nerve transfer.[16] Strength of contractility can be confirmed intraoperatively by stimulation of the donor nerve.[17] A measurable intraoperative nerve action potential upon stimulation implies the presence of at least 3,000–4,000 nerve fibres.[18]

A requisite of nerve transfers is tension-free nerve coaptation close to the recipient muscle. Therefore, the ability to achieve this must be considered when selecting the donor nerve.[5] Consequently, the donor and recipient nerves should be divided at levels that allow for the coaptation to be performed without tension. Nerve transfer requiring a nerve graft negates one of the foremost advantages of this technique. This can be prevented by careful pre-operative planning. It is apt to quote the famous mantra of Susan Mackinnon on dividing nerves for nerve transfer, viz. '*Donor distal, recipient proximal*', as this reminder helps avoid the pitfall of falling short of length during these transfers. While always maintaining a tension-free coaptation, shortening of the recipient nerve to be closer to the target muscle is desirable.

The diameters of the donor and recipient nerves should be comparable. The diameter of the donor nerve branch, or fascicle, can be thought of as a crude proxy for power.

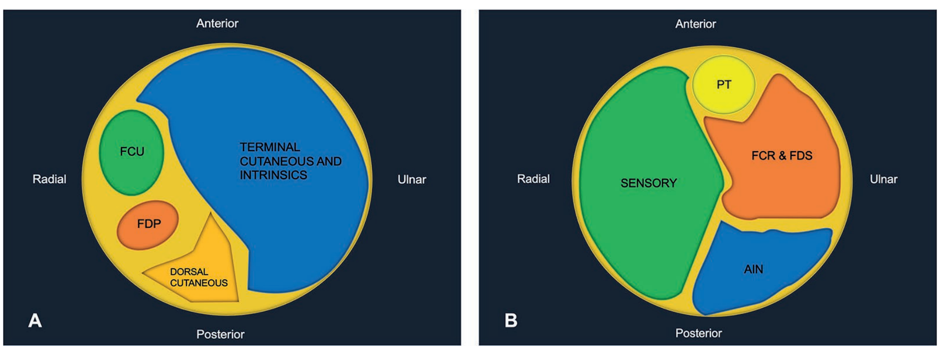

Fig. 1. An illustration showing the fascicular anatomy of the (A) ulnar and (B) median nerves at the mid-arm level. FCU: flexor carpi ulnaris, FDP: flexor digitorum profundus, PT: pronator teres, FCR: flexor carpi radialis, FDS: flexor digitorum superficialis, AIN: anterior interosseous nerve.]

In the original description of nerve transfers by Oberlin et al., the authors performed a morphometric study of the diameters of the ulnar nerve and the motor branch to the biceps. They observed that the cross-sectional area of the biceps motor branch was approximately 10% of that of the ulnar nerve at the same level. Thus, the motor branch of the biceps corresponded in size to only one or two fascicles of the ulnar nerve. They found that donor harvest of this number of fascicles caused no appreciable distal donor deficit. Of note, the original publication did not specify selection of the flexor carpi ulnaris (FCU) fascicle. The authors postulated that the ulnar nerve is a mixed nerve at the arm level and transfer of any fascicles from it must transfer some motor fibres.[8] In addition to being a proxy for power, closely matching nerve diameters between the donor and recipient is conducive to technically sound nerve coaptations and may minimise the risk of axonal escape.[13] Finally, when possible, a synergistic donor for nerve transfer is preferrable.[13] Postoperative rehabilitation protocols following nerve transfers frequently involve concurrent action of the donor and recipient, and synergism between them facilitates retraining. Socolovsky et al. theorised that the distance between cortical areas of donor and recipient neurons and the presence, or absence, of pre-existing cortical neural connection play a role in neuroplasticity and, consequently, outcomes after nerve transfers.[19] Some successful shoulder and elbow nerve transfers are described as follows.[9] Most take the advantage of a synergistic donor source.

OBERLIN NERVE TRANSFER FOR ELBOW FLEXION

In 1994, Oberlin et al. first described the eponymous ‘Oberlin nerve transfer’ in a series of four patients with upper trunk brachial plexus injuries. They were treated with a partial nerve transfer of a fascicle of the ulnar nerve to the biceps motor branch of the musculocutaneous nerve to achieve elbow flexion. All four patients in the original series regained elbow flexion, with three of the four patients regaining MRC Grade 4 strength.[8] Since this landmark article, others have reported successful outcomes of this transfer, with recovery of MRC Grade 4 strength in 85%–95% of the patients without meaningful donor deficits.[20,21]

Because of the importance of strong active elbow flexion in overall upper extremity function, concurrent reinnervation of the brachialis muscle has been advocated to maximise the recovery of elbow flexion.[22] In 2005, Mackinnon et al. described the double fascicular nerve transfer for elbow flexion, transferring a fascicle of the ulnar nerve to the biceps motor branch and a fascicle of the median nerve to the brachialis motor branch. The authors reported recovery of MRC Grade 4 strength in all six patients in their series without meaningful donor deficits.[23] A subsequent and larger series by the same group showed recovery of MRC Grade 4 strength in over 85% of 29 patients without meaningful donor deficits with this transfer for elbow flexion.[24] Dual nerve transfer for elbow flexion is unarguably one of the most reliable operations for brachial plexus injuries with restoration of almost normal elbow flexion power in most of the patients with upper trunk brachial plexus injuries (Fig. 2). Some surgeons, including us, have also performed the double fascicular nerve transfers for elbow flexion in reverse order, transferring the median nerve fascicle to the biceps motor branch and the ulnar nerve fascicle to the brachialis motor branch, with comparable results (Fig. 3). The advantage of this ‘reverse double fascicular nerve transfer’ includes the ease with which the motor fascicle of the median nerve reaches the biceps motor branch, which is often shorter in length and less amenable to mobilisation requiring intraneural dissection to obtain the longer length required to reach the conventional ulnar nerve fascicle. The brachial motor branch is always long and reaches the ulnar nerve fascicle easily. In addition, the fascicle of the median nerve is safer from donor deficits if harvested more proximally.[25] However, Mackinnon speculated that, in respect of ease of motor re-education, the median nerve should not be the donor to the biceps, because the median nerve innervates pronation muscles, and the biceps is a supinator.[26]

The choice between the single and double fascicular nerve transfer for elbow flexion remains controversial. Sneiders et al. performed a systematic review and meta-analysis of 688 patients with upper trunk brachial plexus injuries from 35 studies. In the quantitative analysis, the authors found no difference between the single and double fascicular nerve transfer for restoration of MRC Grade 3 elbow flexion strength. However, the double fascicular nerve transfer group achieved MRC Grade 4 elbow flexion strength in a significantly higher proportion of patients, particularly if surgery was delayed less than 6 months from injury.[27] Donnelly et al. performed a systematic review and meta-analysis of 176 adult patients with upper trunk, or extended upper trunk, brachial plexus injuries from 18 studies. They concluded that the double transfer was associated with a significantly higher likelihood of MRC Grade 4 elbow flexion strength recovery than the single nerve transfer.[28] Since

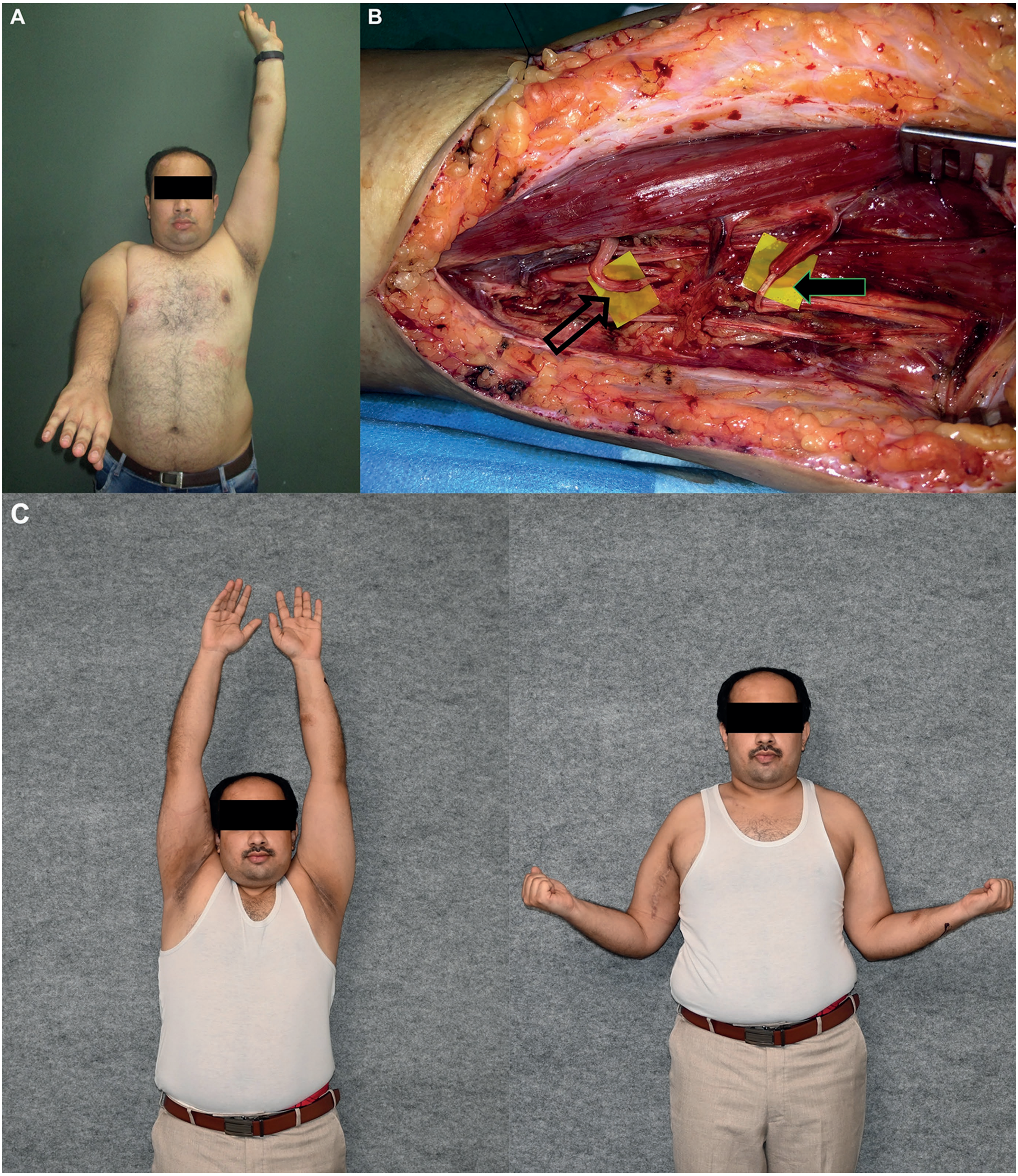

Fig. 2. Conventional dual nerve transfer for elbow flexion. A. Pre-operative photo of a 24-year-old male with paralysis of shoulder abduction and external rotation and elbow flexion of 5 months duration. B. Intraoperative photograph showing the scheme of nerve transfers – ulnar nerve fascicle to biceps motor branch (solid arrow) and median nerve fascicle to brachialis motor branch (open arrow). C. Outcomes of the nerve transfer after 1 year from surgery. (The patient also underwent spinal accessory nerve to suprascapular nerve and medial head of triceps motor branch to axillary nerve transfer by posterior approach for shoulder abduction concomitantly).

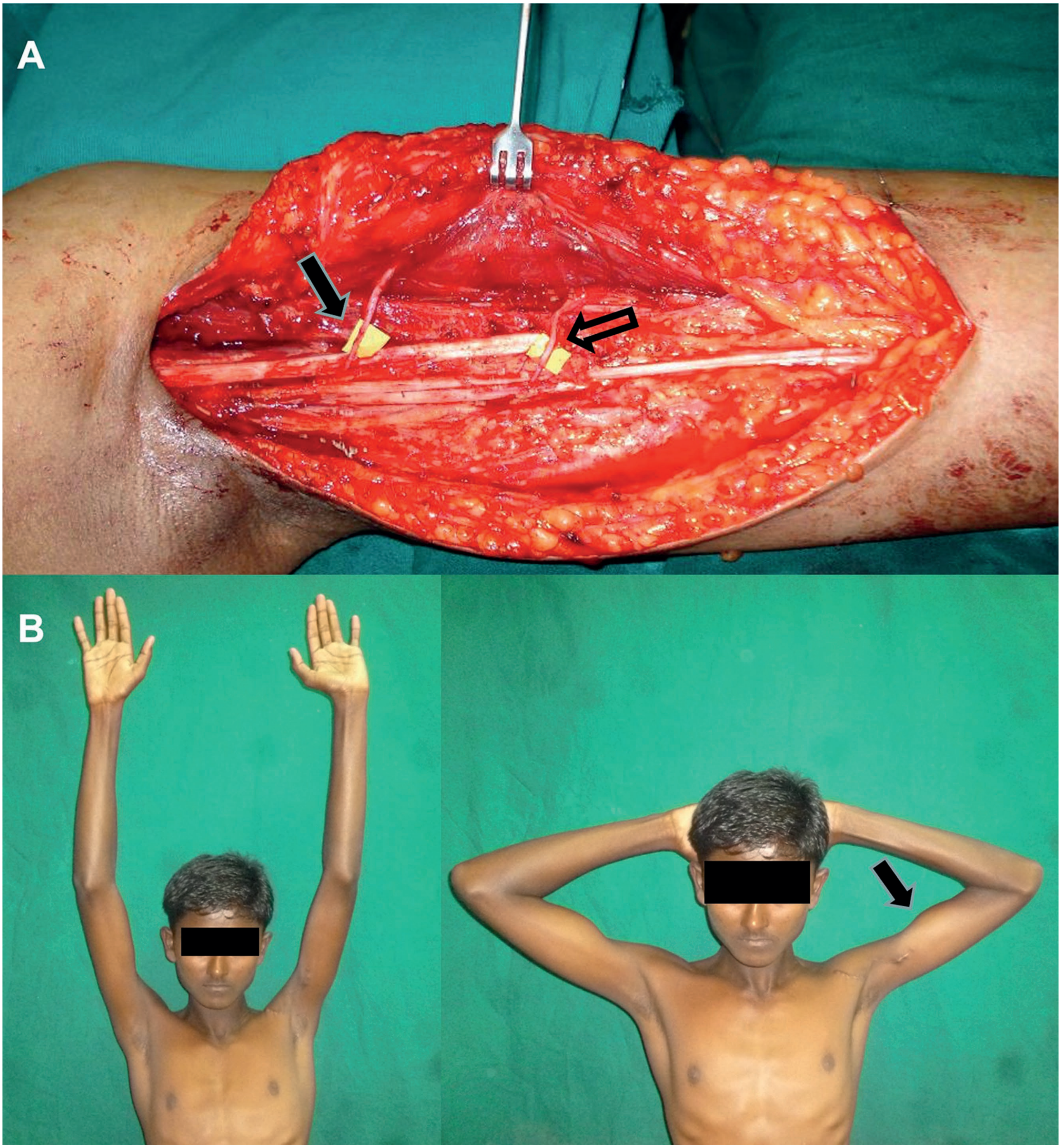

Fig. 3. In this 16-year-old male, the median nerve fascicle was transferred to the biceps motor branch (solid arrow) because the biceps motor branch was short in length and would have necessitated extensive intraneural dissection and mobilisation to reach the ulnar nerve. A. Median nerve fascicle was transferred to biceps motor branch (solid arrow) and ulnar nerve fascicle was transferred to brachialis motor branch (open arrow); along with spinal accessory to suprascapular and triceps long head to axillary nerve transfer by anterior approach for shoulder abduction. B. Photograph showing recovery of shoulder abduction and elbow flexion.

strong active elbow flexion is crucial to upper extremity function, double fascicular nerve transfer should be preferred for its strength advantage.

Use of the Oberlin nerve transfer in a 'weak hand' is a topic of controversy, as the donor fascicles may be weak. The muscle of the donor nerve should have at least MRC

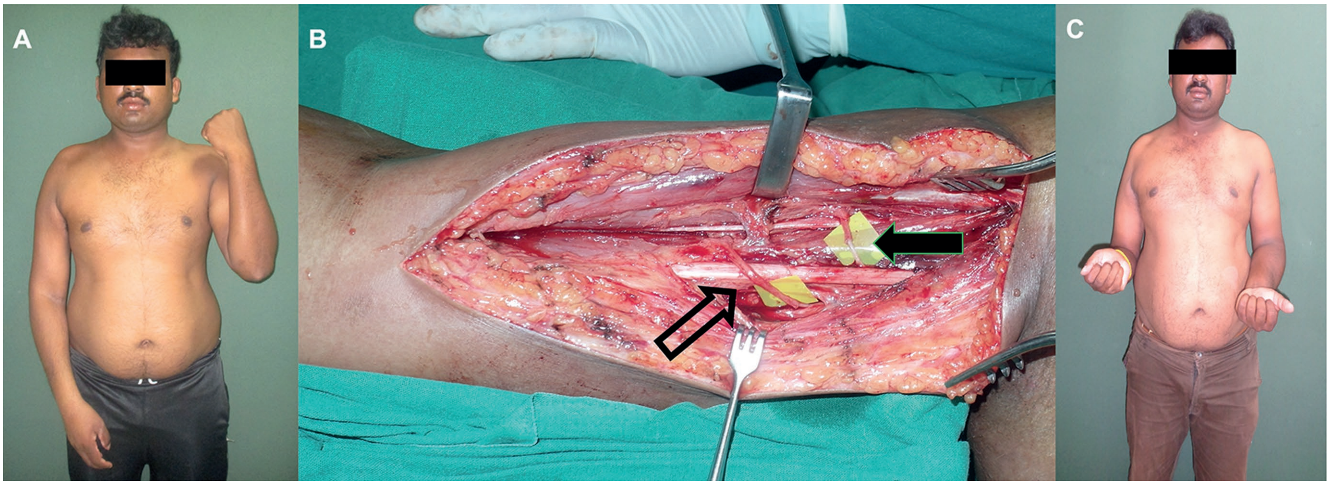

Fig. 4. A. A 24-year-old male with upper extended brachial plexus paralysis, had a weak hand function with grip strength of 2 kg. B. He underwent median nerve fascicle transfer to biceps motor branch (solid arrow) and ulnar nerve fascicle transfer to brachialis motor branch (open arrow), because his intraoperative stimulation revealed much better activity in the median nerve fascicle as compared to the ulnar nerve fascicle. C. At 6 months post surgery, he recovered anti-gravity elbow flexion and photograph at 18 months follow-up shows good elbow flexion recovery. The patient later underwent tendon transfers to improve the wrist and digital extension at 7 months after the initial operation.

Grade 4 strength to serve as an appropriate donor.[12] Pre-operative grip strength of at least 10 kg with the wrist stabilised by the examiner has been recommended by Oberlin and others,[29,30] but this criterion may be too strict. Many patients with extended brachial plexus palsies have weaker grip strength than this but, nevertheless, achieve restoration of elbow flexion successfully after nerve transfers (Fig. 4). Pre-operative weakness in the FCU has been associated with the failure of the Oberlin nerve transfer.[31] In patients with weak donor muscle groups, pre-operative electrodiagnostic studies may be helpful in donor nerve selection. Future studies are necessary to compare the efficacies of alternative donor and recipient combinations for the double fascicular nerve transfer for elbow flexion.

Intraoperative considerations for fascicle selection for the double fascicular nerve transfer for elbow flexion include intraneural topography, intraoperative stimulation and fascicle diameter. Topographically, the ideal motor fascicles of the median nerve for harvest are on the medial side and the ideal motor fascicles of the ulnar nerve, predominantly responsible for innervation of the FCU, are on the lateral side[8,14,16] (Fig. 1). Intraoperative stimulation for fascicle selection is controversial, with most authors finding it helpful, but some reporting that it offers no advantage.[32] In our experience, at the level of the Oberlin nerve transfer, stimulation of any motor fascicle of the ulnar nerve produces contraction of most muscles, and we rely on intraoperative nerve stimulation to select a motor fascicle of the ulnar nerve that produces vigorous FCU activity. In practice, and topographically, this is generally an anterolateral or anteromedial fascicle, and we select the fascicle with the best diameter match (Figs. 2–4). For the median nerve, we recommend selecting a fascicle from the medial half of the nerve as the lateral half is predominantly sensory.[23] One must avoid the posterior fascicle in order to preclude an anterior interosseous nerve (AIN) deficit. We rely on intraoperative nerve stimulation to select a motor fascicle of the median nerve which does not produce vigorous AIN activity. Finally, we prefer to select donor fascicles of comparable diameters to our recipient motor branches in order to facilitate technically sound nerve coaptation. We find intraoperative stimulation to be particularly useful in deciding the nerve transfer strategy in patients with an extended upper trunk brachial plexus palsy and a 'weak hand'. The nerve (ulnar or median) showing better response to the minimum level of stimulus is used for fascicle transfer to the biceps motor branch and the other to the brachialis (Fig. 4). Additionally, within each nerve, the fascicle showing the best response to stimulation is chosen for the transfer. If no intraoperative stimulation is noted in one of the donor nerves, it may be preferable to perform a single fascicular nerve transfer to the biceps motor branch. If both the ulnar and median nerves show a feeble response to intraoperative electrical stimulation, we resort to other options of nerve donor, such as the spinal accessory nerve to the musculocutaneous nerve with a nerve graft or intercostal nerves to the musculocutaneous nerve, as each individual case dictates.

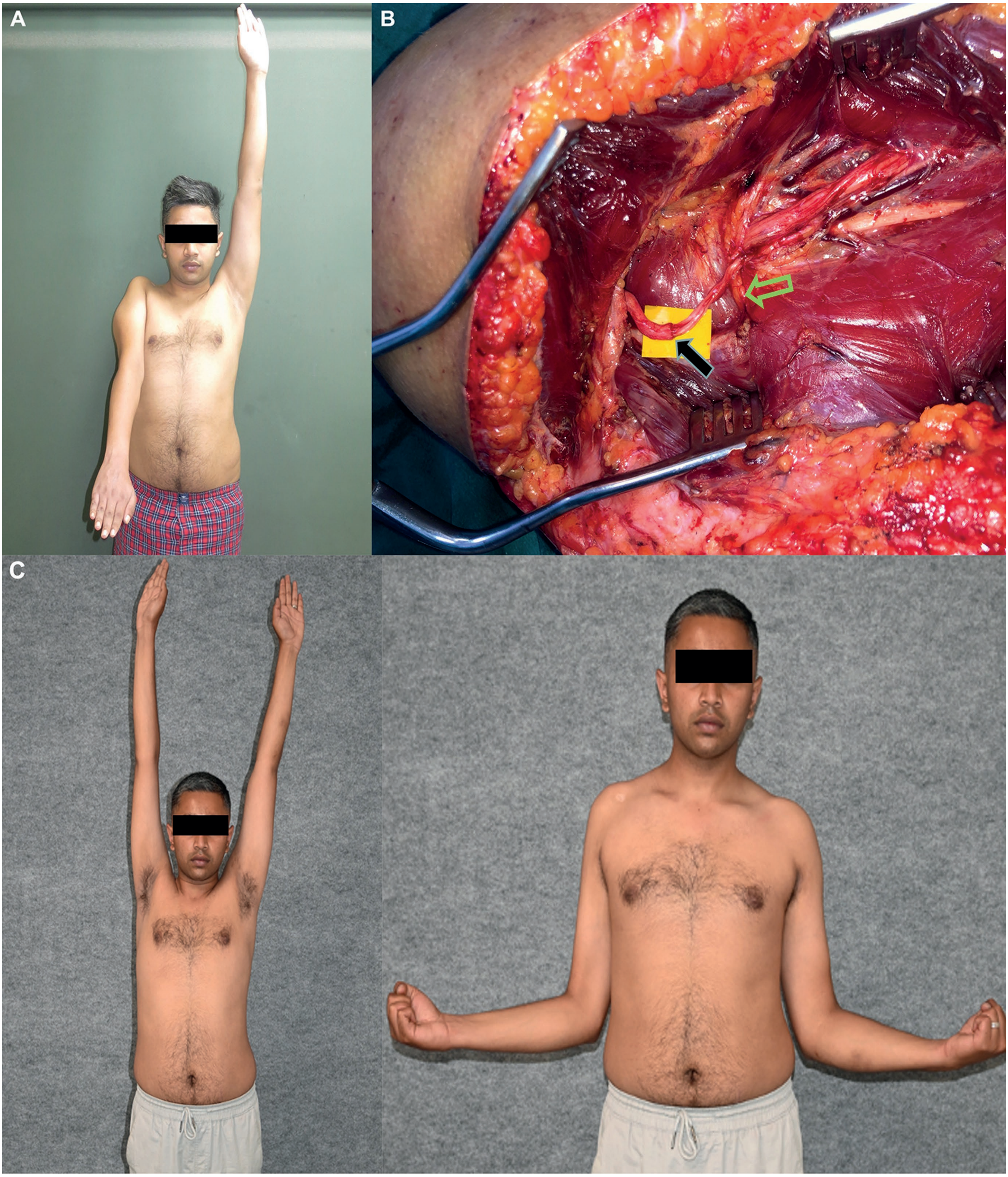

Fig. 5. A. A 19-year-old male with paralysis of shoulder abduction and external rotation. B. He underwent transfer of the triceps medial head branch to the anterior division of the axillary nerve (solid arrow) at 4 months post injury; also seen is the triceps long head branch (open arrow). C. Full shoulder abduction and external rotation recovery seen at 10 months post-surgery.

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Fig. 6. A. A 28-year-old male with C5-6 palsy. B. He underwent nerve transfer of long head of triceps to anterior division of the axillary nerve through anterior approach (open arrow) which is just a more medial extension of the exposure required for Oberlin type dual nerve transfer for elbow flexion (solid arrows); along with spinal accessory to suprascapular nerve transfer. C. Picture showing shoulder and elbow function at 14 months post-surgery.

NERVE TRANSFER TO THE AXILLARY NERVE FOR SHOULDER STABILISATION, ABDUCTION AND EXTERNAL ROTATION

Paralysis of the deltoid and rotator cuff muscles is a common sequel of brachial plexus injuries.[15] In 2003, Leechavengvongs et al. first described the eponymous 'Somsak nerve transfer' in a series of seven patients with upper trunk brachial plexus injuries. These patients were treated by nerve transfer of a branch of the radial nerve to the long head of the triceps to the anterior branch of the axillary nerve through a posterior approach. All seven patients in the original series regained deltoid reanimation, glenohumeral stabilisation and active shoulder abduction with MRC Grade 4 strength.[33,34] The authors preferred the posterior approach for its direct exposure of the axillary nerve, well away from the neurovascular structures encountered in the anterior approach, and its proximity to the target muscle. The authors also preferred the long head of the triceps nerve branch as the donor because it is consistently the most proximal branch of the radial nerve and has been shown to be the least electromyographically active of the three triceps heads in elbow extension.[35,36]

In 2006, Colbert and Mackinnon described the technique of double nerve transfer for shoulder reanimation in upper trunk brachial plexus injuries through a posterior approach. In conjunction with a spinal accessory nerve to suprascapular nerve transfer from a posterior approach, these authors advocated a nerve transfer of a branch of the radial nerve to the medial head of the triceps to the axillary nerve to re-animate the deltoid muscle. The authors preferred the medial head of the triceps nerve branch as the donor because of ease of exposure, length of the nerve branch, and concerns about lack of synergism between the deltoid muscle and the long head of the triceps, which is a humeral adductor.[37] Moreover, an argument can be made for preserving the nerve to the long head of the triceps because it is a glenohumeral stabiliser by virtue of its scapular origin.

Controversies remain with respect to the Somsak nerve transfer and its modifications. Although both the nerve branches to the long and medial heads of the triceps are reasonable donor choices, there remains no comparative evidence to guide donor selection. The ideal recipient is also debatable. Leechavengvongs et al. have advocated nerve transfer to the anterior branch of the axillary nerve, which innervates not only the anterior and middle thirds of the deltoid muscle, but also the posterior third in over 90% of case.[38] Moreover, direct transfer to the anterior branch of the axillary nerve may avoid misdirection of the regenerating axons to the upper lateral cutaneous nerve of tharm and the teres minor muscle, which is a humeral adductor.[34] Bertelli et al. have demonstrated MRC Grade 4 recovery of the deltoid muscle by transfer of the long head of the triceps motor branch to the entire axillary nerve from an anterior approach.[39] Colbert and Mackinnon have also advocated nerve transfer to the entire axillary nerve in order to re-animate teres minor, to achieve greater shoulder stabilisation and external rotation.[37] Future studies of the outcomes of the Somsak nerve transfer and its modifications are necessary, in particular comparison of the anterior approach[39,40] and the original posterior approach.[35,36] While the posterior approach exposes the quadrangular space and triangular interval easily and ensures the nerve coaptation is close to the target end muscle, the anterior approach offers logistical advantages and may be performed through an extension of the Oberlin nerve transfer incision.[40]

We have used both approaches, have observed that both are adequate for nerve transfer of a triceps motor branch to the axillary nerve and provide comparable outcomes (Figs. 5 and 6). However, the posterior approach allows complete exposure of all the branches of the radial nerve to the various heads of the triceps (Fig. 5B) and affords the opportunity to choose the ‘best’ donor branch, especially in cases where the triceps is judged preoperatively to be weak. The donor branch should have a good response to intraoperative electrical stimulation, easily reach the recipient axillary nerve and have an adequate diameter size match. Moreover, the donor selection should leave a good functioning motor branch to the triceps, in order to maintain power of elbow extension. The posterior approach also allows the surgeon to inspect the most terminal part of the axillary nerve to ensure that the repair is beyond the site of injury. It also permits coaptation closer to the target muscle (Fig. 5). Differentiation of the anterior and posterior divisions of the axillary nerve is easier through the posterior approach, allowing one to decide the nature of the coaptation regarding the size of the donor and the recipient nerves. However, in patients with isolated C5–C6 root avulsions and a normal functioning triceps, the anterior approach through an axillary extension of the incision for the Oberlin nerve transfer is easy, safe and decreases operative time (Fig. 6C). In addition, it avoids an additional scar on the more visible posterior aspect of the arm. We have observed comparable outcomes by the two approaches in such cases (Figs. 5 and 6). Regarding nerve transfer to the anterior branch alone or to the whole axillary nerve, the motor branch to each head of the triceps is often much smaller than the whole axillary nerve, so we tend to perform the nerve transfer to the anterior division of the axillary nerve more frequently. This branch can be identified easily as the nerve branch closer to the humerus. However, if the donor–recipient size discrepancy is small, we transfer to the whole axillary nerve. We have achieved satisfactory outcomes with our protocol of performing the nerve transfer from the anterior approach in C5-C6 brachial plexus injuries and from the posterior approach in cases of C5-C7 injuries when triceps power is judged pre-operatively to be weak. When using the anterior approach, we use the long head of the triceps motor branch as our donor, and, when using the posterior approach, we use the triceps motor branch to either the long or medial head, based on the factors detailed earlier.

SUMMARY AND FUTURE DIRECTIONS

Nerve transfers have shifted the paradigm of care of brachial plexus and peripheral nerve injuries, allowing for nerve coaptations of healthy donor nerves to recipient nerve ends close to their motor point and, so, achieving early functional recovery. Thoughtful selection of donor nerves, branches or fascicles is critical to the successful outcome of nerve transfer. The chosen donor should be expendable, powerful and synergistic and allow for a nerve coaptation that is of comparable size and under no tension. The pre-operative clinical and electrodiagnostic strength of the donor, intraoperative nerve stimulation, intraneural topography, nerve length and nerve diameter are all relevant considerations. Well-described and successful donor choices exist for nerve transfers for restoring elbow and shoulder function. However, high-quality comparative studies of donor selection are now needed to better inform surgical decision-making for upper extremity nerve transfers.

DECLARATIONS

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