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GENERAL REVIEW • UPPER LIMB - NERVE GRAFT

Traumatic upper plexus palsy: Is the exploration of brachial plexus necessary?

Ioannis Gkiatas[1] · Dimitrios Papadopoulos[1] · Anastasios Korompilias[1] · Marios Vekris[1] · Alexandros Beris[2] · Ioannis Kostas-Agnantis[1]

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Abstract
Brachial plexus injuries are major injuries of the upper limb resulting in severe dysfunction usually in young patients. Upper trunk injuries of the brachial plexus account for approximately 45% of brachial plexus injuries. Treatment options for upper trunk brachial plexus injuries include exploration of the plexus and microsurgical repair using nerve grafts or nerve transfers. Several published studies presented the results of both techniques, but there are few studies which compared these two techniques. This article summarizes the treatment options for upper trunk brachial plexus injuries, discusses the merits and demerits of each technique, and presents authors' proposed treatment for these injuries.

Keywords Upper trunk brachial plexus injuries · Exploration · Nerve transfers · Nerve grafting

Introduction

Injury to the upper part of the brachial plexus (C5–C6, upper trunk) is one of the most common injury patterns, resulting in major functional loss of arm. It has been reported that it amounts approximately 45% of the cases in adults [1], whereas the in brachial plexus birth palsies, the incidence of upper trunk palsies is approximately 60% [2]. The suprascapular nerve, the axillary nerve, the musculocutaneous nerve, and in many cases the long thoracic nerve are affected. The compromised functions include elbow flexion, glenohumeral stability, shoulder abduction, and rotation [3]. Scapular stability may also be affected in proximal lesions if the serratus anterior is already paralyzed resulting into winging scapula.

It is essential to locate the level of injury in upper brachial plexus palsies. The injury can be located in C5, C6 nerve roots (preganglionic or postganglionic lesions) or in the upper trunk. Besides its prognostic value, the distinction between these two levels may guide treatment planning, since in nerve root injuries (especially in preganglionic lesions), the only option is nerve transfers, while in upper trunk lesions, nerve grafting may also be used. The evaluation of the injury level can be done on physical examination or with the aid of objective studies, including imaging (MRI, CT myelography) and electrodiagnostic (nerve conduction studies, electromyography) studies. Probably, the most significant use of MRI in brachial plexus injuries is the differentiation of pre- and postganglionic injuries. High-resolution 3D T2 images as well as CT myelography can reveal anatomical continuity or lack of intradural nerve rootlets [4]. The MRI examination is also able to depict traumatic meningoceles. The electromyography is useful in order to document and record the axon loss its proximal extent and the completeness of the lesion. Axon loss is objectively confirmed by the presence of fibrillation potentials, which develop about 3 weeks after the injury [5]. Physical examination in nerve root injuries will demonstrate scapular winging due to functional loss of dorsal scapular (innervates rhomboids muscles) and long thoracic (innervates serratus anterior muscle) nerves, while in upper trunk lesions, function of these muscles is preserved.

In traumatic C5–C6 brachial plexus palsy, the surgeons will be faced with the questions whether to explore the entire brachial plexus, to perform intraplexus grafting or nerve transfer, and if nerve transfer is decided, which approach will be better for the patient.

✉ Ioannis Gkiatas
john.gkiatas@gmail.com

1 Department of Orthopaedic Surgery, School of Medicine, University of Ioannina, Ioannina, Greece

2 School of Medicine, University of Ioannina, Ioannina, Greece

The classical approach consists on brachial plexus exploration and nerve grafting procedure connecting the proximal root stump with distal targets using nerve grafts [6]. However, latest authors are supporting that the results of nerve transfers can be superior to nerve graft procedure [7].

Common nerve transfers

The concept of nerve transfer is not new, but it recently has been revived and has gained significant momentum [8]. The first description of nerve transfer was back in 1824 when the French physiologist Marrie Jean Pierre Flourens first theorized that an injured nerve can be bypassed by "joining the proximal end of one nerve with the distal end of the other" [9]. But it was not until 1948 when a Russian surgeon, Alexander Lurje performed the first brachial plexus reconstruction using nerve transfers to restore the upper limb function of a female patient injured by a bomb in the World War [10]. Since then and especially over the last 20 years, there is a growing trend in using nerve transfers for brachial plexus reconstruction [11].

Many donor nerves have been proposed, including intercostal nerves [12], thoracodorsal nerve [12], medial pectoral nerve [12], long thoracic nerve [12], distal accessory nerve [12], ipsilateral C7 root [13], contralateral C7 root [14], suprascapular nerve [12], and hypoglossal nerve [15]. In some cases, the donor nerve is completely dissected, and therefore, the potential permanent sequelae should be clearly established, and additionally, these sequelae should be less important than the result after the reconstruction. In cases where isolated fascicles of the donor nerve are used, there is lack of donor site morbidity [16]. The following sections describe the most common nerve transfers (Table 1).

Spinal accessory to suprascapular nerve transfer

The spinal accessory nerve is a pure motor nerve, innervating both sternocleidomastoid and trapezius muscles. It is of great significance to use as a donor the most distal branch of the nerve so that the upper and middle parts of trapezius are not affected and its function of shoulder stabilization and elevation is preserved. Proximity of the spinal accessory nerve to the suprascapular nerve allows direct coaptation without graft. Although transfers to the more distal musculocutaneous nerve and axillary nerves have been described, both require interpositional nerve grafts [17]. In a study that evaluated single nerve transfer of spinal accessory nerve to the suprascapular nerve, 80% motor recovery was achieved, with 70° of shoulder abduction, 60° of shoulder flexion, and 30° of external rotation [17].

There are two surgical approaches for this nerve transfer. The anterior approach uses a transverse incision situated 1 cm above and parallel to the clavicle. The spinal accessory nerve is identified just deep to the superolateral margin of the trapezius. Confirmation of the nerve and of its viability is done by contraction of the trapezius after nerve stimulation. The nerve is traced up to its distal branch and then divided sharply. This branch is transposed and sutured to the recipient suprascapular nerve using microsurgical technique [18]. The posterior approach has also been recently proposed [19]. The rationale for this approach is that in severe traction injuries, distal migration of the suprascapular nerve can occur, and the nerve can be damaged more distally. Also the presence of callus formation after clavicle fractures can pose a risk in nerve dissection. Lastly, the posterior approach allows for a nerve transfer much closer to its target, so a shorter recovery period will be achieved. For the posterior approach, a transverse incision encompassing the superior angle of the medial border of the scapula and the acromion is used. The suprascapular nerve is identified at its course through the suprascapular notch, located in the middle of the skin incision. In a comparative study concerning the two approaches by Souza et al. [20], the authors concluded that better results as far as it concerns external rotation when spinal accessory to suprascapular nerve transfer was performed with posterior approach.

Triceps nerve branch to axillary nerve

Shoulder abduction can be restored by transferring a motor branch for the long head of the triceps muscle to the anterior deltoid and teres minor branches of the axillary nerve [21].

Table 1 Common nerve transfers for upper trunk injuries of brachial plexus

Common nerve transfers in upper trunk injuries of brachial plexus			
Nerve transfer	Re-innervated muscles	Function	Studies
Spinal accessory to suprascapular nerve transfer	Supraspinatus infraspinatus	Shoulder stabilization Shoulder abduction	Songcharoen et al. [20], Tender et al. [21]
Triceps nerve branch to axillary nerve	Anterior deltoid, teres minor	Shoulder abduction	Nath et al. [27], Hallock [28], Lim et al. [29]
Ulnar nerve to musculocutaneous nerve transfer	Biceps	Elbow flexion	Oberlin et al. [30], Zyaei et al. [41]
Double fascicular transfer for elbow flexion	Brachialis, biceps	Elbow flexion	Humphreys et al. [31], Mackinnon et al. [32]

This transfer was first described by Mackinnon and Nath [22]. Elbow extension is not affected since only a single motor branch is transferred [23, 24]. It is known that the long head of triceps is innervated predominantly by C8-T1 nerve roots; thus, in upper brachial plexus injuries, the radial motor branch for the triceps long head is always intact. Cadaveric arm dissection has been conducted in our department (unpublished data) in order to elaborate the precise anatomy of the radial and axillary nerves along with their motor branches in posterior arm area (Figs. 1, 2). Moreover, pathology evaluation was performed in order to identify the exact number of myelinated nerve fibers of which the donor (motor branch for the long head of the triceps muscle) and recipient (anterior deltoid and teres minor branches of axillary nerve) nerves are consisted. It was shown that the motor branch for the long head of the triceps muscle is consisted of about 1200 nerve fibers, similar to the teres minor branch of axillary nerve which consisted of 1100 nerve fibers. The similar number of nerve fibers between these nerve branches further supports that this particular nerve transfer has several ideal properties for a successful shoulder reanimation.

A posterior incision along the posterior border of deltoid proximally and the interval between the lateral and long head distally is developed during surgery, and the radial nerve is identified between these two heads. The triceps branches located close to the radial nerve are dissected up to the

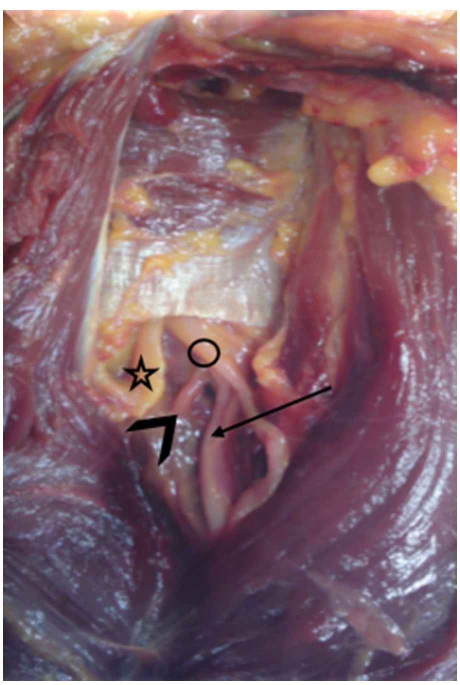

Fig. 1 A photograph of cadaveric arm dissection at the triangular space in the posterior arm demonstrating the exiting radial nerve (arrow) along with its motor branches for the long head (asterisk), for the lateral head (circle), for the medial head (arrowhead) of triceps muscle

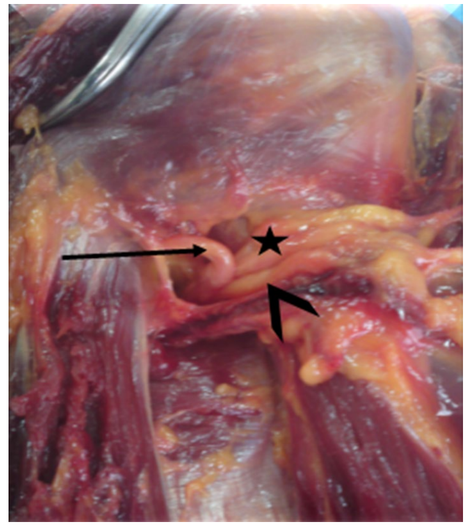

Fig. 2 A photograph of cadaveric arm dissection at the quadrilateral space in the posterior arm showing the branches of axillary nerve for teres minor muscle (arrow), for anterior (asterisk) and posterior deltoid (arrowhead) muscle

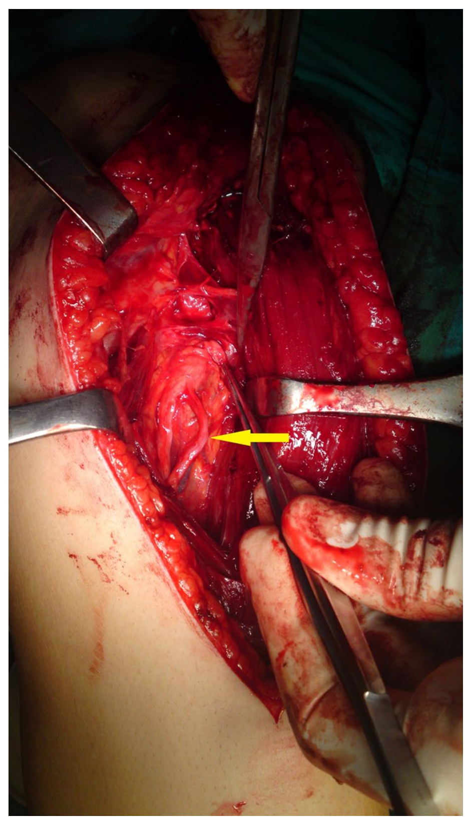

Fig. 3 Intraoperative image showing the radial nerve (yellow arrow) as it descends under the teres major muscle (color figure online)

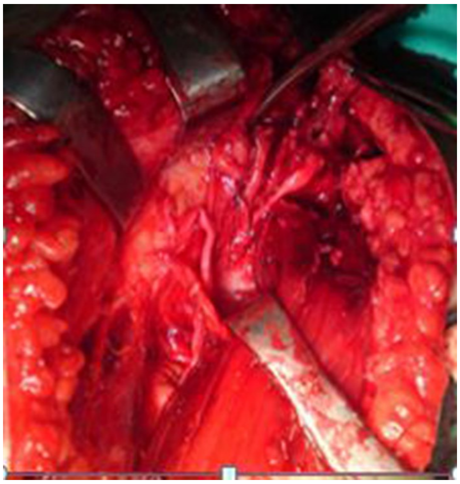

Fig. 4 Intraoperative image showing the axillary nerve and its branches at the quadrilateral space

inferior margin of teres major (Fig. 3). The axillary nerve which passes through the quadrangular space (proximally to the teres major) is exposed and traced to identify its motor components to the teres minor, posterior, and anterior deltoid (Fig. 4). The branch to the long head of the triceps is divided distally and reflected to directly approximate the anterior deltoid and teres minor motor branches of the axillary nerve.

Ulnar nerve to musculocutaneous nerve transfer

The transfer of an ulnar motor branch to the motor branch of the biceps muscle to restore elbow flexion was first described by Oberlin [25]. Since a redundant fascicle (one or two motor fascicles to the extrinsic flexor muscles) of the ulnar nerve is used, there is no functional loss. The selection of the appropriate nerve fascicle of the ulna nerve with the aid of nerve stimulation in order not to disrupt the motor and sensory function of the nerve is recommended. Not only the surgical approach for this transfer is more minimal compared to the intercostal nerve transfer, but the Oberlin transfer also allows for reconstruction at the most distal part of the recipient nerve, close to the target muscle.

Regarding the surgical technique, a longitudinal incision along the medial arm in line with the neurovascular bundle is made. The biceps fascia is opened and the musculocutaneous nerve is identified. The motor branches to both heads of the biceps are identified, dissected proximally toward their origin from the musculocutaneous nerve, and divided. The ulnar nerve is exposed, and the epineurium is opened. The selection of the ulnar nerve fascicles to be transferred is usually made with the aid of nerve stimulation. In most cases, a large fascicle producing a contraction of the flexor carpi ulnaris without significant contraction of the ulnar intrinsic muscles after nerve stimulation can be identified. This fascicle is dissected distally so that a nerve fascicle of adequate length is obtained and transferred to the biceps branch (Fig. 5).

Double fascicular transfer for elbow flexion

Double fascicular nerve transfer for musculoskeletal nerve reconstruction has been proposed by Humphreys and Mackinnon and has become an attractive option [26]. During surgery, nerve fascicles from both median and ulnar nerve are transferred to two distinctive motor branches of the musculoskeletal nerve in order to restore elbow flexion. These two branches innervate brachialis and biceps muscles, respectively. The rationale for this procedure is that besides biceps, additional restoration of brachialis will optimize the functional recovery. Although Mackinnon et al. [27] observed that double nerve transfer increased the rate and success of recovery of elbow flexion, in a comparative study between single and double transfers that did not show any significant differences regarding elbow flexion strength (single 16% vs double 21% of normal side) [28].

Nerve grafting for upper trunk injuries (Table 2)

In general, the use of nerve grafts in brachial plexus surgery aims to the bridging gaps between motor donors and distal targets with coaptation near to the muscle targets and not to reconstruct trunks and cords [29]. In the middle of the twentieth century, Seddon proposed nerve grafting for the surgical treatment of traction injuries [30]. Since then, nerve grafting has been introduced to brachial plexus restoration surgery with the use of microsurgery techniques. There are studies which have indicated that the nerve grafting has the advantage of neuroprotection and prevents cell death of

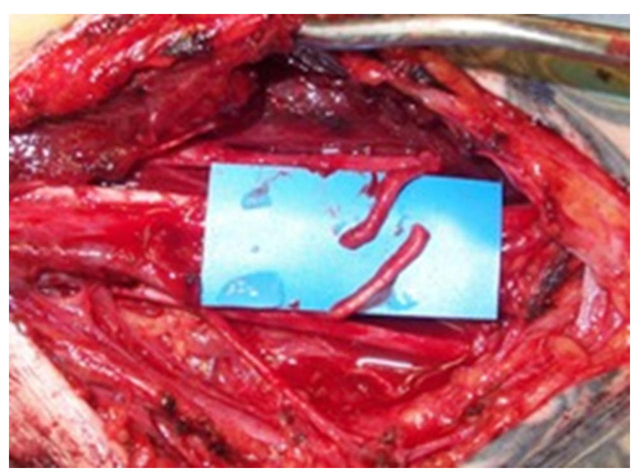

Fig. 5 Intraoperative image showing the transferred ulnar nerve fascicle to the musculocutaneous nerve for restoration of elbow flexion

Table 2 Elbow flexion and shoulder abduction outcomes after nerve grafting for upper trunk injuries of the brachial plexus

Results of nerve grafting after upper trunk injuries of the brachial plexus				
Study	Injury pattern	Nerve graft used	Elbow flexion strength ≥ M4 (%)	Shoulder abduction strength ≥ M4 (%)
Fogarty et al. [42]	Rupture of C5–C6	Sural nerve autograft	60	
Jivan et al. [43]	Avulsion and/or rupture of C5–C6	Sural nerve autograft	27	
Yamada et al. [44]	Avulsion of C5–C6	Sural nerve autograft	100	100
Sedel [48]	Avulsion and/or rupture of C5–C6	Sural nerve autograft	67	67
Malessy et al. [49]	Avulsion and/or rupture of C5–C6	Sural nerve autograft	50	67

motor but not sensory neurons [31, 32]. The survival effect provided by peripheral nerve grafts seems to be mediated by the beta(1)-integrins [33].

The exploration of the brachial plexus is made with a curved incision in the posterolateral aspect of the superior border of the clavicle which is extended to the arm through the deltopectoral groove. The supraclavicular sensory nerves, the external jugular vein, the transverse cervical vessels, the omohyoid muscle, and the cephalic vein are preserved. The pectoralis minor muscle is raised from the coracoid insertion. The clavicle is not osteotomized [34].

In postganglionic injuries of the brachial plexus, nerve grafting seems to be the traditional method for repairing the injury when there is a viable proximal nerve stump [35]. In clear-cut injuries, nerve grafting is indicated [6] due to the better guidance of the neuraxons. There are several nerve grafts which can be used such as the sural nerve, the sensory branch of the ulnar nerve, and the medial cutaneous nerve of the forearm [6]. The most common is the sural nerve which can be harvested from the lateral malleolus till the lower part of the knee through small incisions. The sural nerve graft can be harvested in 30–40 cm of length from the lateral malleolus till the lower part of the knee to the exit of the nerve from the peroneal nerve (lateral sural) and from the posterior tibial nerve (medial sural) [29]. The vascularization of the underlying bed in cases of nerve grafting is of high importance. According to Terzis and Kostopoulos [29], if there is vascular compromise, the nerve graft should be harvested as a vascularized graft. Vascularized ulnar nerve graft can be used for neurotization from the contralateral C7 root [29].

Discussion

The annual incidence of brachial plexus injuries has been constantly increasing over the last years mainly due to the rising number of motorcycle accidents [36]. The primary goal of operative treatment is restoration of the elbow flexion and shoulder reanimation. The current body of literature regarding surgical treatment of upper brachial plexus injuries includes results of both nerve transfers [9, 16, 17] and nerve grafting [37–39].

There are several studies regarding nerve transfers for restoration of elbow flexion in patients with brachial plexus injuries [16, 27, 40]. Teboul et al. [40] presented a case series of 32 patients who underwent fascicular ulnar nerve transfer to musculocutaneous nerve for reinnervation of the biceps brachii muscle. The authors reported fair and good functional results in 30 of these patients. A year later, Mackinnon et al. described a double nerve transfer of fascicular ulnar and median nerve for elbow flexion. The authors reported good functional results with no need for reoperation [27]. Nerve transfers for glenohumeral stability and shoulder abduction have also proved a highly successful treatment strategy. The two main nerve transfers for restoration of these functions include the spinal accessory nerve to the suprascapular nerve and the transfer of triceps radial nerve branch to axillary nerve branches [41]. Kostas-Agnantis et al. [41] studied the results of simultaneous nerve transfer of spinal accessory nerve to suprascapular nerve and triceps nerve branch to axillary nerve branch in nine patients with upper brachial plexus palsy. The mean postoperative value of shoulder abduction was 112.2° (range 60°–170°), while preoperatively none of the patients was able for abduction. The mean postoperative value of shoulder external rotation was 66° (range 35°–110°), while preoperatively none of them was able for external rotation. In another study, Bertelli et al. [42] showed that the postoperative mean range of shoulder abduction in patients with upper brachial plexus injury who underwent transfer of the spinal accessory nerve to the suprascapular nerve was approximately 58°.

There are also several authors who have presented their results concerning the use of nerve grafts for upper trunk injuries of brachial plexus [37–39, 43, 44]. Fogarty et al. [37] presented a case series of nine patients with upper trunk lesion of brachial plexus. All patients underwent brachial plexus exploration and reconstruction with the use of cable grafts. In six patients the final result was described as good whereas in the rest three as poor. Jivan et al. [38] published their results of 27 patients with upper trunk brachial plexus injury who were treated with nerve grafting. The authors concluded that early exploration and reconstruction of these injuries minimizes the possibility of complications. The same year Yamada et al. [39] presented the results of coaptation from C3 and C4 to the upper trunk, and they resulted in recommending the bypass coaptation as a useful technique for these injuries.

Despite the great number of studies dealing with either nerve transfers or nerve grafting for brachial plexus palsies both in adults and [37–39, 41, 45], there are only few [1, 46, 47] which try to compare these two methods. Garg et al. [1] in a comparative analysis of the literature concluded that dual nerve transfer is more advantageous over traditional nerve grafting for restoration of improved shoulder. One year later, Yang et al. [46] despite their findings that nerve transfer yields better outcomes than nerve grafting for upper trunk injuries of brachial plexus, conclude there is no significant difference between the two techniques in shoulder abduction and that supraclavicular brachial plexus exploration plays an important role in developing individual surgical strategies, and nerve repair should remain the standard for treatment of upper brachial plexus injury except in isolated cases solely lacking elbow flexion. Ali et al. [47] concluded that Oberlin procedure and nerve transfers are the more successful approaches to restore elbow flexion and shoulder abduction, respectively, compared with nerve grafting (Table 3).

Authors' commentary

Both techniques in the hands of an experienced microsurgeon may result in favorable results. The authors support that despite the fact that nerve transfers need reeducation of the muscles, the results of this technique offer faster results compared to nerve grafting. Additionally, the skin incision is smaller when nerve transfers are applied. The use of shorter nerve graft seems to provide better results compared to longer ones. More specifically, nerve grafts shorter than 10 cm offer better functional and clinical outcomes [48–50]. With nerve grafting, there is also the danger of neuroma formation, the morbidity of the donor area, and the double suturing of the nerve in both the proximal and the distal stump.

Our suggestion for the patients with C5, C6 root injury even when one or both roots are available for transfer is not to explore the entire brachial plexus but to perform the technique of direct nerve transfer close to the muscle target. Considering all the advantages of nerve transfers over nerve grafting, a treatment strategy of primary nerve transfers in all upper brachial palsies independently of the injury level may be beneficial. This strategy also allows for minimal approaches without the need for extensive surgical exploration of the brachial plexus required for nerve grafting. In cases with C7 involvement, our suggestion is to explore the entire brachial plexus for identification of other donors such as medial pectoral branch or the proximal stump of C5, C6 roots. We finally propose the posterior approach due to its advantages such as the smaller distance from the final target and the faster recovery period.

Conclusion

Upper trunk injuries consist of almost half of brachial plexus injuries, and their management is a challenge for the microsurgeon. According to comparative studies for patients with complete upper trunk palsy, without clinical or electromyographic evidence of recovery at 3 to 6 months after the injury, the functional outcomes for restoration of elbow flexion and shoulder function will be improved by the use of nerve transfers rather than autogenous nerve grafts [1, 47].

With this technique, nerve transfer and coaptation can be done close to the muscle target, and thus earlier return of the muscle function is anticipated compared to the long recovery period of nerve grafting. Moreover, nerve transfers can be performed without the use of interpositional grafts, achieving more reliable functional results. Conversely in nerve transfers muscle reeducation is required. Certain degree of functional loss of the innervated muscle by the donor nerve may occur.

Table 3 Comparative studies of nerve transfers and grafting

Study	Year	Studies included	Shoulder abduction	Elbow flexion
Garg et al. [1]	2011	31	74% patients with dual nerve transfer had shoulder abduction strength ≥ M4 compared to 46% with nerve grafts	83% of patients with nerve transfers had elbow flexion strength ≥ M4 compared to 56% of patients with nerve grafts
Yang et al. [46]	2012	33	No significant difference for shoulder abduction	71% of patients with nerve transfers had elbow flexion strength ≥ M4 compared to 46% of patients with nerve grafts
Ali et al. [47]	2015	71	Nerve transfer was significantly more successful	Oberlin procedure was more successful than nerve grafting

The evolution and developments in microsurgical techniques such as the neurorrhaphy without tension have expanded the strategies in the reconstruction of brachial plexus injuries. In addition, the use of microscope or magnifying loupes is mandatory. Regardless the preferred reconstruction method for upper trunk injuries of the brachial plexus, the surgeon should have been trained in microsurgery in order to perform these demanding operations.

Compliance with ethical standards

Conflict of interest All authors declare that they have no conflict of interest.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Declaration of Helsinki and its later amendments or comparable ethical standards.

Informed consent Informed consent was obtained from all individual participants included in the study.

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