Nerve transposition for the restoration of elbow flexion following brachial plexus avulsion injuries

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Despite technical advances, the ability to restore motor function following a brachial plexus avulsion is limited. Twenty patients who suffered the loss of elbow flexion following a brachial plexus avulsion injury underwent a neurotization procedure in an attempt to restore that lost function. Of 16 patients who underwent intercostal to musculocutaneous nerve anastomosis, seven obtained good elbow flexion. Four patients who no longer had a viable biceps brachialis muscle underwent an anastomosis between transposed intercostal nerves and a free vascularized gracilis muscle grafted to the position of the biceps. Two of these patients obtained good elbow flexion. Although synkinesis between the biceps brachialis and the inspiratory muscles can be demonstrated during coughing and deep inspiration, the patients learn to flex their reinnervated biceps brachialis muscle and maintain flexion independent of respiration.

KEY WORDS • brachial plexus avulsion • intercostal nerve • elbow flexion • gracilis muscle • anastomosis, nerve

AVULSION injuries of the brachial plexus most frequently occur in healthy young males who are then left with a severe permanent handicap. Following such an injury, patients come to the neurosurgeon seeking pain relief and restoration of function. Of those with intractable pain, approximately three-quarters can be adequately treated by dorsal root entry zone (DREZ) lesions.\textsuperscript{14} Despite technical advances, the ability to restore lost motor function is more limited.

In the past 6 years, we have attempted to restore elbow flexion following brachial plexus avulsion injuries by transposing intercostal nerves to the musculocutaneous nerve in 16 patients and to a free flap of gracilis muscle in four patients. In this communication we describe the results of these procedures.

Clinical Material and Methods

Patient Population

The series included 19 males and one female with ages ranging from 7 to 43 years (Table 1). Fifteen patients were injured in motor-vehicle accidents, one in an airplane crash, and four in falls. The time interval between the initial injury and the patients' reconstructive surgery varied from 3 months to 3 years. Prior to surgical reconstruction, 13 patients had a completely flaccid arm and six patients had some retained lower brachial plexus function. One patient underwent a concomitant Steindler flexoplasty\textsuperscript{30} to augment elbow flexion. Seven patients were referred because of chronic pain, and DREZ lesions were performed prior to the intercostal nerve transposition procedure.

Procedure

Before transposing nerves to the brachial plexus, it must be clearly established that the upper nerve roots of the brachial plexus have been avulsed from the spinal cord. Several of our patients had undergone prior DREZ procedures at which time the avulsion was confirmed.

If an avulsion of the C5–6 roots was not positively demonstrated preoperatively, the proximal plexus was surgically explored. The upper trunk was exposed by the method of Henry.\textsuperscript{15} The phrenic nerve was identified and the anterior scalene muscle was partially resected, exposing the C-5 and C-6 roots. If the upper trunk was found to be sclerotic and fibrosed, the trunk and roots were serially incised from distal to proximal until normal-appearing fascicles were encountered. Biopsy specimens frequently demonstrated displaced sensory ganglia. If the upper trunk appeared relatively...
TABLE 1

Clinical characteristics of 20 patients with nerve transposition for brachial plexus avulsion injury*

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Age (yrs), Sex</th>
<th>Cause of Injury</th>
<th>Neurological Deficit</th>
<th>Duration from Injury to Surgery</th>
<th>Procedure</th>
<th>Follow-Up Period</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20, M</td>
<td>motorcycle</td>
<td>complete plegia</td>
<td>12 mos</td>
<td>IC (T3, 4) to MC, sural nerve grafts</td>
<td>2 yrs</td>
<td>poor</td>
</tr>
<tr>
<td>2</td>
<td>15, M</td>
<td>bicycle</td>
<td>some retained C-4</td>
<td>9 mos</td>
<td>IC (T5, 6) to MC</td>
<td>3 yrs</td>
<td>excellent function</td>
</tr>
<tr>
<td>3</td>
<td>19, M</td>
<td>fall</td>
<td>complete plegia</td>
<td>8 mos</td>
<td>IC (T5, 6) to MC, sural nerve grafts</td>
<td>5 yrs</td>
<td>poor</td>
</tr>
<tr>
<td>4</td>
<td>33, M</td>
<td>motorcycle</td>
<td>complete plegia</td>
<td>3 mos</td>
<td>IC (T3-5) to MC</td>
<td>17 mos</td>
<td>poor</td>
</tr>
<tr>
<td>5</td>
<td>19, M</td>
<td>fall</td>
<td>complete plegia</td>
<td>5 mos</td>
<td>IC (T3-5) to MC</td>
<td>2 yrs</td>
<td>excellent</td>
</tr>
<tr>
<td>6</td>
<td>10, M</td>
<td>minihike</td>
<td>complete plegia</td>
<td>10 mos</td>
<td>IC (T3-5) to MC</td>
<td>2 yrs</td>
<td>poor</td>
</tr>
<tr>
<td>7</td>
<td>24, M</td>
<td>automobile</td>
<td>complete plegia</td>
<td>10 mos</td>
<td>IC (T3-5) to MC</td>
<td>2 yrs</td>
<td>poor</td>
</tr>
<tr>
<td>8</td>
<td>20, M</td>
<td>motorcycle</td>
<td>root avulsion at C5-7</td>
<td>9 mos</td>
<td>IC (T3-5) to MC</td>
<td>3 yrs</td>
<td>poor</td>
</tr>
<tr>
<td>9</td>
<td>43, M</td>
<td>airplane</td>
<td>complete plegia</td>
<td>12 mos</td>
<td>IC (T3-5) to MC</td>
<td>3 yrs</td>
<td>referred sensation only</td>
</tr>
<tr>
<td>10</td>
<td>17, M</td>
<td>motorcycle</td>
<td>root avulsion at C5-7</td>
<td>4 mos</td>
<td>IC (T4, 5) to MC</td>
<td>3 yrs</td>
<td>excellent</td>
</tr>
<tr>
<td>11</td>
<td>17, M</td>
<td>motorcycle</td>
<td>avulsion at C5-7</td>
<td>4 mos</td>
<td>IC (T4, 5) to MC</td>
<td>3 yrs</td>
<td>excellent (augmented by Steindler flexoplasty)</td>
</tr>
<tr>
<td>12</td>
<td>18, M</td>
<td>automobile</td>
<td>avulsion C5-7</td>
<td>8 mos</td>
<td>IC (T4, 5) to MC</td>
<td>18 mos</td>
<td>2/5 movement (improving)</td>
</tr>
<tr>
<td>13</td>
<td>19, M</td>
<td>fall</td>
<td>complete plegia</td>
<td>7 mos</td>
<td>IC (T3-5) to MC</td>
<td>18 mos</td>
<td>2/5 movement (improving)</td>
</tr>
<tr>
<td>14</td>
<td>16, M</td>
<td>automobile</td>
<td>complete plegia</td>
<td>4 mos</td>
<td>IC (T3-5) to MC</td>
<td>2 yrs</td>
<td>excellent</td>
</tr>
<tr>
<td>15</td>
<td>20, M</td>
<td>automobile</td>
<td>complete plegia</td>
<td>8 mos</td>
<td>IC (T3-5) to MC</td>
<td>1 yr</td>
<td>excellent</td>
</tr>
<tr>
<td>16</td>
<td>37, M</td>
<td>automobile</td>
<td>root avulsion at C5-7</td>
<td>7 mos</td>
<td>IC (T3-5) to MC</td>
<td>2 yrs</td>
<td>poor</td>
</tr>
<tr>
<td>17</td>
<td>32, M</td>
<td>automobile</td>
<td>root avulsion at C5-7</td>
<td>13 mos</td>
<td>IC (T3-5) to gracilis</td>
<td>2 yrs</td>
<td>excellent</td>
</tr>
<tr>
<td>18</td>
<td>42, M</td>
<td>motorcycle</td>
<td>complete plegia</td>
<td>18 mos</td>
<td>IC (T3-5) to gracilis transfer</td>
<td>1 yr</td>
<td>poor</td>
</tr>
<tr>
<td>19</td>
<td>29, M</td>
<td>motorcycle</td>
<td>complete plegia</td>
<td>3 yrs</td>
<td>IC (T3-5) to gracilis transfer</td>
<td>8 mos</td>
<td>poor</td>
</tr>
<tr>
<td>20</td>
<td>7, F</td>
<td>fall off truck</td>
<td>root avulsion at C-6, 7, partial C-5 avulsion</td>
<td>22 mos</td>
<td>IC (T3-5) to gracilis transfer</td>
<td>7 mos</td>
<td>excellent</td>
</tr>
</tbody>
</table>

*IC = intercostal nerve; MC = musculocutaneous nerve.

normal, intraoperative electrical conduction studies were performed prior to incising the nerves. When normal fascicles were found, sural grafts were directed from these fascicles to the musculocutaneous nerve and the intercostal nerve transposition was abandoned.

Next, the infraclavicular brachial plexus was exposed by an incision made along the deltopectoral groove and extending down the medial aspect of the arm. After reflecting the pectoralis major muscle from the humerus, the musculocutaneous nerve was identified. Usually this nerve was found branching from the lateral cord at approximately the level of the cortical process, but occasionally it was found to originate from the medial nerve. The musculocutaneous nerve was inspected to ascertain that it contained normal-appearing fascicles.

The patients were then rotated laterally and the intercostal nerves were identified and dissected free. A standard posterior lateral thoracotomy incision was made in the fourth interspace below the tip of the ipsilateral scapula. The incision was deepened through the latissimus dorsi and serratus anterior muscles, exposing the ribs. A subperiosteal dissection of the third through fifth ribs was performed. The third through fifth intercostal nerves were dissected free from beneath the ribs from the transverse spinal processes to at least the anterior axillary line. With the aid of intraoperative nerve stimulation, a large predominantly sensory nerve branch was always identified and separated from a predominantly motor branch of the intercostal nerve in the midaxillary line. The motor branches of the intercostal nerves were then transposed through a subcutaneous axillary tunnel to the anterior axillary wound, and the thoracotomy wound was closed in anatomical layers (Fig. 1).

Under the microscope, all three intercostal nerves were anastomosed to the musculocutaneous nerve with 10-0 suture as close to the first motor branch to the biceps as possible. The anterior wounds were closed and the patient was placed in a Velpeau shoulder-immobilizing splint. Six weeks after surgery, gradual shoulder abduction was begun.

In three patients an attempt was made to separate the fascicles destined to join the lateral antebrachial cutaneous nerve from those destined to innervate the biceps brachialis muscles. The lateral antebrachial nerve was isolated above the lateral condyle and dissected proximally toward the shoulder. Motor fascicles destined for the biceps brachialis muscles could usually be separated from the sensory nerve distally, but in each case the dissection was abandoned as significant cross connections between the motor and sensory fascicles were encountered close to the shoulder.

In two patients operated on early in our series, nerve grafts were interposed between the musculocutaneous and intercostal nerves. Biceps function was not obtained in either case. With proper dissection of the anterior motor portion of the intercostal nerve, this maneuver should not be necessary. In another instance, the brachial plexus was explored through an axillary incision.
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Fig. 1. Artist's drawing demonstrating exposure of the brachial plexus through the deltopectoral groove. The musculocutaneous nerve branches from the lateral cord at approximately the level of the coracoid process and travels to the biceps. Three intercostal nerves have been transposed into the field through the axilla.

Fig. 2. Photographs in Case 1 demonstrating elbow flexion 18 months following an intercostal to musculocutaneous nerve anastomosis. In this patient, the proximal brachial plexus was explored prior to the anastomosis.

incision instead of an incision in the deltopectoral groove. This exposure was found to be confining and offered no real advantage over the standard anterior exposure.

In four patients who were operated on 2 years after their original injury, a free gracilis muscle was transplanted on its vascular bundle to the position of the biceps brachialis muscles and became the recipient of the intercostal nerves rather than the atrophied fibrotic biceps brachialis.

Results

Nine of the 20 patients (45%) obtained useful anti-gravity strength following surgery (Fig. 2). All of these patients regained an excellent range of elbow flexion. Two additional patients had some return of motor function but not enough to flex the elbow against gravity, and one patient was found to have voluntary motor units on postoperative electromyography (EMG), although this patient did not obtain useful elbow flexion. Two patients who did not obtain motor function noted that compression of the paralyzed biceps brachialis muscles resulted in paresthesias across their chest. Only two patients showed no signs of reinnervation, and significant fibrosis of their musculocutaneous nerve was noted in each case at the time of surgery. As a result of this experience, the procedure has been abandoned in patients found intraoperatively to have a fibrosed musculocutaneous nerve.

Patients destined to have a return of biceps brachialis function first noted approximately 6 to 8 months following the surgical anastomosis that elbow flexion occurred with coughing or laughing. As the reinnervation matured, patients reported voluntary elbow flexion independent of respiration. Surprisingly, coughing and deep respirations were never associated with more than slight arm movement. The patients who were able to contract their gracilis muscle grafts noted movement 4
months postoperatively. Patients who experienced return of elbow flexion could maintain elbow flexion while carrying out a conversation and could maintain constant elbow flexion through several respiratory cycles. Patients noted that the newly acquired function was helpful in carrying light objects and in providing a support against which objects could be steadied.

Three patients with good postoperative elbow flexion underwent EMG. With deep breathing, there was synkinetic activity of both the intercostal and biceps brachialis muscles. The interference pattern seen on EMG was more dense in the intercostal muscles than in the biceps brachialis muscles. When the patients attempted biceps brachialis contraction, prominent interference patterns developed in the biceps brachialis muscles but no intercostal motor unit activity was recorded.

No patient noted dysesthesias in the chest wall following intercostal nerve grafting. Two patients had chest tubes placed for the treatment of iatrogenic pneumothorax.

Discussion

Patients who have suffered a brachial plexus injury come to the physician for an attempt at restoration of lost limb function. Restoration of function remains a difficult problem. Although a prosthesis can be employed, very few patients who have undergone an amputation will consistently use an artificial limb. Prior to embarking on a reconstructive procedure, it is important to ascertain the probability that the patient will recover function spontaneously. Approximately two-thirds of patients with a stretch injury and a dysfunction confined to the C5-6 nerve roots will recover biceps brachialis function. The prognosis is more bleak for patients who initially have a completely flaccid extremity.

Three alternative surgical approaches are employed to restore function to an extremity paralyzed by a disrupted brachial plexus. If the brachial plexus is disrupted distal to the exit of the nerve root from the spinal canal, nerve grafting techniques are employed in an attempt to restore continuity. When the nerve roots have been avulsed directly from the spinal cord, this approach is not useful; instead, tendon transfers of the retained functioning muscles may be employed to increase the mobility of the affected extremity. Unfortunately, in many cases of brachial plexus injury, the muscles that could be transposed to replace the biceps have been compromised and are not strong enough to act as a successful elbow flexor once transposed. When muscle transposition is not possible, an attempt can be made to restore function by the third operative approach—nerve transposition. Tuttle was the first to report neurotization of the injured brachial plexus using intact elements of the cervical plexus. First reports of successful anastomosis using intercostal nerves were reported by Yeoman and Kotani. Functional neurotization of biceps brachialis muscles has been accomplished by using the spinal accessory nerve, other elements of the cervical plexus, or intercostal nerves. Solonen, et al., reported their results following the anastomosis of two to seven intercostal nerves to various elements of the brachial plexus. Three of nine patients with anastomosis to their biceps brachialis muscles regained useful elbow flexion and another two regained less than antigravity strength. No useful results were obtained when the intercostal nerves were anastomosed to the trunks or cords within the plexus; however, anastomosis to the distal nerves of the brachial plexus was successful. Simesen and Haase performed intercostal to musculocutaneous anastomosis in four patients, none of whom obtained useful elbow flexion. Sede reported that five of nine patients who underwent neurotization with intercostal nerves obtained antigravity elbow flexion. Narakas restored antigravity strength to the biceps brachialis in nine of 25 patients. He used a combination of intercostal, long thoracic, and spinal accessory nerves as donor nerves. Millesi reported that nine of his 22 nerve transfers resulted in useful function; however, he did not describe the exact anatomy of his anastomosis. Dolenc reported extremely good results following the anastomosis of individual intercostal nerves to multiple sites in the brachial plexus. The reason for his exceptional results could not be discerned from his report.

Allieu, et al., employed the accessory nerve for neurotization of the brachial plexus. In 15 cases, they used an interposition graft between the accessory nerve and the musculocutaneous nerve. Three patients achieved better than 3/5 strength and seven others obtained 3/5 strength in their reinervated biceps brachialis muscles. Like Solonen, et al., these authors also concluded that the best results were obtained when anastomoses were performed to the distal elements of the brachial plexus. Brunelli and Monini described a method for neurotization of the proximal musculature of the arm with elements of the anterior cervical plexus. All 13 patients who underwent neurotization of their biceps brachialis muscles by the spinal accessory nerve or by the nerve to the levator scapulae were reported to have postoperative elbow flexion. In the majority of patients, the elbow flexed 70° to 100°.

In our series, all reinnervation was accomplished using the third, fourth, and fifth intercostal nerves. Because of the disparity in size between the intercostal and the musculocutaneous nerves, three intercostal nerves were anastomosed to the musculocutaneous nerve.

Two patients were found to have fibrotic musculocutaneous nerves. Although it was hoped that there were enough intact myelin tubes to restore biceps brachialis muscle function, neither of these patients noted any postoperative function. At present, if the musculocutaneous nerve is found to be severely injured in the stretch injury, the procedure is modified and a gracilis muscle graft is performed. Free gracilis muscle grafts have been employed successfully to restore facial...
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A gracilis muscle graft can be used to supply a fresh muscle mass to replace a fibrotic muscle. Unlike fibrotic muscle, the transferred muscle will have motor endplates that are receptive to reinnervation. Two of four patients obtained good elbow flexion with this technique.

The optimal technique for neurotization with intercostal nerves is not settled. Some authors advocate amputating the intercostal nerve close to its origin and establishing the anastomosis with nerve grafts. This approach allows all motor axons in the intercostal nerve to be directed toward the target muscle. In an attempt to avoid the second anastomosis and to avoid the use of a long interposition graft, others have advocated dissecting out the intercostal nerve to allow a primary anastomosis. This is the technique employed in our patients. Its drawback is that fewer motor axons are present in the intercostal nerve at the midaxillary line than at its origin. Other surgeons have suggested dissecting the intercostal artery and vein in continuity with the intercostal nerve in order to maintain the nerve's vasculature supply. This technique was advocated by Tomita, et al., after demonstrating a high success rate of intercostal to musculocutaneous nerve anastomosis in dogs. There are not enough data in the literature to determine the advantage of these vascularized grafts. Certainly, the most interesting aspect of this series of patients is the patient's ability to flex the elbow without recruitment of the intercostal muscle. Our findings are different from those of Millesi, who reported that learned functions were difficult to accomplish via intercostal neurotization. Sunderland was also of the opinion that biceps brachialis muscle flexion is synchronous with respiration following neurotization of the musculocutaneous nerve with intercostal nerves.

The interchange of muscle innervation has been a subject of interest since the late 18th century. Cushing noted that as time passed a patient with an accessory to the median sensory distribution activated the cerebral cortex has some capacity for change has been demonstrated by others. This raises the possibility of synaptic modification within the cortex. At this time the mechanisms by which our patients learn to flex their elbows remain speculative.

In conclusion, it appears that neurotization of biceps brachialis muscles with intercostal nerves will result in functional elbow flexion in almost 50% of patients. The elbow flexion obtained by this operation occurs independent of respiration.

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