B RACHIAL plexus injuries are rare but catastrophic events that result in the partial or total loss of motor and sensory function in the upper extremity. These debilitating injuries involve young male patients 90% of the time,29,42 and up to 84% of the injuries are sustained in motorcycle accidents.10 The task of reconstructing the traumatized brachial plexus can be complex and daunting, yet the use of nerve transfers and an increased understanding of peripheral nerve biology has provided the field with a recent period of rapid evolution.

Reconstructive procedures for injuries involving the upper plexus are first directed toward the restoration of elbow flexion, followed by shoulder abduction and external rotation.25 Many surgical options have been offered to restore elbow flexion when primary nerve repair is not technically feasible: muscle and tendon transfers of the pectoralis major, latissimus dorsi, and triceps muscles, along with Steindler flexorplasty.8,18,19,30,47,48 However, nerve reconstruction is frequently a more attractive option because it allows for the maintenance of original musculotendinous dynamics6,16,31 and avoids the formation of restrictive scar tissue.44 Nerve grafting has been used to restore the continuity of interrupted nerves, but this technique has been limited by the long distances over which axons are required to regenerate and by the time-critical nature of motor endplate reinnervation.11,22,26,32,43,44

Nerve transfers have been used with increasing frequency and success for the reconstruction of brachial plexus and other proximal upper-extremity nerve injuries.26,44 In 1994 Oberlin et al.35 described the successful reestablishment of elbow flexion after transfer of an expendable ulnar nerve fascicle to the biceps branch of a nonfunctional MCN. A follow-up series showed that this technique resulted in MRC Grade M5, 15 patients recovered Grade M4, and 4 patients recovered Grade M3 elbow flexion strength. There was no evidence of functional deficit in the donor nerve distributions.

Conclusions. Study results demonstrated the reliable restoration of M4–M5 elbow flexion following double fascicular transfer in patients with brachial plexus injuries. (DOI: 10.3171/2011.1.JNS10810)

Abstract

Objective. The clinical outcomes of patients with brachial plexus injuries who underwent double fascicular transfer (DFT) using fascicles from the median and ulnar nerves to reinnervate the biceps and brachialis muscles were evaluated.

Methods. The authors conducted a retrospective chart review of 29 patients with brachial plexus injuries that were treated with DFT for restoration of elbow flexion. All patients underwent pre- and postoperative clinical evaluation using the Medical Research Council grading system.

Results. The mean patient age was 37 years (range 17–68 years), and there was a mean follow-up of 19 ± 12 months (range 5–68 months). At the most recent follow-up, all but 1 patient (97%) had regained elbow flexion. Eight patients recovered Grade M5, 15 patients recovered Grade M4, and 4 patients recovered Grade M3 elbow flexion strength. There was no evidence of functional deficit in the donor nerve distributions.

Conclusions. Study results demonstrated the reliable restoration of M4–M5 elbow flexion following double fascicular transfer in patients with brachial plexus injuries.
Double fascicular nerve transfer to the biceps and brachialis

son for the better results in these patients as compared with those who underwent biceps reinnervation alone. Therefore, we began to include reinnervation of the brachialis nerve, and in June 2001 we performed what is described here as the DFT to reinnervate the nerve to the biceps muscle and the nerve to the brachialis muscle with expendable motor fascicles from the median and ulnar nerves. Our initial experience with this procedure yielded Grade M4–4+ elbow flexion strength in all 6 patients, with a mean follow-up of 20.5 months. The purpose of the present case series is to describe the senior author’s (S.E.M.) continued experience with the DFT for elbow flexion in a larger and more diverse patient population.

Methods

After obtaining approval from our institution’s Human Studies Committee, a retrospective chart review was performed. Included patients had presented with a brachial plexus injury and between 2001 and 2009 had undergone a DFT in which redundant motor fascicles of the ulnar and median nerves were used to reinnervate the biceps and brachialis muscles.

Patient Population

Twenty-nine patients (22 men and 7 women) with a mean age of 37 ± 17 years (range 17–68 years) were included in this study. The dominant arm was injured in 20 of 29 patients. Brachial plexus injury involved the C-5 root in 1 patient, C5–6 roots in 16 patients, C5–7 roots in 8 patients, C6–7 roots in 1 patient, C4–7 roots in 1 patient, and the infraclavicular MCN in 2 patients. There was evidence of only partial injury to the most caudal root in 1 patient with C5–6 and 2 patients with C5–7 involvement. The most common mechanism of injury was motorcycle accident (7 patients), followed by motor vehicle collision (6 patients).

Surgery was performed at a mean of 4.9 ± 2 months after injury (range 0–11 months). Concomitant motor nerve transfers were performed in 18 cases, most often for restoration of shoulder function. The most common concomitant procedures were spinal accessory nerve to suprascapular nerve (11 patients), triceps nerve to axillary nerve (10 patients), and medial pectoral nerve to axillary nerve (10 patients).

Clinical Evaluation

All patients underwent preoperative clinical evaluation including detailed physical examination, pinch and grip strength testing, 2-point discrimination, electromyography, and nerve conduction studies. Postoperative evaluation included physical examination, pinch and grip strength testing, and other studies as indicated by the clinical context. Physical examination involving testing of bilateral upper-extremity musculature using the MRC grading system (Table 1). Demographics and other preoperative variables are detailed in Table 2.

Surgical Procedure

Reconstruction was undertaken if there was no clini-

<table>
<thead>
<tr>
<th>Observation</th>
<th>Muscle Grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>no contraction</td>
<td>M0</td>
</tr>
<tr>
<td>flicker or trace of contraction</td>
<td>M1</td>
</tr>
<tr>
<td>active movement, w/ gravity eliminated</td>
<td>M2</td>
</tr>
<tr>
<td>active movement against gravity</td>
<td>M3</td>
</tr>
<tr>
<td>active movement against gravity &amp; resistance</td>
<td>M4</td>
</tr>
<tr>
<td>normal power</td>
<td>M5</td>
</tr>
</tbody>
</table>

| TABLE 1: Medical Research Council Grading System |
### TABLE 2: Summary of patient variables, operative procedures, and results*

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Date of Surgery</th>
<th>Age, Sex</th>
<th>Mechanism of Injury</th>
<th>Extent of Injury</th>
<th>Time to Surgery (mos)</th>
<th>DFT Procedure</th>
<th>Concomitant Motor Nerve Transfers &amp; Grafts</th>
<th>MRC Grade</th>
<th>Postop FU (mos)</th>
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<tbody>
<tr>
<td>1</td>
<td>6/20/2001</td>
<td>19, M</td>
<td>pedestrian hit by car</td>
<td>C5–6</td>
<td>5</td>
<td>median to biceps, ulnar to biceps</td>
<td>SAN to SSN, MPN to AXN</td>
<td>M5</td>
<td>25</td>
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<tr>
<td>2</td>
<td>3/11/2003</td>
<td>47, M</td>
<td>boating accident</td>
<td>C5–6</td>
<td>7</td>
<td>median to biceps, ulnar to biceps</td>
<td>SAN to SSN, MPN to AXN</td>
<td>M3</td>
<td>18</td>
</tr>
<tr>
<td>3</td>
<td>8/15/2003</td>
<td>17, M</td>
<td>ATV accident</td>
<td>infraclavicular</td>
<td>5</td>
<td>median to biceps, ulnar to biceps</td>
<td>none</td>
<td>M5</td>
<td>25</td>
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<td>59, F</td>
<td>radiation induced</td>
<td>C5–6</td>
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<td>M4</td>
<td>24</td>
</tr>
<tr>
<td>5</td>
<td>11/4/2003</td>
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<td>motorcycle</td>
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<td>median to biceps, ulnar to biceps</td>
<td>SAN to SSN (w/ graft), TCN to AXN</td>
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<td>68</td>
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<td>MPNST resection</td>
<td>infraclavicular</td>
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<td>M4</td>
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<td>1/30/2004</td>
<td>53, F</td>
<td>MVC</td>
<td>C5–6 &amp; partial C-7</td>
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<td>median to biceps, ulnar to biceps</td>
<td>none</td>
<td>M4</td>
<td>32</td>
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<td>8/5/2005</td>
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<td>MVC</td>
<td>C5–6</td>
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<td>SAN to SSN (w/ graft), TCN to AXN</td>
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<td>C5–6</td>
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<td>MPN &amp; TDN to AXN, LTN to SSN</td>
<td>M4</td>
<td>17</td>
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<td>17, M</td>
<td>MVC</td>
<td>C5–6</td>
<td>4</td>
<td>median to biceps, ulnar to biceps</td>
<td>MPN to SSN, TCN to AXN</td>
<td>M4</td>
<td>16</td>
</tr>
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<td>12/30/2005</td>
<td>18, M</td>
<td>motorcycle</td>
<td>C5–6</td>
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<td>median to biceps, ulnar to biceps</td>
<td>MPN to SSN, TCN &amp; MPN to AXN</td>
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<td>12</td>
<td>2/13/2006</td>
<td>37, M</td>
<td>pipe fell onto neck</td>
<td>C5–6</td>
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<td>SAN to SSN, TCN to AXN</td>
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<td>32</td>
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<tr>
<td>13</td>
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<td>30, M</td>
<td>motorcycle</td>
<td>C5–6</td>
<td>9</td>
<td>median to biceps, ulnar to biceps</td>
<td>SAN to SSN, TCN to AXN</td>
<td>M4</td>
<td>12</td>
</tr>
<tr>
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<td>3/13/2006</td>
<td>36, M</td>
<td>MVC</td>
<td>C5–6</td>
<td>5</td>
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<td>SAN to SSN, TCN to AXN</td>
<td>M5</td>
<td>11</td>
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<tr>
<td>15</td>
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<td>26, F</td>
<td>motorcycle</td>
<td>C5–7</td>
<td>3</td>
<td>median to biceps, ulnar to biceps</td>
<td>SAN to SSN, FDS to RN, MPN to AXN</td>
<td>M5</td>
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<tr>
<td>16</td>
<td>11/21/2006</td>
<td>51, M</td>
<td>pedestrian hit by car</td>
<td>C5–7</td>
<td>6</td>
<td>median to biceps, ulnar to biceps</td>
<td>MPN &amp; TCN to AXN (w/ graft)</td>
<td>M4</td>
<td>8</td>
</tr>
<tr>
<td>17</td>
<td>6/18/2007</td>
<td>21, M</td>
<td>motorcycle</td>
<td>C5–7</td>
<td>3</td>
<td>median to biceps, ulnar to biceps</td>
<td>MPN to AXN</td>
<td>M4</td>
<td>23</td>
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<tr>
<td>18</td>
<td>8/13/2007</td>
<td>26, M</td>
<td>skiing</td>
<td>C5–7</td>
<td>5</td>
<td>median to biceps, ulnar to biceps</td>
<td>SAN to SSN, MPN to AXN (w/ graft), RAN &amp; ICN to TCN (w/ graft)</td>
<td>M5</td>
<td>26</td>
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<td>19</td>
<td>11/6/2007</td>
<td>36, M</td>
<td>MVC</td>
<td>C6–7</td>
<td>3</td>
<td>median to biceps w/ nerve graft, ulnar to biceps</td>
<td>none</td>
<td>M5</td>
<td>18</td>
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<tr>
<td>20</td>
<td>11/20/2007</td>
<td>21, M</td>
<td>football</td>
<td>C5–6</td>
<td>4</td>
<td>median to biceps, ulnar to biceps</td>
<td>SAN to SSN, TCN to AXN</td>
<td>M5</td>
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<td>12/26/2007</td>
<td>22, M</td>
<td>fall</td>
<td>C5–6</td>
<td>3</td>
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<td>TDN to SSN, MPN to AXN</td>
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<td>8</td>
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<tr>
<td>22</td>
<td>1/21/2008</td>
<td>63, M</td>
<td>cervical vertebral radiculopathy</td>
<td>C5–6</td>
<td>11</td>
<td>median to biceps, ulnar to biceps</td>
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<td>M0 after DFT, M4 after Steindler</td>
<td>25</td>
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<tr>
<td>23</td>
<td>4/2/2008</td>
<td>51, M</td>
<td>lifting</td>
<td>C5–6</td>
<td>chronic onset</td>
<td>median to biceps, ulnar to biceps</td>
<td>TCN to AXN</td>
<td>M1</td>
<td>12</td>
</tr>
</tbody>
</table>

(continued)
Double fascicular nerve transfer to the biceps and brachialis

**Postoperative Management**

Postoperatively all patients are placed in a shoulder immobilizer for 2–3 days. The initial wound dressing, bupivacaine pump, and drain are removed 2–3 days after surgery. The immobilizer is discontinued at the first postoperative visit and exchanged for a sling, which remains for 10 days. In 11 patients who underwent concomitant medial pedicular to axillary or subscapular nerve transfer via an anterior approach, immobilization was extended to 4 weeks to allow reattachment of the pectoralis major muscle.

After 2 weeks, patients are referred to a physical therapist familiar with the surgical procedure and are instructed in upper extremity range of motion exercises. Patients are educated regarding postoperative motor reeducation before there is evidence of muscle reinnervation. To allow biceps and brachialis muscle contraction, patients are initially instructed to contract the muscles previously innervated by the donor nerves. This action is facilitated by having the patient perform grip-strengthening exercises activating the FCU, FCR, and FDS muscles. Place-and-hold exercises in varying degrees of elbow flexion are used to isometrically strengthen the biceps and brachialis muscles. As strength is regained, progressive resistance exercises are added and elbow flexion is isolated from donor muscle activation. Initially elbow and finger flexion occur together, and as the elbow flexors strengthen, patients are taught to flex at the elbow with the fingers extended.

**Results**

Clinical evidence of elbow flexor reinnervation was first noted at a median of 5.4 months (mean 6.4 ± 4 months, range 3–18 months) after surgery in all but 1 patient, who achieved no reinnervation. The mean follow-up for this patient group was 19 ± 12 months (range 8–68 months).

At the most recent follow-up, all but 2 patients had at least 9 months of follow-up. At the most recent follow-up, all but 2 patients had at least 9 months of follow-up. Of note, there is more excursion of the ulnar nerve near the elbow, and if the ulnar nerve is transferred to the brachialis branch, the proposed transfer (Figs. 1 and 2).

**TABLE 2: Summary of patient variables, operative procedures, and results (continued)**

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Date of Surgery</th>
<th>Age (yrs), Sex</th>
<th>Mechanism of Injury</th>
<th>Extent of Injury</th>
<th>Time to Surgery (mos)</th>
<th>DFT Procedure</th>
<th>Concomitant Motor Nerve Transfers &amp; Grafts</th>
<th>MRC Grade Postop</th>
<th>FU (mos)</th>
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<tr>
<td>24</td>
<td>7/23/2008</td>
<td>58, F</td>
<td>MVC</td>
<td>C5–7</td>
<td>6</td>
<td>median to brachialis, ulnar to biceps</td>
<td>none</td>
<td>M4</td>
<td>12</td>
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<tr>
<td>25</td>
<td>10/28/2008</td>
<td>38, M</td>
<td>neck laceration</td>
<td>C-5</td>
<td>3</td>
<td>median to brachialis, ulnar to biceps</td>
<td>none</td>
<td>M4</td>
<td>8</td>
</tr>
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<td>26</td>
<td>11/14/2008</td>
<td>26, M</td>
<td>motorcycle</td>
<td>C-5 &amp; partial C-6</td>
<td>6</td>
<td>median to brachialis, ulnar to biceps</td>
<td>SAN to SSN, MPN to AXN</td>
<td>M4</td>
<td>17</td>
</tr>
<tr>
<td>27</td>
<td>11/18/2008</td>
<td>67, M</td>
<td>idiopathic polyneuropathy</td>
<td>C5–6 &amp; partial C-7</td>
<td>chronic onset</td>
<td>median to brachialis, ulnar to biceps</td>
<td>none</td>
<td>M3</td>
<td>17</td>
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<td>28</td>
<td>2/9/2009</td>
<td>48, M</td>
<td>motorcycle</td>
<td>C4–7</td>
<td>9</td>
<td>median to brachialis, ulnar to biceps</td>
<td>none</td>
<td>M4</td>
<td>15</td>
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<tr>
<td>29</td>
<td>8/11/2009</td>
<td>55, M</td>
<td>bicycle</td>
<td>C5–7</td>
<td>4</td>
<td>median to brachialis, ulnar to biceps</td>
<td>none</td>
<td>M4</td>
<td>8</td>
</tr>
</tbody>
</table>

* All patients except one had complete MCN palsy before surgery; the patient in Case 25 had palsy associated with the brachialis branch and 1 of 2 biceps branches. Abbreviations: ATV = all-terrain vehicle; AXN = axillary nerve; FU = follow-up; ICN = intercostal nerve; LTN = long thoracic nerve; MPN = medial pectoral nerve; MPNST = malignant peripheral nerve sheath tumor; MVC = motor vehicle collision; PNET = primitive neuroectodermal tumor; RAN = rectus abdominus nerve; RN = radial nerve; SAN = spinal accessory nerve; SSN = suprascapular nerve; TCN = triceps nerve; TDN = thoracodorsal nerve.

FDs muscle is selected and isolated. Median and ulnar nerve fascicles found to mediate forearm pronation, intrinsic hand muscle activation, and flexion via the flexor digitorum profundus muscle are carefully avoided. In 15 cases, a median nerve fascicle was transferred to the brachialis branch, and an ulnar nerve fascicle was transferred to the biceps branch. In the other 14 cases, the opposite donor/recipient pairing was selected. Either transfer suffices, and we make a judgment based on which will yield the shortest cumulative distance to motor endplate targets. Of note, there is more excursion of the ulnar nerve near the elbow, and if the ulnar nerve is transferred to the brachialis branch this must be taken into account while planning the neurolysis. Prior to selecting the median or ulnar nerve donor fascicles, we place the recipient nerves adjacent to the potential donor nerve, mark the proposed area of neurolysis just distal to the recipient, and move the arm through the full range of motion to ensure that there will be no tension on the proposed transfer (Figs. 1 and 2).

The fascicle used for transfer generally represents 15% of the entire nerve. Sufficient residual median and ulnar nerve motor function is verified via stimulation of the remaining nerve. Selected donor fascicles are mobilized between 1 and 2 cm as permitted and then divided as distally as necessary to allow tensionless transfer to the recipient branch. In a single case, scar tissue around the proximal MCN necessitated the use of a 4-cm LABCN nerve graft from the median nerve fascicle to the biceps branch. The paired donor and recipient branches are directly coapted in an end-to-end fashion with 9-0 nylon suture and standard microsurgical technique.
least MRC Grade M3 elbow flexion strength (Fig. 3 and Video 2).

**Video 2.** One-year follow-up demonstrating excellent reinnervation of bicep and brachialis muscles. Click here to view with Windows Media Player. Click here to view with Quicktime.

Eight patients had normal Grade M5 strength, 15 had Grade M4 strength, 4 had Grade M3 strength, and 1

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**Fig. 1.** Photograph showing direct end-to-end transfer of an expendable motor fascicle of the median nerve to the biceps branch and an expendable FCU fascicle of the ulnar nerve to the brachialis branch. **Inset** features the longer view, with a gray box indicating the orientation of the magnified view.

**Fig. 2.** Schematic of the DFT shown photographically in Fig. 1.
had Grade M1 elbow flexion strength (Table 2). A single patient had no reinnervation of the elbow flexors at 29 months postoperatively and thus subsequently underwent a Steindler flexorplasty, which restored Grade M4 elbow flexion strength.

Preoperative and postoperative pinch and grip strengths were available in 23 of 29 patients. The maximum postoperative pinch (mean 15 ± 7 lb) and grip (mean 48 ± 27 lb) strengths were superior to preoperative pinch (mean 10 ± 6 lb) and grip (mean 28 ± 25 lb) strengths. Both of these differences were significant at the p < 0.01 level. There was no evidence of sensory nerve palsy in any patient during the early or late postoperative period.

Discussion

Brachial plexus injuries occur following 0.67%–1.3% of motor vehicle collisions and 4.2% of motorcycle accidents. Reconstructive procedures for injuries involving the upper plexus are first directed toward restoration of elbow flexion, followed by shoulder abduction and external rotation. When primary nerve repair is not possible, traditional options for the restoration of elbow function have included a myriad of muscle and tendon transfers. While these procedures have met with some success, they are limited by donor site morbidity and extensive dissection and scarring in the muscle bed.

The use of nerve grafts involves less dissection and avoids scarring in the muscle bed; however, grafting of proximal injuries requires axonal regeneration over long distances. Nerve grafts can result in a failure to provide regenerating axons to the denervated motor endplate within the critical window of 1 year after injury, leading to suboptimal functional recovery.

The central principle of nerve transfers is the conversion of a high nerve injury to a low injury that is closer to the target end organ. Nerve transfers allow prompt reinnervation of the motor endplate before the onset of severe degeneration and fibrosis. Additional benefits of motor nerve transfers include shorter operative times, the exclusion of the sensory environment, and the utilization of expendable donor fascicles that cause no functional deficit in the donor nerve distribution. Increased experience with nerve transfer procedures has markedly improved the functional outcomes obtained in comparison with traditional graft and repair techniques.

Many nerve transfer procedures have been proposed for the restoration of MCN function after upper brachial plexus injury. In 1993 Brandt and Mackinnon described a series of 4 patients who underwent MPN to MCN transfer. Three of these patients obtained Grade M4 elbow flexion, and 1 recovered Grade M3 strength. A larger series by Samardzic et al. in 10 patients who underwent MPN to MCN transfer in 2002 showed that 2 patients recovered excellent (M4+) function, 4 recovered good (M4) function, 3 recovered fair (M3) function, and 1 recovered no (M0) elbow flexion. An additional 4 patients included in this series underwent MPN to MCN transfer augmented by spinal accessory or intercostal nerve transfer. Two of these patients recovered excellent (M4+) function, 1 recovered good (M4) function, and 1 recovered no (M0) elbow flexion.

The TDN is another potential donor of motor axons for which significant clinical outcomes data have been collected. In 2002 we described a series of 6 patients who underwent TDN to MCN transfer for restoration of elbow flexion. One patient recovered M5, 4 recovered M4, and 1 recovered M2 elbow flexion strength. Another series by Samardzic et al. showed that among 8 patients who underwent TDN to MCN transfer, 2 recovered excellent (M4+) strength, 5 recovered good (M4) strength, and 1 recovered fair (M3) strength of the elbow flexors. An additional 4 patients in this study underwent TDN to MCN transfer augmented by axons from the intercostal, subscapular, or long thoracic nerve. One of these patients had an excellent (M4+) result, and the remaining 3 had good (M4) results.

Because it offered an easily accessible donor to the biceps muscle, the transfer of an expendable FCU fascicle to the biceps nerve represented a significant step forward in the evolution of nerve transfers for upper brachial plexus injuries. By reinnervating the biceps, the expendable ulnar fascicular transfer restored Grade M3 or M4 strength in 24 of 32 patients. However, 10 of these patients required secondary Steindler flexorplasty to achieve satisfactory elbow flexion strength. Our group recognized that the brachialis muscle is a stronger flexor of the elbow than the biceps, and in 1997 we modified the Oberlin procedure to reinnervate the biceps rather than the brachialis. We then described a series of 8 patients who underwent concomitant reinnervation of the biceps and brachialis utilizing the ulnar nerve and either the TDN or the MPN as donors. All patients regained Grade M4–4+ muscle strength without the need for additional procedures. Although the advantage of reinnervating the brachialis in addition to the biceps was made clear,
the MPN and TDN were believed to be sub-ideal donors to the median nerve, as the former requires takedown of the medial pectoral muscles and the latter is often useful for muscle transfer in shoulder reconstruction.\(^1\) We will, however, use these donors when a DFT is not feasible.

The transfer of expendable fascicles of the median nerve to the biceps muscle has been described,\(^3,5,20,40\) and we recognized that this donor could be used in concert with the expendable ulnar nerve fascicle to reinnervate both the biceps and brachialis muscles. In June 2001, we first performed the DFT to reinnervate both the biceps and brachialis muscles using expendable motor fascicles from the median and ulnar nerves.\(^27\) In 2003 we presented the procedure at the annual meeting of the American Society for Surgery of the Hand and coined the term “double fascicular transfer.” In 2005 we reported our preliminary results in a series of 6 patients followed up for a mean period of 20.5 months.\(^27\) At the final evaluation, all patients had recovered Grade M4–4+ elbow flexion strength. Several other groups have documented their experiences with the DFT.\(^2\) In a study by Livernaux et al.,\(^23\) published in 2006, Grade M4 elbow flexion strength was restored in 10 of 10 patients at a mean follow-up of 15 months. In 2007 Goubier et al.\(^15\) documented the restoration of M4 elbow flexion strength to all 5 patients in their study at a mean follow-up of 14 months. In all of these studies, there was no evidence of postoperative hand weakness, and no secondary procedures for elbow flexion were indicated in any patient.

In the present study, we documented the clinical outcomes following DFT in a larger and more diverse group than previously described. We were able to achieve Grade M4 or M5 strength in 23 (79%) of 29 patients. Excellent clinical outcomes were obtained in the setting of both limited and extensive brachial plexus injuries, regardless of concomitant procedures.

There was no evidence of donor nerve morbidity, as demonstrated by the significant increase in pinch and grip strength and the absence of subjective sensory deficits. This outcome is in keeping with the findings of other authors\(^15,23\) and underscores the importance of understanding and intraoperatively defining the internal topography of the donor nerves during fascicular selection.

In only a single patient did reinnervation fail across nerve transfers after 29 months, necessitating a subsequent Steindler flexorplasty, which restored M4 elbow flexion strength. Although we do not know the cause of this poor outcome, it is notable that it occurred in the only patient without a known cause of brachial plexus dysfunction. Given his provisional diagnosis of idiopathic polyneuropathy, it is possible that this patient continued to undergo occult nerve injury even after undergoing DFT. Interestingly, this same patient experienced temporary median nerve palsy as a complication of the secondary Steindler flexorplasty. It is possible that the prior DFT predisposed the median nerve to retraction injury by tethering it proximally, and this potential complication should be considered in planning future secondary procedures.

There was a significant correlation between a short time to surgery and a favorable surgical outcome (\(r = -0.57\)); all 8 patients who recovered M5 elbow flexion underwent surgery within 5 months of injury. This result supports the current belief that the prompt delivery of regenerating axons to the denervated motor endplate is a critical factor in achieving ideal clinical outcomes.\(^9,14,24,38,44,46\) Despite this relationship, we were able to achieve M4 elbow flexion strength in patients who underwent surgery up to 9 months from injury, indicating that such a delay should not be considered a contraindication to DFT.

Other authors have suggested that the DFT procedure should be conducted specifically by transferring an expendable fascicle from the ulnar nerve to the biceps branch and from the median nerve to the brachialis branch of the MN.\(^5,27\) In contrast, in the present series we noted excellent clinical outcomes regardless of the donor-recipient pairing. Based on this finding, we will continue to choose our donor-recipient pairings on a case-by-case basis, as guided by the individual patient’s surgical anatomy.

The initial concern for most surgeons doing a DFT for the first time will be worry about downgrading important motor or sensory function of the ulnar or median nerve. This same concern was certainly ours initially, but we have not seen any sensory or motor downgrading of neurological function with these procedures. We have found that the redundant or expendable component of the ulnar nerve is located on its lateral superior surface. After neurolysis of this fascicle, we stimulate the remaining portion of the nerve to ensure that intrinsic function of the flexor digitorum profundus muscle and ulnar nerve remain intact. Additionally, we have recently completed a number of cadaveric studies that have helped to detail the internal topography of the median nerve. The redundant median nerve motor component is located in the superior medial portion of the nerve, while the inferior medial portion consists of fibers to the anterior interosseous nerve. The sensory component of the median nerve is located in its lateral half, and a fascicular group to the pronator teres muscle is in a superior central position. After selecting a donor fascicle from the medial superior region, the remaining nerve is stimulated to confirm the preservation of anterior interosseous nerve, pronator teres muscle, and median intrinsic hand function.

Despite the evidence that median nerve transfer can be done without functional downgrade, some surgeons continue to advocate a single nerve transfer technique of lone ulnar fascicular transfer to the biceps or brachialis muscle.\(^1\) The argument for this approach is that preservation of native innervation to one of the elbow flexors allows the possibility of late spontaneous neurological recovery. Certainly if the biceps or brachialis muscle demonstrated motor unit potentials on electromyography, we would anticipate recovery from a second- or third-degree nerve injury. If, however, there are no motor unit potentials in the biceps or brachialis muscle at 3 months, we are reasonably confident that fourth-degree injury has occurred and recovery will not be forthcoming. While we recognize the uncommon case of spontaneous recovery after 3 months, we believe that the benefit of providing a superior surgical intervention in the ideal time frame outweighs the risk of aborting the unlikely possibility of late spontaneous recovery.
Double fascicular nerve transfer to the biceps and brachialis

Conclusions

The DFT is a reliable intervention for the restoration of elbow flexion after upper brachial plexus injury. Favorable results were obtained in a population of patients that was diverse in terms of age, extent of injury, and mechanism of injury. There was no evidence of functional deficit in the distributions of the donor nerves. Outcomes in the featured cases were slightly better than those found in previous series in that the restoration of Grade M5 elbow flexion has not previously been reported. Excellent outcomes were associated with a shorter interval between injury and surgical intervention.

Disclosure

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified. Author contributions to the study and manuscript preparation include the following. Conception and design: Ray. Acquisition of data: Pet. Analysis and interpretation of data: Pet, Yee. Drafting the article: Ray, Pet. Critically revising the article: Mackinnon, Ray, Yee. Reviewed final version of the manuscript and approved it for submission: all authors. Video and image generation: Yee.

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