Restoration of Elbow Flexion by Transfer of the Phrenic Nerve to Musculocutaneous Nerve after Brachial Plexus Injuries

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Abstract Traumatic brachial plexus injuries are a devastating injury that results in partial or total denervation of the muscles of the upper extremity. Treatment options that include neurolysis, nerve grafting, or neurotization (nerve transfer) has become an important procedure in the restoration of function in patients with irreparable preganglionic lesions. Restoration of elbow flexion is the primary goal in treating patients with severe brachial plexus injuries. Nerve transfers are used when spinal roots are avulsed, and proximal stumps are not available. In the present study, we analyze the results obtained in 20 patients treated with phrenic–musculocutaneous nerve transfer to restore elbow flexion after brachial plexus injuries. A consecutive series of 25 adult patients (21 men and 4 women) with a brachial plexus traction/crush lesion were treated with phrenic–musculocutaneous nerve transfer, but only 20 patients (18 men and 2 women) were followed and evaluated for at least 2 years postoperatively. All patients had been referred from other institutions. At the initial evaluation, eight patients received a diagnosis of C5–6 brachial plexus nerve injury, and in the other 12 patients, a complete brachial plexus injury was identified. Reconstruction was undertaken if no clinical or electrical evidence of biceps muscle function was seen by 3 months post injury. Functional elbow flexion was obtained in the majority of cases by phrenic–musculocutaneous nerve transfer (14/20, 70%). At the final follow-up evaluation, elbow flexion strength was a Medical Research

Council Grade 5 in two patients, Grade 4 in four patients, Grade 3 in eight patients, and Grade 2 or less in six patients. Transfer involving the phrenic nerve to restore elbow flexion seems to be an appropriate approach for the treatment of brachial plexus root avulsion. Traumatic brachial plexus injury is a devastating injury that result in partial or total denervation of the muscles of the upper extremity. Treatment options include neurolysis, nerve grafting, or neurotization (nerve transfer). Neurotization is the transfer of a functional but less important nerve to a denervated more important nerve. It has become an important procedure in the restoration of function in patients with irreparable preganglionic lesions. Restoration of elbow flexion is the primary goal in treating patients with severe brachial plexus injuries. Nerve transfers are used when spinal roots are avulsed, and proximal stumps are not available. Newer extraplexal sources include the ipsilateral phrenic nerve as reported by Gu et al. (Chin Med J 103:267–270, 1990) and contralateral C7 as reported by Gu et al. (J Hand Surg [Br] 17(B):518–521, 1992) and Songcharoen et al. (J Hand Surg [Am] 26(A):1058–1064, 2001). These nerve transfers have been introduced to expand on the limited donors. The phrenic nerve and its anatomic position directly within the surgical field makes it a tempting source for nerve transfer. Although not always, in cases of complete brachial plexus avulsion, the phrenic nerve is functioning as a result of its C3 and C4 major contributions. In the present study, we analyze the results obtained in 20 patients treated with phrenic–musculocutaneous nerve transfer to restore elbow flexion after brachial plexus injuries.

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Materials and Methods

A consecutive series of 25 adult patients (21 men and 4 women) with a brachial plexus traction/crush lesion were treated with phrenic–musculocutaneous nerve transfer, but only 20 patients (18 men and 2 women) were followed and evaluated for at least 2 years postoperatively. All patients were initially seen and treated at outlying hospitals and then referred for repair of the brachial plexus injury. At the initial evaluation, 8 patients received a diagnosis of C5–6 brachial plexus nerve injury, and in the other 12 patients, a complete brachial plexus injury was identified. Reconstruction was undertaken if no clinical or electrical evidence of biceps muscle function was seen by 3 months post injury. Surgery was performed a mean of 4.1 ± 1.6 months post injury ($\pm$ SD, range 2.8–8.6 months). The nerve transfer was part of an extended brachial plexus reconstruction. The mean age of the patients at surgery was 23.4 ± 4.8 years (SD). All 20 patients had sustained their injuries in traffic accidents. A needle electromyographic examination was performed before surgery.

Before surgery, radiographs of the chest during deep inspiration and full expiration were made to exclude the possibility of phrenic nerve injury or pulmonary disease. Pulmonary function tests and electrocardiography are also routinely performed to identify any pulmonary dysfunction or cardiac disease.

Surgical Procedure

The operation was carried out with the patient under general anesthesia and supine position with a pillow under the

shoulder and the head turning to healthy side. The procedure is performed with microsurgical loupe magnification.

Combined supra- and infraclavicular incision for exploration of brachial plexus is used. In all cases, the entire trajectory of the brachial plexus was exposed [23], and root avulsions were confirmed by the emptiness of the intervertebral foramen. The phrenic nerve is identified on the surface of the scalenus anterior and is followed proximally until it crosses the lateral aspect of that muscle.

The function of the phrenic nerve was tested with a nerve stimulator. Along the surface to scalenus anterior, the phrenic nerve was sufficiently isolated toward the deep layer to the costal end of the scalenus and distally transected. The proximal cut end of the phrenic nerve is coapted via a sural nerve graft to the distal cut end of the musculocutaneous (MC) nerve using 10/0 nylon through the epineural sheath (Fig. 1). The shoulder was immobilized in adduction, internal rotation, and the elbow in flexion during 4 weeks.

Physical therapy and electrostimulation started 4 weeks postoperatively. Patients are controlled regularly in time periods of 3 months. When muscle reinnervation was evident, strengthening exercises and motor reeducation were begun.

During the primary brachial plexus surgery, additional nerve transfers for reconstruction of shoulder function (spinal accessory nerve–suprascapular nerve transfer) were performed in 16 of 20 patients. Secondary procedures were performed in six patients: trapezius transfer to restore shoulder abduction (four patients) and arthrodesis of the wrist (two patients; Table 1).

Figure 1 Operative photograph showing transfer of the phrenic nerve to the musculocutaneous nerve. **a** Exposure of C6 root avulsed (Penrose drain and white arrow) and the phrenic nerve on the surface of the scalenus anterior (black arrow). **b** The phrenic nerve (large black arrow) was distally transected and neurotized with the MC nerve via the sural nerves (large white arrow). Tension and pressure at the suture site must be avoided during the repair (two small black arrows).

Table 1 Phrenic to musculocutaneous nerve transfer in 20 patients.

	Diagnosis	Age	Delay in Surgery (Months)	Nerve Graft Length (cm)	Outcome MRC Grade Biceps	Additional Nerve Reconstruction (Nerve Transfer)	Secondary Procedures
1	C5/C6 AV	21	3	10	3	SAN to SS	
2	C5/C6 AV	17	3.2	8	5		Trapezius transfer
3	C5/T1 AV	28	4	8.5	3	SAN to SS	Wrist arthrodesis
4	C5/C6 AV	23	3.5	8	3	SAN to SS	
5	C5/T1 AV	16	5.3	11	4	SAN to SS	
6	C5/C6 AV	22	5.7	10.5	2	SAN to SS	Trapezius transfer
7	C5/T1 AV	32	2.8	9.5	3	SAN to SS	
8	C5/C6 AV	18	3	10	4	SAN to SS	
9	C5/T1 AV	28	3.5	9	3	SAN to SS	
10	C5/T1 AV	18	3.1	8.5	5	SAN to SS	
11	C5/T1 AV	23	6.5	10	1	SAN to SS	Wrist arthrodesis
12	C5/T1 AV	27	4.6	10.5	2		
13	C5/C6 AV	22	4.2	12	2	SAN to SS	
14	C5/T1 AV	24	6.3	9	2		Trapezius transfer
15	C5/C6 AV	34	3.2	10	3	SAN to SS	
16	C5/C6 AV	19	3	10	4		
17	C5/T1 AV	24	8.6	10	2	SAN to SS	
18	C5/T1 AV	20	3.1	9	3	SAN to SS	Trapezius transfer
19	C5/T1 AV	27	3.2	10	4	SAN to SS	
20	C5/T1 AV	25	3	8	3	SAN to SS	

AV Avulsion, MRC Medical Research Council, SAN spinal accessory nerve, SS suprascapular nerve

Electromyographic evaluation was performed every 3 months to understand the condition of nerve regeneration. Motor function was evaluated on a scale ranging from 0 to 5 points according to the Medical Research Council (MRC) grades. Good or useful recovery was defined as Grade 3 or higher, poor recovery Grade 2 or less.

The delay between the injury and the operative intervention, the length of the graft, and the age of the patient at the time of the operation were evaluated as prognostic factors. Quantitative data were evaluated with use of a Student *t* test, and qualitative data were evaluated with use

of a chi-square test. A difference was considered to be significant if *p* was less than 0.05.

Results

Good or useful elbow flexion was obtained in the majority of cases by phrenic–MC nerve transfer (14/20, 70%; Fig. 2).

Evidence of reinnervation of the biceps muscle was clinically noted at a mean of 7.2 ± 2.7 months postoperatively

Figure 2 Photograph of the patient in Case 1 after surgical treatment of C-5 and C-6 nerve root avulsion. Flexion of the elbow joint against gravity was possible after operation in most cases. Note the bulk of the previously paralyzed left biceps muscle.

($\pm$ SD, range 5.4–15.2 months) and the mean length of follow up was 31.3 ± 13 months ($\pm$ SD, range 24–67 months). At the final follow-up evaluation, elbow flexion strength was an MRC Grade 5 in two patients, Grade 4 in four patients, Grade 3 in eight patients, and Grade 2 or less in six patients.

A statistical analysis revealed that an operative delay of less than 6 months was a significant factor with respect to recovery of the function of the biceps ($p=0.004$); the longer the delay, the poorer the result (mean delay, 3.4 ± 0.6 months for the good results compared with 6.0 ± 1.6 months for the poor ones). However, with the number of patients available for study, we could not detect a significant relationship between the clinical outcome, the age of the patient, and the length of the graft ($p=0.09$, $p=0.12$, respectively).

Discussion

Brachial plexus injuries are often devastating injuries that can lead to significant long-term functional disability. Brachial plexus lesions usually occur from high-speed motor vehicle or motorcycle accidents and affect young men.

Patients with traction brachial plexus lesions are generally observed for spontaneous recovery for several months. Patients who do not demonstrate clinical or electrical recovery by 3 to 6 months should undergo operative intervention.

Surgery may be performed earlier than 3 months if there is evidence of avulsion or ruptures. Poorer outcomes have been achieved in patients who undergo nerve surgery after 6 months, especially after 9 months. Nerve surgery after 1 year is typically not advised.

Primary treatment of traction brachial plexus injuries includes neurolysis, nerve grafting, extraplexal and intraplexal (plexoplexal) neurotization, free muscle transfer, and nerve reimplantation. Priorities for reconstruction include elbow flexion, shoulder abduction/external rotation and stability, wrist extension, finger flexion, wrist flexion, finger extension, and hand sensibility.

The restoration of elbow flexion by nerve transfer has generally focused on reinnervation of the biceps muscle (primary forearm supinator and secondary elbow flexor), but the brachialis muscle is the primary elbow flexor; therefore, reinnervation of both the biceps and brachialis muscles should maximize the potential for recovery of strong elbow flexion.

Nerve transfers (neurotization) can be performed in cases of preganglionic or combined preganglionic and postganglionic injuries. Root avulsions are considered to be irreparable. In addition, nerve transfers are being used increasingly in cases of postganglionic injury (instead of nerve grafting) in an attempt to provide more rapid and perhaps more reliable recovery of specific vital functions. The basis of a nerve transfer is using an expendable nerve for another function, often permitting nerve repair closer to the motor end plate. Widely used neurotization sources include the intercostals [4, 15, 24, 25] and the spinal accessory [2, 19, 21] nerves. These nerves can result in good functional recovery and can be sacrificed with little morbidity.

Over the years, the intercostal nerve (ICN) transfer has remained a popular and reliable nerve transfer. Typically, two to four nerves are used for motor neurotization (each ICN has approximately 1,200 axons). Intercostal neurotization is frequently used for recovery of biceps function or for powering free functioning muscle transfers.

The spinal accessory nerve is used frequently as a nerve transfer. This nerve can be identified readily in the supraclavicular exposure. The distal trunk has approximately 1,500 myelinated fibers and is used for neurotization. The fibers of the spinal accessory nerve are predominantly motor. The spinal accessory nerve provides reliable results when it is coapted directly to the supraclavicular nerve [6] or when used with an interpositional graft to the biceps [26].

The phrenic nerve contains a large number of pure motor axons that allow the possibility of entire or partial transfer with success (800 myelinated fibers) [20]. Its anatomic position directly within the surgical field makes it a tempting source for nerve transfer. Even in cases of complete brachial plexus avulsion, the phrenic nerve often (although not always) is functioning as a result of its C3 and C4 major contributions. When the phrenic nerve is sacrificed, one important issue is the resulting respiratory compromise, although not clinically important in the majority of situations, this degree of respiratory loss will produce symptoms in higher-demand situations and should not be used in patients who have sustained severe chest trauma or in children younger than 2 years of age. Since the adoption of phrenic transfer by Gu et al. [8], many patients have recovered elbow flexion, which would otherwise remain paralyzed. Recently, Xu et al. [27] harvested a longer phrenic nerve by using video-assisted thoracic

surgery. This technique allows direct nerve transfer to the biceps. Gu [7] started using the entire contralateral C7 as a nerve transfer in 1986. Ulnar nerve fascicle transfer to the biceps branch of the MC nerve and a separate transfer to the brachialis branch provide excellent elbow flexion strength in patients with brachial plexus nerve injuries [14].

We report the results obtained in 20 patients who had root avulsions of the brachial plexus treated by phrenic nerve–MC nerve transfer to restore elbow flexion. After this procedure, 70% of the patients recovered biceps muscle function (MRC Grade 5, 4, or 3; Fig. 2). This outcome differs slightly from those in two previous studies conducted by other authors, which were successful between 58 and 75% [5, 8, 10, 11, 27].

Different factors have to be taken into account when judging the pros and cons of the phrenic transfer.

The time between the moment of the accident and the surgical intervention is one of the factors' more important presage, and this belong together with the signal for other authors [12, 16]. A delay of the surgery after the 8 months implied a bad presage for the recovery of the function.

Narakas and Hentz [18] found that when the reconstruction delay is more than 8 to 12 months, the recovery is minor, but if it is carried out before the 4th month, the answer is more satisfactory.

Bentolila et al. [3] pointed out that the retard between the moment of the lesion and the intervention is one of the factors' more important presage, and they added that, to reach a functional result, the retard should be minor of 4 months.

Akasaka et al. [1] used the factor "interval" in their treatment strategy. In their series, results were good or fair in 50% of cases when the ICN–MC nerve transfer was performed within 6 months post injury. Therefore, in cases in which surgery was delayed for more than 6 months, these investigators opted for free muscle transfer reinnervated by the ICN.

There was no significant relationship between surgical outcomes, the age of the patient, and the length of the implant.

In our series, the extent of recovery in older patients could not be distinguished statistically from that in younger patients, which is in accordance with other reports [13, 15, 17].

In conclusion, transfer involving the phrenic nerve to restore elbow flexion seems to be an appropriate approach for the treatment of brachial plexus root avulsion.

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