UPPER LIMB

Use of quantitative intra-operative electrodiagnosis during partial ulnar nerve transfer to restore elbow flexion

THE TREATMENT OF EIGHT PATIENTS FOLLOWING A BRACHIAL PLEXUS INJURY

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The transfer of part of the ulnar nerve to the musculocutaneous nerve, first described by Oberlin, can restore flexion of the elbow following brachial plexus injury. In this study we evaluated the additional benefits and effectiveness of quantitative electrodiagnosis to select a donor fascicle. Eight patients who had undergone transfer of a simple fascicle of the ulnar nerve to the motor branch of the musculocutaneous nerve were evaluated. In two early patients electrodiagnosis had not been used. In the remaining six patients, however, all fascicles of the ulnar nerve were separated and electrodiagnosis was performed after stimulation with a commercially available electromyographic system. In these procedures, recording electrodes were placed in flexor carpi ulnaris and the first dorsal interosseous. A single fascicle in the flexor carpi ulnaris in which a high amplitude had been recorded was selected as a donor and transferred to the musculocutaneous nerve. In the two patients who had not undergone electrodiagnosis, the recovery of biceps proved insufficient for normal use. Conversely, in the six patients in whom quantitative electrodiagnosis was used, elbow flexion recovered to an M4 level.

Quantitative intra-operative electrodiagnosis is an effective method of selecting a favourable donor fascicle during the Oberlin procedure. Moreover, fascicles showing a high-amplitude in reading flexor carpi ulnaris are donor nerves that can restore normal elbow flexion without intrinsic loss.

The transfer of part of the ulnar nerve to the musculocutaneous nerve, first described by Oberlin et al., is beneficial for early restoration of elbow flexion following brachial plexus injury. It is now the most advanced and widely used procedure to reinnervate biceps in patients who suffered an upper root injury. However, one of the most critical influences on functional outcome is the number of motor neurons in the donor fascicle. We have developed a new method to evaluate the number of the motor neurons in a fascicle of the ulnar nerve following electrical stimulation with a commercially available electromyographic system. In this study, we examined whether quantitative intra-operative electrodiagnosis to select a suitable donor fascicle for an Oberlin procedure results in better restoration of elbow function.

Patients and Methods

Eight patients with a brachial plexus injury were included (Table I). The mean age at operation was 31 years (18 to 52). All presented with an injury of the upper roots; a C5, C6 injury in three cases and a C5, C6, C7 injury in five. Cervical myelography and electrodiagnostic studies were undertaken pre-operatively in all patients. Reconstruction was performed if there was no clinical or electrical evidence of biceps function. As part of the operation, all patients underwent exploration of the brachial plexus to record the spinal cord evoked potential. When none was evident despite stimulation of the root, or the root was absent in the normal position, a diagnosis of injury was made. The mean time between the injury and the nerve transfer was six months (five to nine). All patients underwent transfer of a single fascicle of the ulnar nerve to the motor branch of the biceps. We only used a single fascicle because removal of two can jeopardise ulnar nerve function.

In patients 1 and 2, quantitative electrodiagnosis was not carried out during the nerve transfer. For patient 1, the donor fascicle was selected by the method originally described by
Oberlin et al., and for patient 2 nerve stimulation was performed using a neurostimulator. Conversely, during the nerve transfer in patients 3 to 8, the fascicles of the ulnar nerve were separated for about 25 mm at the medial aspect of the upper arm, with the aid of an operating microscope (Fig. 1a) to protect the integrity of the axons in different bundles. The number of separated fascicles of the ulnar nerve ranged from five to seven (Table I). Subsequently electrodiagnosis was performed using a commercially available electromyographic (EMG) system (Viking IV; Nicolet Biomedical, Madison, Wisconsin). Bipolar forceps-shaped stimulating electrodes were used to discharge a current for 0.2 ms. This was adjustable, and the supramaximal intensity was used for the stimulation. Accordingly, a 0.6 mA current was used in one patient, 1.2 mA in three and 2.4 mA in the other two. Bipolar needle recording electrodes were placed in the flexor carpi ulnaris muscle (FCU, Fig. 1b) and the first dorsal interosseous muscle (FDI, Fig. 1c). The former represents the extrinsic muscle and the latter acts as an intrinsic muscle. An earthing electrode was set on a wristband. Only a single stimulation was performed, and compound muscle action potentials (CMAP) in the FCU and FDI were recorded. Both the simulations and the recordings were carried out using the Viking IV system.

Evoked potential patterns observed by the electrodiagnosis were classified into three types. In type A, the FCU showed a high amplitude and the FDI a moderate amplitude (Fig. 2a). In type B, both the FCU and the FDI had a moderate amplitude (Fig. 2b), although in some cases that of the FDI was slightly higher than that of the FCU. In type C the amplitude was low in both the FCU and the FDI.

### Table I. Patient profiles and recovery of biceps contraction

<table>
<thead>
<tr>
<th>Patient</th>
<th>Age (yrs)</th>
<th>Gender</th>
<th>Injured roots</th>
<th>Time from injury to surgery (mths)</th>
<th>Electro-diagnosis</th>
<th>Number of fascicles</th>
<th>Type of CMAP</th>
<th>First reaction on EMG† after surgery (mths)</th>
<th>Power of elbow flexion by MRC‡ grade after surgery (mths)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>33</td>
<td>Male</td>
<td>Right C5C6</td>
<td>6</td>
<td>No</td>
<td>Only 1 divided</td>
<td>A</td>
<td>M1 (14)</td>
<td>M1 (18)</td>
</tr>
<tr>
<td>2</td>
<td>52</td>
<td>Female</td>
<td>Right C5C6C7</td>
<td>5</td>
<td>Stimula-</td>
<td>5</td>
<td>B</td>
<td>M2 (11)</td>
<td>M3 (18)</td>
</tr>
<tr>
<td>3</td>
<td>30</td>
<td>Male</td>
<td>Left C5C6C7</td>
<td>9</td>
<td>Yes</td>
<td>7</td>
<td>A</td>
<td>M3 (9)</td>
<td>M4 (14)</td>
</tr>
<tr>
<td>4</td>
<td>31</td>
<td>Male</td>
<td>Right C5C6C7</td>
<td>5</td>
<td>Yes</td>
<td>5</td>
<td>C</td>
<td>M3 (7)</td>
<td>M4 (8)</td>
</tr>
<tr>
<td>5</td>
<td>18</td>
<td>Male</td>
<td>Left C5C6C7</td>
<td>5</td>
<td>Yes</td>
<td>6</td>
<td>B</td>
<td>M3 (5)</td>
<td>M4 (6)</td>
</tr>
<tr>
<td>6</td>
<td>22</td>
<td>Male</td>
<td>Right C5C6</td>
<td>6</td>
<td>Yes</td>
<td>5</td>
<td>B</td>
<td>M3 (4)</td>
<td>M4 (7)</td>
</tr>
<tr>
<td>7</td>
<td>23</td>
<td>Male</td>
<td>Left C5C6C7</td>
<td>7</td>
<td>Yes</td>
<td>7</td>
<td>C</td>
<td>M3 (2)</td>
<td>M4 (4)</td>
</tr>
<tr>
<td>8</td>
<td>23</td>
<td>Male</td>
<td>Right C5C6</td>
<td>5</td>
<td>Yes</td>
<td>6</td>
<td>B</td>
<td>M3 (3)</td>
<td>M4 (5)</td>
</tr>
</tbody>
</table>

* CMAP, compound muscle action potential
† EMG, electromyography
‡ MRC, Medical Research Council

Intra-operative photographs of quantitative electrodiagnostic examination to select the most appropriate donor fascicle during a partial ulnar nerve transfer showing a) all fascicles of the ulnar nerve separated under an operating microscope and stimulated by an electrode discharging a 1.2 mA current (in patient 3 seven fascicles were identified), b) a recording electrode placed into the flexor carpi ulnaris muscle (arrow) with an earthing electrode set on a wristband and c) a recording electrode placed into the first dorsal interosseous muscle (arrow).
A single fascicle from the former in which a high amplitude had been recorded (Fig. 2a) and classified as type A, was then selected as the donor nerve and transferred to the motor branch of the musculocutaneous nerve. We wished to identify fascicles containing numerous motor neurons that would facilitate strong muscle contraction. We would then use those neurons principally to innervate the extrinsic muscles to prevent intrinsic loss and reduce co-contraction of the biceps with the intrinsics. Post-operative EMG examinations for the biceps were continued until the first action potential could be recorded (Table I). The strength of flexion of the elbow was recorded after surgery using the Medical Research Council (MRC) grading system. Ulnar nerve donor site morbidity was assessed by measuring grip strength, sensation using a Semmes-Weinstein monofilament test at the tip of the little finger, and lateral pinch strength between the thumb and the index finger. The problem of co-contraction of the biceps with muscles innervated by the ulnar nerve in the forearm and hand, and continuous neuropathic pain after internal neurolysis, were also investigated.

Results
Post-operatively, all eight patients were capable of biceps contraction and had an action potential in biceps (Table I). However, the power of elbow flexion differed among the patients, with or without electrodiagnosis. In patient 1, elbow flexion recovery was poor, with an MRC grade of M1. In patient 2, the biceps power eventually improved to M3, but this is insufficient for normal use. Conversely, in patients 3 to 8 the power of the flexion of the elbow recovered well, to a grade of M4 (Table I). The mean time for these six patients to obtain M4 flexion was seven months (4 to 14). Four of these patients later underwent a shoulder joint stabilising procedure involving multiple muscle transfers, and were very satisfied with the improved function of the affected limb. The remaining two patients are undergoing post-operative rehabilitation.

Three types of evoked potential pattern were observed. Two of seven fascicles presented as type A (Fig. 2a) in patient 3, who was the first to undergo quantitative examination. This type of CMAP was observed in one to two fascicles (mean 1.5; Table I). Three of seven fascicles were type B (Fig. 2b) in patient 3, and two to four fascicles (mean 2.8) were type B (Table I). Two of seven fascicles were type C (Fig. 2c) in patient 3 and one to two fascicles (mean 1.3) were type C (Table I). Strong flexion of the elbow was achieved when type A fascicles were selected as donors.

The grasping power increased from a mean of 13.4 kg (3 to 29) pre-operatively to 16.5 kg (7 to 24) post-operatively for all patients (Table II). Although the post-operative grip strength improved over the pre-operative levels in six cases, patients 6 and 8 showed a 70% to 80% decrease. Sensory morbidity, measured by the Semmes-Weinstein test at the tip of the little finger, was not observed in five patients (Table II). Although touch sense was reduced in three patients during the early post-operative period, it gradually improved thereafter (Table II). No patient had impaired pinch strength between the thumb and little finger (Table II), which increased from a mean of 2.4 kg (0.6 to 4.4) pre-operatively to 3.2 kg (0.6 to 6.5) post-operatively. No patient had co-contraction of the biceps with muscles innervated by the ulnar nerve in the forearm and hand. All patients achieved finger movement and wrist independent of elbow flexion, and none had post-operative neuropathic pain. Consequently, none complained of impairment in the daily use of the affected limb except for one patient who had the most severe sensory deficit (Table II).

Discussion
Intercostal nerves have previously been the most commonly used donor nerves for reconstruction of the brachial plexus. Seddon first reported their use with an interposition nerve graft to reinnervate the musculocutaneous nerve. Others subsequently used direct neurotisation without a nerve graft, which allows better recovery of...
biceps. Oberlin et al., however, proposed the use of part of the ulnar nerve for such procedures, and this has given satisfactory results over the past ten years. Reinnervation of the recipient nerve with a donor nerve that is close to the motor endplate provides a shorter reinnervation time, and as the ulnar nerve is the closest to the biceps branch of the musculocutaneous nerve, the Oberlin procedure is commonly used to reinnervate biceps in patients with an upper root injury. However, post-operative elbow flexion is not always guaranteed after this procedure. Several factors may influence the outcome, such as the patient’s age, the time between injury and nerve transfer, the number of active motor neurons in the donor fascicle, and the condition of the donor nerve. Indeed, all our patients who underwent quantitative intra-operative electrophysiological examinations achieved strong flexion of the elbow. We therefore believe that electrophysiological examination can greatly improve the success rate of the Oberlin procedure because the condition of the donor fascicle at operation will be clarified by this examination.

Three types of evoked potential were observed during our quantitative examinations. In the first, the type A fascicles, FCU showed a higher potential than FDI. These fascicles included many motor neurons, which mainly innervated the extrinsic muscle. They potentially had sufficient active motor neurons to reinnervate the biceps, and indeed, all our patients who underwent nerve transfer using fascicles of this type regained strong flexion of the elbow. In type B fascicles, the FDI discharges at the same or a slightly higher potential than the FCU, but we did not select these as donor nerves to avoid intrinsic loss. Therefore, none of our patients had impaired pinch grip. In type C fascicles the evoked potential was low in both FCU and FDI. These fascicles included many sensory neurons or inactive motor neurons. Although CMAP is not directly proportional to the number of nerve fibres innervating the muscle, a reduction of amplitude or no amplitude indicates some degree of damage to the fibres. Sungpet et al. and Liverneaux et al. reported that the restoration of biceps function is often weak in patients with a C5, C6, C7 root avulsion compared to those whose injury is limited to C5 and C6. Damaged motor neurons are also more likely to be included in the donor fascicle in patients with injury to C5, C6 and C7. It is also possible that partial damage to the C7 root may have occurred in patients with injury to C5-6 and of the C8 root in C5, C6, C7 injuries. The use of damaged fascicles for nerve transfer must be avoided, and quantitative diagnosis will reliably select intact fascicles that include many active motor neurons. According to Oberlin et al., the motor and sensory fibres of the ulnar nerve in the arm are mixed and this experience is similar to that of Sunderland. The transferred part of the ulnar nerve must therefore include some motor fibres. These two reports are of great consequence, as many surgeons

Table II. Donor site morbidity

<table>
<thead>
<tr>
<th>Patient</th>
<th>Pre-operative</th>
<th>Post-operative (mths)</th>
<th>Pre-operative</th>
<th>Post-operative (mths)</th>
<th>Pre-operative</th>
<th>Post-operative (mths)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>11</td>
<td>18 (14)</td>
<td>2.83</td>
<td>2.83 (14)</td>
<td>0.6</td>
<td>0.8 (3)</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>10 (21)</td>
<td>3.61</td>
<td>4.17 (6): 4.08 (6)</td>
<td>2.3</td>
<td>2.4 (2)</td>
</tr>
<tr>
<td>3</td>
<td>9</td>
<td>10 (11)</td>
<td>3.61</td>
<td>3.61 (6)</td>
<td>3.1</td>
<td>3.2 (22)</td>
</tr>
<tr>
<td>4</td>
<td>20</td>
<td>24 (27)</td>
<td>2.83</td>
<td>2.83 (27)</td>
<td>4.4</td>
<td>6.5 (27)</td>
</tr>
<tr>
<td>5</td>
<td>19</td>
<td>20 (11)</td>
<td>2.36</td>
<td>2.36 (3)</td>
<td>4.4</td>
<td>5.1 (3)</td>
</tr>
<tr>
<td>6</td>
<td>10</td>
<td>7 (8)</td>
<td>2.83</td>
<td>Unmeasurable (0): 4.74 (8)</td>
<td>0.8</td>
<td>2.3 (9)</td>
</tr>
<tr>
<td>7</td>
<td>8</td>
<td>20 (6)</td>
<td>3.22</td>
<td>2.83 (6)</td>
<td>1.2</td>
<td>2.8 (6)</td>
</tr>
<tr>
<td>8</td>
<td>29</td>
<td>23 (6)</td>
<td>2.83</td>
<td>4.31 (6): 2.83 (6)</td>
<td>2.4</td>
<td>2.8 (6)</td>
</tr>
</tbody>
</table>

Table III. Reported outcomes from the Oberlin procedure

<table>
<thead>
<tr>
<th>Authors</th>
<th>M4</th>
<th>M3 or less (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oberlin et al</td>
<td>3</td>
<td>1 (25)</td>
</tr>
<tr>
<td>Loy et al</td>
<td>12</td>
<td>6 (33)</td>
</tr>
<tr>
<td>Leechavengvongs et al</td>
<td>30</td>
<td>2 (6)</td>
</tr>
<tr>
<td>Sungpet et al</td>
<td>30</td>
<td>6 (17)</td>
</tr>
<tr>
<td>Teboul et al</td>
<td>19</td>
<td>8 (30)</td>
</tr>
<tr>
<td>Total</td>
<td>91</td>
<td>23 (26)</td>
</tr>
</tbody>
</table>

Indeed, all our patients who underwent quantitative intra-operative electrophysiological examination for suitable donor fascicles achieved strong flexion of the elbow. We therefore believe that electrophysiological examination can greatly improve the success rate of the Oberlin procedure because the condition of the donor fascicle at operation will be clarified by this examination.
have been encouraged to undertake nerve transfer and our study aims to highlight the issue of damaged fibres, based on the concepts of these reports.

In early studies describing the Oberlin procedure, one or two fascicles of the ulnar nerve were selected at random and sutured to the musculocutaneous nerve.1,4 Sungpet et al5 and Teboul et al6 reported the use of an electrical nerve stimulator to select donor fascicles for this procedure. Thus the ulnar nerve was stimulated to locate the fascicles that were mainly supplying the flexor muscles of the wrist.3 Birch, Bonney and Wynn Parry18 described a notably less-invasive procedure, whereby the epineurium is incised and low-intensity stimulation is used to distinguish the bundles. Those going to the extrinsic muscles are often located on the anterolateral aspect of the ulnar nerve.19 These approaches are not dissimilar to our method, in which quantitative diagnosis has shown significant benefits. Muscle contractions occur in an instant, but can be recorded precisely using electrodagnosis, which greatly improves the accuracy of selecting the most suitable donor nerve. Moreover, this can also directly detect the reactions of the muscle cells. Consequently, the correct diagnosis can be obtained even in patients with some level of contracture in the affected extremity.

As described, many authors have used the fascicles that mainly supply the extrinsic flexor muscles,5,6,10,19,38 in order to prevent intrinsic loss. This may also reduce co-contraction with intrinsics. Although severe problems caused by co-contraction have not previously been reported,5,6,10,19,38 Kakinoki et al22 indicated that patients undergoing partial ulnar nerve transfer spent more time disconnecting elbow flexion from finger and wrist movement than those who had intercostal nerve transfer.

A major disadvantage of our electrodagnostic method is that it is more invasive than Oberlin’s original procedure,5 as all the fascicles of the ulnar nerve need to be separated and stimulated electrically. This technique carries some risks with regard to the integrity of the axons in the different bundles, as it interferes with blood flow and can induce post-operative fibrosis in the nerve trunk. In two of our patients who underwent a quantitative examination, the post-operative grip strength was considerably reduced compared to the pre-operative state. A sensory deficit measured by the Semmes-Weinstein monofilament test was also evident in three patients during the early post-operative period, but appears to be recovering. More long-term studies are required to evaluate whether such deficits are temporary, particularly given the distance between the site of operation and the innervated muscle. Internal neurolysis should be undertaken very gently to avoid iatrogenic neuro-pathic pain.23,24 Fortunately, none of our patients complained of continuous post-operative pain, which can lead to a poor outcome.8,25 In future operations, the number of divided fascicles may be reduced owing to the availability of information regarding potential patterns. If the fascicles are separated one by one, the earliest fascicle to indicate a type A potential could be used as the donor.

Recently, Mackinnon et al10 and Liverneaux et al18 proposed transfer of one or more fascicles of the ulnar nerve to the biceps and a fascicle of the median nerve to the motor branch of brachialis. The reinnervation of the brachialis, the primary flexor of the elbow provides an additional biomechanical advantage.10 Although we have no experience of double nerve transfer using a part of the median nerve, we speculate that quantitative electrodagnosis would be useful in this regard, by setting the recording electrodes on the flexor digitorum superficialis and the thenar muscles. Electrodagnosis can also be effective in selecting a donor fascicle for functional muscle transplantation. In conclusion, this diagnostic method has great potential to select the most suitable fascicles in a variety of situations that require the transfer of donor motor neurons.

No benefits in any form have been received or will be received from a commercial party related directly or indirectly to the subject of this article.

References


