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ARTICLE

Shoulder abduction reconstruction for C5–7 avulsion brachial plexus injury by dual nerve transfers: spinal accessory to suprascapular nerve and partial median or ulnar to axillary nerve

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ABSTRACT

Results of shoulder abduction reconstruction in partial upper-type brachial plexus avulsion injuries are better when a triceps nerve is transferred to the axillary nerve in addition to the spinal accessory to suprascapular nerve transfer. However, in C5–7 avulsion injuries, the triceps nerve may be unavailable as a donor nerve. We report the results of an alternative neurotization to the axillary nerve using either a partial median or ulnar nerve. Patients with C5, 6 ± 7 avulsion injuries and weak triceps who underwent dual nerve transfers for shoulder abduction reconstruction were recruited for the study. The second neurotization to the axillary nerve was from either a partial median or ulnar nerve that had an expandable muscle innervation of ≥ M4 motor power. Patients were assessed for recovery of shoulder abduction and external rotation. Nine patients (median age = 23 years) underwent these dual neurotizations from March 2005 to April 2013. The median time to surgery was 4.5 months. Recovery of shoulder abduction averaged 114.4° (range 90°–180°) and external rotation averaged 136.3° (range 135°–140°). Final shoulder abduction power was > M3 in all 9 patients and ≥ M4 in 6 patients. One patient with partial median nerve transfer had transient hypoaesthesia in his thumb and index finger and another had a residual M4 power in his thumb and index finger flexors. In C5-7 avulsion injuries, dual nerve transfers of the spinal accessory to suprascapular nerve and partial median or ulnar nerve to axillary nerve are good options for shoulder abduction reconstruction with minimal morbidity. Level of evidence is level IV.

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Introduction

In C5–6 ± C7 brachial plexus avulsion injuries, shoulder abduction reconstruction by a single neurotization to the suprascapular nerve with the spinal accessory nerve alone had modest results (Narakas'drawings [1], Malessy et al [2], Chuang et al. [3]. Only a minority of patients achieved a mean shoulder glenohumeral joint abduction of 45° and external rotation up to 70° [2]. Shoulder abduction at the glenohumeral joint is more efficiently initiated by the supraspinatus muscle before 45°. Any further abduction in the coronal plane to 90° requires external rotation of the humerus for its head to clear the mechanical block of the acromial process. Beyond 90°, it is essentially the deltoid muscle (nerve supply from the axillary nerve) that works under the best mechanical conditions for abduction and external rotation [4,5]. The external rotator muscles of the shoulder joint include the infraspinatus (nerve supply from the suprascapular nerve) and the teres minor (nerve supply from the axillary nerve). Thus, where the infraspinatus may fail, the other shoulder external rotator muscle (the teres minor) can be reinnervated to initiate humeral external rotation for improvement of shoulder abduction range. Significant improvement in shoulder abduction and external rotation outcomes have been reported with the method of dual neurotization to the suprascapular nerve and the axillary nerve with nerve transfers from the spinal accessory nerve and nerve to triceps respectively [6,7].

However, in C5-6 ± C7 brachial plexus avulsion injuries where the triceps is weak (Medical Research Council grading [8] of less than M4), the nerve to the triceps is not an ideal second donor nerve. In these circumstances, other intra-plexal donors for transfer to the axillary nerve have been reported. These include a partial median nerve (Gu et al.[9]), or partial ulnar nerve (Haninec and Kaiser [10]. In this study, we report our results and further evaluate the effectiveness of dual nerve transfers for shoulder abduction reconstruction in upper type brachial plexus avulsion injuries; using the partial distal nerve (either the median or ulnar nerve) as the second donor nerve for transfer to the axillary nerve.

Materials and methods

Institutional ethical board approval was obtained prior to commencement of this study. We retrospectively reviewed the surgical outcomes of all adult patients with traumatic partial upper type brachial plexus avulsion injuries in whom the triceps muscles were paralysed or weak, with pre-operative MRC grading of less than M4. Patients were included in this study if they had shoulder abduction reconstruction using the spinal accessory nerve transfer to the suprascapular nerve; as well as a distal nerve transfer using either a partial median or ulnar nerve to the axillary nerve. The selection criterion for the partial distal nerve transfer was that the expandable donor's innervated muscle had M4 or greater motor power pre-operatively. This was crucial in deciding whether the

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Table 1. Summary of cases.

Case	Age (years)	BPI type	Time from injury to surgery (mths)	Neurotizations	Post-operative outcomes Abduction ROM/MRC	External rotation ROM	Elbow flexion MRC
1	33	C5-C6 avulsion	4.5	SAN → SSN MN → AxN UN → Bi	180°/4+	135°	4+
2	20	C5-C6 avulsion	4.5	SAN → SSN MN → AxN UN → Bi	180°/4+	140°	4+
3	32	C5-C6 avulsion	6	SAN → SSN MN → AxN UN → Bi	90°/4−	–	4+
4	23	C5-C7 avulsion	2.5	SAN → SSN UN → AxN MN → Bi	120°/4+	135°	4+
5	34	C5-C7 avulsion	6.5	SAN → SSN UN → AxN MN → Bi	90°/4−	–	4
6	19	C5-C7 avulsion	2	SAN → SSN UN → AxN MN → Bi	90°/4+	135°	4+
7	50	C5-C7 avulsion	5	SAN → SSN MN → AxN UN → Bi	100°/4	–	4+
8	18	C5-C7 avulsion	2.5	SAN → SSN MN → AxN UN → Bi ICN 4,5 → Tri	90°/4−	– Triceps MRC: 4	4
9	20	C5-C7 avulsion	7.5	SAN → SSN UN → AxN MN → Bi ICN 3,4,5 → Tri	90°/4	– Triceps MRC: 4−	3

ROM: Range of motion; MRC: Medical Research Council Grading Scale; SAN: Spinal accessory nerve; SSN: Suprascapular nerve, MN: Partial median nerve; UN: Partial ulnar nerve; AxN: Axillary nerve; Bi: biceps motor branch of musculocutaneous nerve; ICN: intercostal nerve; Tri: nerve to long head of triceps.

median or ulnar nerve was used as the donor. Cases were identified from our brachial plexus surgery database. Exclusion criteria were patients with obstetric brachial plexus palsies, upper-type post-ganglionic injuries, complete brachial plexus palsies, and those who underwent alternative neurotizations for shoulder abduction reconstruction.

The study period was from March 2005 to April 2013. A total of 9 male patients were included. The diagnosis of an upper type brachial plexus root avulsion injury was made pre-operatively from serial clinical examinations, electrodiagnostic studies and magnetic resonance imaging (MRI) scans of the brachial plexus. The diagnosis of root avulsion was also confirmed at intra-operative exploration. Three patients had C5–6 roots avulsion injuries and 6 patients had C5–7 roots avulsion injuries. Pre-operatively, all patients had M0 motor power in shoulder abduction, external rotation and elbow flexion in the affected upper limb. Triceps motor power was less than M4 in all patients and M0 in 2 of the patients with C5–7 nerve root avulsions. Pre-operative sensory and muscle motor power assessments were done to determine the expandability and hence suitability of the donor nerve fascicles as follows: for the ulnar nerve, the ulnar-innervated flexor carpi ulnaris (FCU) should have a motor power $\geq$ M4. For the median nerve, the expandable muscle could be the flexor carpi radialis (FCR), pronator teres (PT) or flexor digitorum superficialis (FDS). Though the FCR and PT have their main nerve root supply from C7, they also receive contributions from C6 and C8 (Zancolli's clinical observations in tetraplegia [11]. Thus, in our case series of C5–6 $\pm$ C7 brachial plexus avulsion injuries, partial median nerve transfers to the axillary nerve were still possible as long as the donor fascicle's muscle had a motor power $\geq$ M4. Patients with FCR, PT, or FDS motor power $<$ M4 were precluded from partial median nerve transfers. Intra-operatively, the nerve fascicle with the strongest muscle contraction observed on nerve stimulation would be selected for transfer to the biceps motor branch of musculocutaneous nerve. While not rooted in prior clinical evidence, this decision theoretically prioritizes a "better" donor nerve to be used for elbow flexion reconstruction. If the expandable donor fascicles' muscles were of equal power, the ulnar nerve would be chosen for transfer to the biceps motor branch. This choice was influenced by the excellent outcomes of the Oberlin procedure [12,13].

In our series, the median age was 23 years (range = 18–50 years). The median time interval from injury to surgery was 4.5 months (range = 2–7.5 months). All 9 patients also had simultaneous neurotization of the biceps motor branch for reconstruction of elbow flexion. The 2 patients with triceps power M0 had additional two and three intercostal nerves transferred respectively to the nerve to triceps long head for reconstruction of elbow extension (Table 1).

Post-operative evaluation was done by the senior author at three monthly intervals and the final outcome results were recorded at 18 months. Shoulder abduction range of motion and power (MRC grading scale), and external rotation were assessed. Shoulder abduction was measured as the combined glenohumeral joint and scapulothoracic motion. Shoulder external rotation was measured as the angle between the position of the 90° (actively or passively) flexed elbow resting against the belly and the position of the flexed elbow after external rotation, with the upper arm in adduction, until the scapula starts rotating [2]. Additional outcomes studied were the elbow flexion power and the presence of any post-operative complications.

Surgical technique

All surgeries were performed in the supine position. A supraclavicular approach was used for brachial plexus roots exploration and nerve transfer of the spinal accessory to the suprascapular nerve. The spinal accessory nerve was identified on the deep surface of the trapezius muscle and confirmed with a nerve stimulator. The dissection was continued distally to its termination into two or three branches. A vessel loop was placed around it for later identification when it would be transected at this junction for coaptation to the suprascapular nerve stump. The suprascapular nerve was identified as it branches off from the upper trunk of the brachial plexus. It was dissected and traced distally until healthy nerve tissue was encountered. This was verified by its turgor and the visualization of nerve fascicles within the epineurium upon transection of the nerve. When scarred or fibrotic nerve tissue was encountered, the nerve would be progressively cut back distally until a healthy nerve stump was seen. Coaptation of the spinal accessory nerve to the healthy suprascapular nerve stump was performed under magnification with 10–0 nylon sutures, and reinforced with a biological adhesive (TISSEEL Fibrin Sealant, Baxter International Inc.).

The distal nerve transfer (with either a partial median or ulnar nerve) to the axillary nerve was performed via an anterior axillary approach. The axillary nerve was identified anteriorly at the inferior border of the subscapularis muscle just before it entered the quadrangular space. (Figure 1) Zhao et al. [14] reported that although the nerve has not yet divided into branches at this level, two fascicular groups can be identified: one lateral and one medial. They are enclosed within an outer-epineurium. The lateral fascicular group continues as the anterior branch of the axillary nerve while the medial fascicular group continues as the posterior branch. A vessel loop was similarly placed around the nerve for later identification, after the prepared donor nerve is ready for coaptation to the axillary nerve. For the neurorrhaphy, the recipient fascicular groups of the axillary nerve were prepared by performing a transverse partial outer-epineurotomy on the anterior wall of the nerve and neurotomy of the fascicular groups. The posterior wall of the outer-epineurium was kept intact, such that there would be minimal retraction of the fascicular groups at their cut ends (Figure 2) – which facilitated the nerve coaptation.

The donor median or ulnar nerve and biceps branch of musculocutaneous nerve were identified via the same anterior axillary incision extended distally. (Figure 3) A partial longitudinal epineurotomy was made on the donor nerve for intra-operative nerve stimulation to identify suitable donor fascicles. For the median nerve, suitable donors include the fascicles to wrist or finger flexors (FCR or FDS), or forearm pronator (PT). The suitable donor fascicles for the ulnar nerve would be the fascicles to the FCU. The donor fascicles were identified when strong muscle contractions were observed with nerve stimulation and isolated to the expandable muscle. Fascicles that did not elicit a response to nerve stimulation were assumed to be sensory fascicles and were spared. Fascicles that elicited a motor response to any of the flexor digitorum profundus or flexor pollicis longus on stimulation were spared as well. The chosen fascicles were then isolated with a vessel loop. The nerve fascicle that elicited the stronger muscle contraction was chosen for neurotization to the nerve to the biceps muscle. If the ulnar nerve and median nerve fascicles elicited similarly strong muscle contractions, the ulnar nerve was chosen for neurotization to the nerve to the biceps muscle. The other donor nerve fascicle was then utilized for neurotization to the axillary nerve.

The selected donor nerve fascicles were then mobilized from the level of the recipient nerve stump distally to a point where there would be sufficient length for a turn around to reach the recipient nerve. The donor fascicles were then transected distally and brought proximally to be coapted to the recipient nerve stump. The nerve coaptation for the axillary nerve was done to the lateral and medial group fascicles. End-to-end nerve coaptation was performed under magnification using 10-0 Nylon sutures (Figure 4) and the repair site reinforced with the same biological

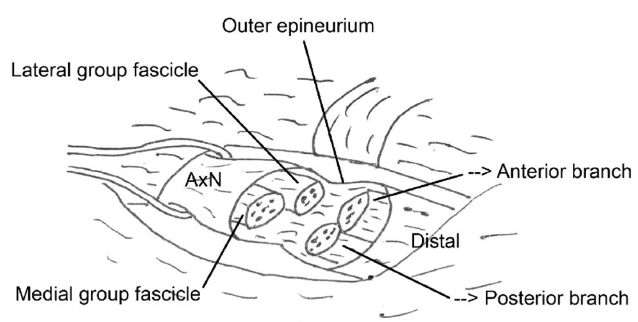

Figure 2. Diagrammatic representation of the left axillary nerve, isolated with a vessel loop, after partial outer epineurotomy and neurotomy at the quadrangular space. AxN: axillary nerve.

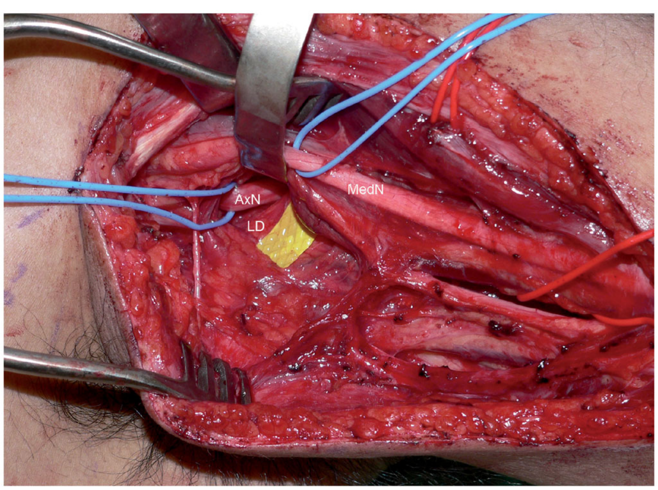

Figure 1. Exposure for the left axillary nerve (at quadrangular space) and median nerve. AxN: axillary nerve; LD: latissimus dorsi; MedN: median nerve.

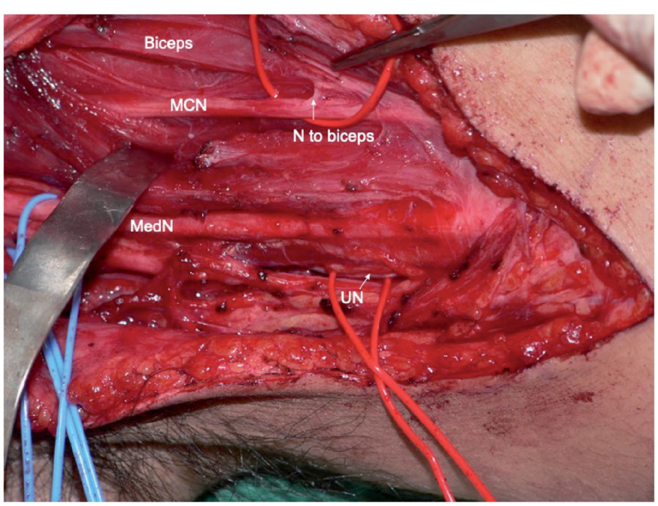

Figure 3. Exposure of the median nerve, ulnar nerve and biceps branch of the musculocutaneous nerve of the upper limb. MCN: musculocutaneous nerve; MedN: median nerve; UN: ulnar nerve.

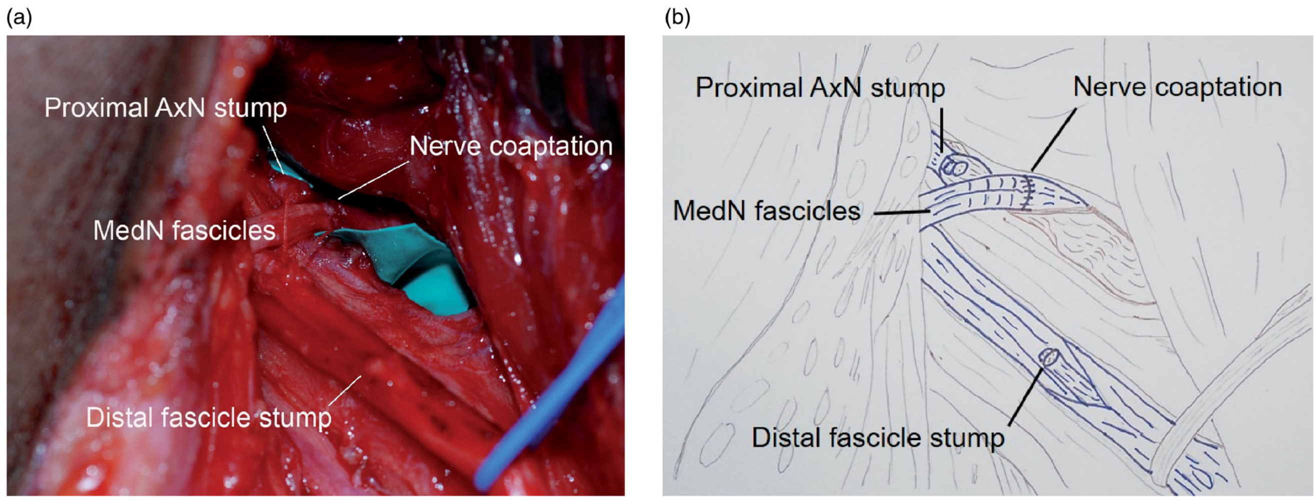

Figure 4. Coaptation of left median nerve fascicles to the axillary nerve fascicles. (a) Operative view. (b) Diagrammatic representation. AxN: axillary nerve; MedN: median nerve.

Table 2. Summary of shoulder reconstruction outcome results at 18 months.

Abduction power	Number of patients		Median
MRC grade			
M4−	3		M4
≥M4	6		
Shoulder motion	Range		Mean
Abduction (glenohumeral ± scapulothoracic)	C5–C6 avulsion	90 – 180°	114.4°
	C5–C7 avulsion	90 – 120°	(Combined)
External rotation (measured from full internal rotation, arm adducted, elbow flexed)	135 – 140°		136.3°

MRC: Medical Research Council Grading Scale.

adhesive as described above. The procedure was similarly performed for neurotization of the biceps motor branch of the musculocutaneous nerve.

Post-operatively, the upper limb was immobilized in an arm sling for 3 weeks, prior to commencement of post-operative therapy. The therapy regime consisted of two main tenets: passive range of motion and "nerve induction" exercises. Passive shoulder abduction and external rotation consisted of gradual increments in the range of motion to reach 90° over 3 weeks. The "nerve induction" exercises involved repeated active isometric contraction of the donor nerve muscles to initiate recipient actions – sustained for 10 s and repeated 20 times per exercise session. For shoulder abduction, the patient is taught to perform resisted shrugging of the shoulder; and depending on the donor fascicle used for the axillary nerve transfer; either resisted wrist flexion, finger flexion or forearm pronation. It is important that the patient does not revert to pre-injury initiation of the shoulder abduction action, but rather, to mindfully recruit his trapezius and either the wrist or finger flexors or forearm pronator to initiate shoulder abduction, for induction training of the donor nerves. When reinnervation of the target muscle occurs, the patient would have attained a new pattern of initiating shoulder abduction.

Results

Table 2 summarizes the outcomes at 18 months post-surgery. All 9 patients (100%) achieved shoulder abduction power > M3 and it was ≥ M4 in 6 of them (range M4- to M4+). The median abduction power was M4. The mean abduction range was 114.4° (range 90°–180°) (Figure 5). Results for external rotation were only available in 4 patients as we only started measuring shoulder external rotation from 2008. The mean range of external rotation was 136.3° (range 135°–140°) (Figure 6). The mean time for motor recovery to M3 for the supraspinatus muscle was 9.3 months and 10.1 months for the deltoid.

Figure 5. Shoulder abduction; fingers extended. Left = injured side.

All patients achieved elbow flexion power ≥ M4 except one with M3. This patient had partial median nerve to biceps motor branch of musculocutaneous nerve transfer at 7.5 months

Figure 6. Shoulder external rotation. Left = injured side.

Figure 7. Elbow flexion with wrist and fingers extended. Right = injured side (elbow).

post-injury (Table 1, Case 9). Though the patients were taught to do isometric exercises, the "Oberlin phenomenon" (flexing the wrist and fingers to abduct the shoulder or flex the elbow) was encountered in the early phase of rehabilitation. By 18 months, most of the patients were able to dissociate these movements (Figures 5 and 7). The two patients with two and three intercostal nerves transfers to the nerve to triceps' long head for elbow extension achieved motor power M4 and M4- respectively (Table 1, Cases 8 and 9).

Post-operatively, two patients had sensory complaints that resolved spontaneously within a month. One had hypoaesthesia of the thumb and index finger and the other had hyperaesthesia of the little finger. One patient who had biceps motor branch neurotization with a partial median nerve, had a reduction in flexor pollicis longus and index finger flexor digitorum profundus motor power to M4.

Discussion

Our results of the dual neurotization procedure of spinal accessory to suprascapular nerve and partial median or ulnar nerve to axillary nerve for shoulder abduction reconstruction in upper-type brachial plexus avulsion injuries were encouraging. All patients achieved shoulder abduction of at least 90° (range 90°–180°) with motor power range M4- to M4+. Shoulder external rotation was 135° or more. These compare well with Gu et al.'s [9] report of the transfer of the medial fascicles of the median nerve to the lateral fascicles of the axillary nerve in C5–C6 avulsion injuries. In their series of 16 patients, shoulder abduction recovery was 75°–120° with motor power M3–M4. Our results are generally better than Haninec and Kaiser's [10] report of the second neurotization to the axillary nerve with the partial ulnar or median nerve in patients with C5-C6 or C5-C7 avulsion injuries. In their series of 14 patients, shoulder abduction achieved was 50°–120°. The motor recovery ranged from M0–M4.

We propose that a contributing factor for our results could be the modification in surgical technique.

Gu and Haninec and Kaiser [9,10] isolated a length of the axillary nerve proximally, before it separates into the lateral and medial fascicular groups, and mobilized it distally for a tension-free neurorraphy. Our surgical technique as described above did not involve mobilization of the recipient axillary nerve stump. Thus, the vascularity of the recipient nerve was minimally affected and the reinnervation distance was shorter. Additionally, the mean age of our patients was lower – at 26.7 years compared to 32.1 years in Haninec and Kaiser's series.

Another factor leading to improved results could be the definitive targeting of both the teres minor and deltoid muscles separately, in the axillary nerve neurotization [15]. If the neurorraphy were performed at a level before the axillary nerve divides into its branches, the teres minor (supplied by the posterior branch of the axillary nerve) may not be reinnervated. Such a phenomenon was observed in single neurotization of the suprascapular nerve (supplying the supraspinatus and infraspinatus muscles) with the spinal accessory nerve – various authors found that the supraspinatus was preferentially reinnervated over the infraspinatus [2,16,17]. Thus, we prefer a neurorraphy to the terminal nerve supplying the target muscle – in the case of the axillary nerve, this refers to its lateral and medial fascicular groups. The inferior border of the subscapularis is a convenient site for neurotization of both the anterior and posterior branches of the axillary nerve before it enters the quadrilateral space. This directly targets the lateral and medial fascicular groups respectively, to innervate both the deltoid and teres minor muscles. Two of our three cases with C5–C6 avulsion injuries had excellent shoulder abduction of 180°. We believe that in these patients, the inferior serratus anterior muscle function may be preserved and its action complements the deltoid muscle function [4,18].

This study did not seek to determine whether the partial median or ulnar nerve was a better donor nerve, as the number of cases were too small. The choice of suitable donor fascicles was simply based on the pre-operative expandable muscle power M4 or M5. A single partial distal nerve transfer to the nerve to biceps resulted in a median elbow flexion power M4+. This is clinically adequate for useful motor function. Thus, our opinion is that dual neurotization for elbow flexion [19] to achieve greater flexion power is not necessary. The second donor nerve may be better utilized to improve shoulder abduction and external rotation range than to augment elbow flexion power.

A complication of reduced thumb and index finger flexion power (to M4) was noted in one patient. Songcharoen et al. [20] reported a similar complication in one of the 15 patients who had partial median nerve transfer to the biceps branch of musculocutaneous nerve. This may be due to the funicular and plexiform pattern of the nerve fasciculations of the peripheral nerves at the arm level, before they split to form collateral branches proximal or distal to the elbow [21]. Thus, a nerve fibre destined for the thumb and index finger flexor may have entered the fascicle for the wrist flexor or FDS proximally and exited at some distance distally. This nerve fibre could have been divided during mobilization of the donor fascicle for a distance sufficient for transfer to the recipient nerve stump. Also, we may have accepted a suboptimal motor response during the nerve stimulation process of the different nerve fascicles in confirming the important motor function to be spared. We recommend a more discerning approach during intra-operative nerve fascicle stimulation to isolate and choose the donor nerve fascicles.

The main limitations of this study are its retrospective nature, the small number of patients and that post-operative evaluation of results were assessed by the senior author only – which may contribute to an observer bias. Additionally, our outcome data could have been more rigorous; such as including objective measures for elbow flexion force in addition to the MRC grading scale. For instance, the results of elbow flexion strength in Newton-meters on a dynamometer could more objectively justify our view that elbow flexion power M4 is sufficient for useful motor function. Nevertheless, this report adds to the numbers of patients with good results after the above dual neurotization procedure in C5–6 ± C7 brachial plexus avulsion injuries where the triceps is weak.

In conclusion, the dual neurotization method of spinal accessory to suprascapular nerve and partial median or ulnar to axillary nerve is a good option for shoulder abduction reconstruction in C5-6 ± C7 brachial plexus avulsion injuries where the triceps is weak.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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