SCIENTIFIC ARTICLE

Upper Limb Reinnervation in C6 Tetraplegia Using a Triple Nerve Transfer: Case Report

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Restoration of elbow extension, grasp, key pinch, and release are major goals in low-level tetraplegia. Traditionally, these functions are achieved using tendon transfers. In this case these goals were achieved using nerve transfers. We present a 21-year-old man with a C6 level of tetraplegia. The left upper limb was treated 6 months after injury with a triple nerve transfer. A teres minor nerve branch to long head of triceps nerve branch, brachialis nerve branch to anterior interosseous nerve, and supinator nerve branch to posterior interosseous nerve transfer were used successfully to reconstruct elbow extension, key pinch, grasp, and release simultaneously. *(J Hand Surg Am. 2014;39(9):1779–1783. Copyright © 2014 by the American Society for Surgery of the Hand. All rights reserved.)*

Key words Nerve transfer, neurotization, reinnervation, spinal cord injury, tetraplegia.

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Nerve transfers are an attractive surgical option for the restoration of hand function in the tetraplegic patient because they allow direct reanimation of the muscle, which is anatomically and mechanically designed to perform that function. The technical challenges of tendon transfer including joint positioning, tendon tensioning, and tendon graft harvest are avoided along with postoperative tendon adhesions, stretching, rupture, and subluxation. Long postoperative immobilizations are also avoided. Certain nerve transfers, such as the supinator nerve branch to the posterior interosseous nerve (PIN), can reanimate multiple muscles simultaneously and allow independent movement of these reanimated muscles. Carefully chosen nerve transfers can successfully restore elbow extension, grasp, key pinch, and release and also preserve the muscles traditionally used for tendon transfer reconstruction of these functions. These preserved muscles can then be used as tendon transfers to reconstruct more distal hand functions such as thumb opposition and intrinsic function. Therefore, the number of functions that can be restored is expanded. This case report describes the successful simultaneous restoration of elbow extension; thumb flexion, extension and abduction; finger flexion and extension, and ulnar deviation of the wrist using triple nerve transfers.

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CASE REPORT

Preoperative assessment

A 21-year-old man sustained a complete C6 spinal cord injury from a C6/7 flexion-compression teardrop fracture-dislocation after a shallow water dive. Magnetic resonance imaging revealed extensive cord edema from C4 to T1 and hematoma within the cord at C6/7, which is a poor prognostic indicator for neurological recovery. A C6 corpectomy and C5 to C7 stabilization surgery was performed the next day. Clinical examination detected no nerve root sparing below the level of injury either immediately after the injury or in the following 6 months. One month after injury, spinal shock was resolved as determined by the

TABLE 1. Preoperative and Postoperative Motor Examination Using Medical Research Council Scale

Muscle	Right		Left	
	Presurgery	17 Mo Postsurgery	Presurgery	19 Mo Postsurgery
Donor movement				
Shoulder external rotation	5*	5*	5	5
Supination	5	5	5	5
Elbow flexion	5	5	5	5
Recipient muscles				
Triceps	3*	4*	0	4
Extensor carpi ulnaris†	0	4	0	4
Extensor digitorum communis	0	4	0	4
Extensor pollicus longus	0	3	0	3
Abductor pollicus longus	0	4	0	4
Flexor digitorum profundus	0	4 (IF, MF, RF)	0	3 (IF, MF, RF)
Flexor digitorum superficialis	0	4 (MF, RF)	0	4 (IF, RF)
Flexor pollicus longus	0	4	0	4
Non-involved muscles				
Brachioradialis	5	5	5	5
Pronation	5	5	4	4
Extensor carpi radialis longus/brevis	5	5	5	5
Flexor carpi radialis	3	3	0	2

IF, index finger; MF, middle finger; RF, ring finger.
*Comparison only, no surgery performed.
†Tested via ulnar deviation.

development of hyperreflexia and spasticity. Five months after injury, the patient was referred for surgical reconstruction of hand function. Muscle strength was recorded using the Medical Council Research Council Scale (Table 1).[1] Upper limb function was classified as group 4 bilaterally according to the international classification for muscle function in tetraplegia.[2]

Preoperative electromyography of the muscles supplied by the prospective donor nerves (teres minor, brachialis, and supinator) showed near normal recruitment, although there was some reduced activation reflecting a degree of upper motor neuron injury. No voluntary activity was confirmed in the nerve transfer target muscles; however, fibrillations were observed revealing a component of lower motor neuron injury in addition to the expected upper motor neuron injury. The patient was educated regarding the rehabilitation program for nerve transfer surgery and goals were set using the Canadian Occupational Performance Measure.[3]

Surgical technique

Three nerve transfers were performed on the left upper limb 6 months after injury: teres minor nerve branch to the long head of triceps nerve branch,[4] brachialis nerve branch to the anterior interosseous nerve (AIN),[5] and supinator nerve branch to the PIN.[6] Two months later the latter 2 transfers were performed on the right upper limb because the triceps function was adequate on that side. Using the technique described by Brown,[5] donor and recipient nerves were identified intraoperatively with a biphasic nerve stimulator/locator (Checkpoint Stimulator/Locator, Cleveland, OH), which has the advantage of allowing repeated stimulation while minimizing fatigue. Intraoperative motor-evoked potentials using trained multi-pulse transcranial electrical stimulation of the motor cortex were used to confirm motor system pathway integrity from brain to donor nerve. Nerves were coapted under an operating microscope using a 9.0 nylon interrupted suture and protected with Tisseel fibrin sealant (Baxter AG, Vienna, Austria).

Postoperative course

After surgery the upper limb was immobilized for 3 weeks to protect the nerve transfers with the wrist and forearm in neutral and the elbow flexed to 90°. A week later, the patient resumed supervised lift transfers and use of a manual wheelchair and was discharged from inpatient care. Because the patient lived rurally he completed daily exercises diligently with the assistance of caregivers and was reviewed by the therapist every 2 to 4 weeks via video conferencing. He visited the clinic every 1 to 3 months. Initially the patient activated the donor nerve movement while the therapist or caregiver passively moved the joints through the range of motion of the recipient muscle. For example, in the brachialis nerve branch to AIN transfer, the patient actively flexed the elbow with the forearm pronated while the therapist or caregiver passively flexed the digits. Once a flicker of motion was detected in the recipient muscle(s) this was strengthened until M3 power was attained. The patient then learned to dissociate donor from recipient movement by practicing performing recipient movement without consciously thinking of donor movement.

Table 1 lists muscle strength at 19 and 17 months postsurgery in the left and right upper limbs, respectively. Table 2 provides objective measures of strength. Video 1 (available on the *Journal's* Web site at www.jhandsurg.org) shows right-hand grasp and release 17 months postsurgery, and Video 2 (available on the *Journal's* Web site at www.jhandsurg.org) shows left-hand grasp and release 19 months postsurgery. The patient achieved M4 elbow extension on the left, M4 thumb and finger flexion bilaterally, and M3 thumb and M4 finger extension bilaterally. He was also able to extend the thumb independently without extending the fingers (Fig. 1), abduct the thumb against gravity, and deviate the wrist ulnarly. He was able to actively extend the left elbow holding a 2-kg weight for 10 repetitions. His most recent lateral pinch strengths were 0.9 kg in the right hand and 0.72 kg in the left (Jamar Mechanical Pinch Gauge, Patterson Medical, Warrenville, IL; adapted by the Cleveland FES Centre, Cleveland, OH). Pinch between index and middle fingers measured 2.5 kg right and 2.0 kg left. Grasp strength (position 3) measured 7 kg right and 3 kg left (Jamar Plus Hand dynamometer, Patterson Medical). After surgery, the patient also reported a decrease in the frequency and strength of spasms in the finger flexors, which he was then able to break by actively extending the fingers.

No functional deficit of shoulder external rotation, elbow flexion, or forearm supination was detected after surgery. However, M3 flexion in the right wrist was temporarily lost after brachialis nerve branch to AIN transfer. This was regained 9 months later. The patient successfully dissociated all donor from recipient muscle movement. Reconstruction of thumb opposition using an extensor carpi radialis longus tendon transfer is planned for the future. There is no clawing in either hand so intrinsic substitution will not be necessary.

TABLE 2. Objective Measures of Strength 17 (Right) and 19 (Left) Months Postoperation

Test	Right, kg	Left, kg
Bicep curl (8 repetitions)	7.5	7.5
Elbow extension (10 repetitions)	2	2
Pinch between index and middle finger	2.5	2
Lateral pinch	0.9	0.72
Grasp (position 3)	7	3

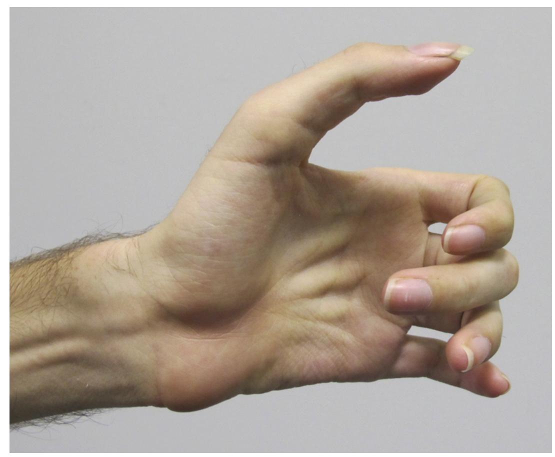

FIGURE 1: Independent thumb extension after supinator to PIN transfer.

We noted improvement in the Canadian Occupational Performance Measure in both the satisfaction and performance of all goals, with an improvement of 5 and 7 points, respectively.

DISCUSSION

The success of nerve transfers in the treatment of brachial plexus and peripheral nerve injury has inspired interest in nerve transfers for patients with spinal cord injuries.[4–12] In this case, elbow extension, grasp, key pinch, and release were simultaneously reconstructed using nerve transfers. In addition, thumb abduction and wrist ulnar deviation were restored.

In spinal cord trauma, injury to the anterior horn cells of motor neurons at the level of the lesion results in a lower motor neuron (LMN) denervation of the muscles supplied by that segment of the spinal cord. In contradistinction, motor neurons arising caudad to the site of trauma are intact, but the muscles they supply are no longer under voluntary control because the spinal cord injury interrupts communication between the motor cortex and these neurons. As such, these muscles are paralyzed as a result of the upper motor neuron (UMN) paralysis.[13] However, the real picture seems to be less distinct. It is common on electromyographic testing to find a degree of UMN and LMN injury in the recipient and even, to a lesser degree, in the donor neuromuscular units. If a prospective donor nerve's muscle functions at full strength and if full power has been present since one month after injury, a minor degree of UMN or LMN injury evident only on electromyography is not clinically meaningful. However, evidence for an LMN injury in recipient muscles is highly relevant to the timing of surgery because the neuromuscular end plates in denervated muscle fibers degenerate over 2 years.[6,10] At our center, electromyographic testing of 14 tetraplegic patients in preparation for nerve transfer surgery revealed fibrillation potentials (reflecting denervation and therefore a component of LMN injury) in 64% of the 39 recipient muscles examined (unpublished). In a group of 16 complete cervical or thoracic spinal cord injury patients, Riley et al[14] demonstrated spontaneous activity in at least 1 of 4 tested leg muscles in all subjects. Similarly when examining muscles caudad to the lesion in 11 C 5/6 tetraplegic patients, Gorman et al[15] revealed fibrillations in at least 1 muscle group in all but 1 subject. These findings support the argument for nerve transfer surgery within 12 months after spinal cord injury, especially when spontaneous activity is present on electromyelogram, to capture the LMN component of the injury. Further work is needed to correlate the relationship between the type of injury and the timing of nerve transfer surgery to outcomes.

Early intervention needs to be balanced against the chance of spontaneous recovery, which can occur up to 12 months after injury.[13,16] Waters et al[16] studied motor recovery in 61 individuals after cervical spinal cord injury and showed that the rate of motor recovery declined rapidly in the first 6 months and plateaued at 9 months. One month after injury, muscles scoring M1 or M2 strength had a 97% chance of attaining M3 strength by 1 year. Muscles scoring M0 and located 1 neurological level caudad to the most caudal functional muscle had a 27% chance of recovering to M3 or greater. Muscles scoring M0 and 2 levels caudad to the most caudal functional muscle had only a 1% chance of attaining M3 or greater strength by 1 year. The target functions in the triple nerve transfer described here were elbow extension (C7), finger/thumb extension (C7,8), and finger/thumb flexion (C7,8). In a C6 injury this puts the first 2 targets 1 level below the neurological level and the third 2 levels below. Transfer target muscles scoring M0 at 6 to 9 months are unlikely to recover useful function, and as such we offer nerve transfers after 6 months after complete spinal cord injury.

Motor-evoked potentials are an important addition to routine intraoperative nerve stimulation in tetraplegia. If a nerve is LMN denervated, there is no muscle contraction with stimulation using a standard intraoperative nerve stimulator. If the nerve is paralyzed owing to a UMN lesion, its muscle will contract when its nerve is stimulated. Normal nerves will also stimulate, and so these last 2 situations cannot be distinguished from each other. Intraoperative motor-evoked potentials using trained multi-pulse transcranial electrical stimulation of the motor cortex are needed to confirm motor system pathway integrity from the brain through the spinal cord to donor nerve. The presence of motor-evoked nerve action potentials makes a clinically important UMN injury to the donor nerve less likely.

In the brachialis nerve branch to AIN transfer, the median nerve must be dissected into its component fascicles.[5] As was the case here, we have frequently observed that when stimulating the AIN fascicle of the median nerve at the mid-arm level it is common to see flickers of movement in flexor carpi radialis (FCR) and flexor digitorum superficialis (FDS). Although this phenomenon could be due to retrograde conduction through adjacent median nerve fascicles, it is possible that the AIN fascicle at this level carries axons destined for FCR and FDS. In this case FCR function on the right was lost after surgery as a result of division of the recipient AIN fascicle, but it returned by 9 months, which was the time expected for this transfer to reach it target muscles. Similarly, if FDS axons were present in the recipient AIN fascicle, this had the potential to result in incidental FDS reanimation. At a recent review of this patient some FDS function was noted bilaterally. Although this may represent recovery through an un-sectioned portion of the median nerve supplying the FDS, this is unlikely when FDS strength at 6 months was M0.[16]

The supinator nerve branch to PIN transfer described by Bertelli et al[6] for tetraplegia demonstrates the mechanical advantage of reanimating the native muscle. Active hand opening has been an elusive goal in the C5/6 tetraplegic patient (International Classification group 4); static tenodesis of extensor tendons is the standard treatment.[17] When the pronator teres is transferred to the extensor digitorum communis it produces a single mass extension of the fingers. Most of the pull is expended on the metacarpophalangeal joints, leaving the interphalangeal joints flexed unless a passive intrinsic tenodesis is performed. The supinator nerve branch to PIN transfer gives excellent hand and first web space opening even without intrinsicplasty. Differential thumb and finger extension is possible, and reanimation of extensor carpi ulnaris centralizes an otherwise radially deviated wrist. Active thumb abduction places the thumb in a favorable position for key pinch, avoiding the need for carpometacarpal joint arthrodesis or extensor tenodesis.

In a review of the literature for outcomes in pinch and elbow extension reconstruction in tetraplegia, Hamou et al[18] found that the mean Medical Research Council score for elbow extension after reconstruction was 3.3 and the mean postoperative key pinch strength was 2 kg. A key pinch of 2 kg after tendon transfer reconstruction enables persons with tetraplegia to perform a number of essential daily tasks such as opening and closing zippers; inserting and removing a key, a 3-prong plug, and an automated teller machine card; and securing food with a fork.[19] Superior hand mobility, a stable centralized wrist, as well as a 2.5-kg pinch between the index and middle fingers on the right (2 kg on the left) allowed our patient to complete all of these tasks bilaterally using either key pinch or pinch between the index and middle fingers. Most notably he was able to insert a plug into a socket using key pinch, a task that requires 3 kg of key pinch strength.[19] Even between 26 and 28 months after injury, grasp and pinch strength continued to improve. As such, the ultimate strengths have not been attained. Improvement in satisfaction and performance of the Canadian Occupational Performance Measure goals exceeded the published levels for clinical importance.[3]

The addition of nerve transfers to the skill set of the hand surgeon for tetraplegia reconstruction has the potential to expand the number of functions that can be reconstructed, especially if they are combined with tendon transfers. Although the utility of nerve transfers in tetraplegia has yet to be fully determined, early results show promise.

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