Restoration of hand function after C7–T1 brachial plexus injuries has long been challenging for surgeons. Since 2010, staged approaches with nerve and tendon transfer have been performed at our institution. During the first stage, the brachialis motor branch is transferred to the finger flexor functional fascicles of the median nerve for the recovery of finger flexion, while the supinator motor branch is transferred to the posterior interosseous nerve (PIN) for finger extension. During the second stage and after the recovery of finger flexion and extension, a brachioradialis muscle transfer is performed for thumb opposition. Through this strategy, patients with C7–T1 brachial plexus palsies have recovered finger flexion, finger extension, and thumb opposition, which has led to successful grasping and pinching motions. Moreover, compared with previous cases, the patient in the present case achieved stronger finger flexion and grip strength, suggesting practical improvements to the reconstructed hand.

https://thejns.org/doi/abs/10.3171/2016.8.JNS151749

KEY WORDS nerve transfer; tendon transfer; brachial plexus injury; hand reconstruction; peripheral nerve
combined nerve transfers result in satisfactory outcomes for increasing donor nerve sources and the reinnervation of more synergistic muscles.

Inspired by satisfactory outcomes following these combined nerve transfers, we sought to transfer 2 donor nerves to neurotize both the anterior interosseous nerve (AIN) and flexor digitorum superficialis (FDS) branch. We expected that the reinnervation of the full finger flexors (flexor pollicis longus [FPL], flexor digitorum profundus [FDP], and FDS) would maximize the potential for strong finger flexion recovery.

Feasible donor nerves for finger flexion recovery in a lower brachial plexus injury (as reported in previous studies) include the brachialis motor branch, the brachioradialis motor branch, the extensor carpi radialis brevis branch, and the pronator teres (PT) branch. Considering that the brachioradialis muscle is used for thumb opposition and the extensor carpi radialis brevis is an alternate donor muscle for intrinsic muscle function recovery if necessary, we selected the brachialis motor branch and PT branch as potential donor nerves. We sought to transfer the PT branch to the AIN and the brachialis motor branch to the FDS branch for reinnervation of both the FPL/FDP and the FDS, respectively.

In the present study we evaluated the results of these combined nerve and tendon transfers in C7–T1 brachial plexus avulsions. The first-stage operation involved nerve transfer of 1) the PT branch to the AIN, 2) the brachialis motor branch to the FDS branch with a nerve graft, and 3) the supinator motor branch to the PIN. The second-stage operation involved muscle transfer of the brachioradialis to the abductor pollicis brevis with a tendon graft.

Case Report

History

A 40-year-old man sustained a left brachial plexus injury during a blunt trauma to his left shoulder. His shoulder, elbow, and wrist function recovered spontaneously 4 months following the injury. He was referred to our institute 5 months after the injury.

Physical and Electrophysiological Examination

Normal shoulder and elbow function with M4 muscle strength was noticed. The muscle strength of the clavicular head of the pectoralis major was M4, the sternal head was M0, and the latissimus dorsi was M1. Pronation and supination were normal. Muscle strength of the flexor carpi radialis was M4, while those of the palmaris longus and flexor carpi ulnaris were M0. Wrist extension was preserved with radial deviation; muscle strength of the extensor carpi radialis longus and extensor carpi radialis brevis was M4, while that for the extensor carpi ulnaris was M0. No active flexion or extension of the finger and thumb were observed. Intrinsic muscles of the hand were also paralyzed. Pinprick sensation disappeared in the ulnar 2 fingers as well as the ulnar aspect of the hand and forearm and decreased in the radial 3 fingers. The Hornér’s sign was positive. Electromyography assessments revealed normal innervation in the muscles innervated by the C-5 and C-6 nerve roots and total denervation in the muscles innervated by the C-7, C-8, and T-1 nerve roots. The somatosensory evoked potential disappeared, and the sensory nerve action potential was preserved. Magnetic resonance imaging was not performed in this case.

First-Stage Operation

The first-stage operation (multiple nerve transfers) was performed 5 months after the injury.

Finger Flexion Recovery. Pronator Teres Branch–AIN. An S-shaped incision was made in the medial upper arm from the antebrachial fossa to the forearm and continuing for a length of 15 cm. The median nerve was easily exposed after incision of the bicipital aponeurosis and separation of the PT. Then, the PT branches were identified as arising from the median nerve. Three individual motor branches were entering the PT, and their diameters were 1.5, 0.5, and 1.0 mm (Fig. 1A). Intraoperative electrophysiological stimulation was performed to confirm functioning via the presence of compound muscle action potentials recorded in the PT through a needle electrode. The AIN originated from the dorsal part of the median nerve and could be easily traced back to the antebrachial fossa through the interfascicular dissection. The AIN was then sectioned proximally near its atraumatic dissection point after the confirmation of paralysis through electrophysiological stimulation. Considering that each PT branch was long enough to be sutured to the AIN without tension, we selected the proximal section because of its diameter and sectioned it distally, near its muscle entrance. From there, a tension-free coaptation of the proximal PT branch and the AIN was performed with 9-0 nylon sutures under a ×10 surgical microscope (Fig. 1B).

Brachialis Motor Branch to the FDS Branch. After separation of the biceps and brachialis muscles, the musculocutaneous nerve and its branches were exposed. The brachialis motor branch was identified about 14 cm proximal to the medial epicondyle. Then, the FDS branch was identified 1 cm distal to the AIN. Finally, the brachialis motor branch was transferred to the FDS branch with a graft of the medial antebrachial cutaneous nerve for the reinnervation of the FDS (Fig. 1B).

Finger Extension Recovery. Supinator Motor Branch to the PIN. A longitudinal incision was made on the proximal third of the dorsal forearm. The supinator muscle was exposed after separation of the extensor carpi radialis brevis and extensor digitorum communis. After dividing the superficial portion of the supinator muscle, the PIN and the supinator motor branches were identified. The 2 supinator motor branches were transferred to the PIN for finger extension (Fig. 1C).

After completion of the surgery, the elbow was immobilized at 45° of flexion, with the forearm and wrist in a neutral position for a period of 4 weeks.

Second-Stage Operation

Thumb Opposition Recovery. Nine months after the first-stage operation, the patient underwent the thumb opposition surgery when finger flexion and extension strength had recovered to M3.

The brachioradialis muscle tendon was detached from
the radius and released proximally. Then, the brachioradialis tendon was elongated by the palmaris longus tendon graft and rerouted along the ulnar side of the ulna. The tendon was finally sutured to the tendinous portion of the abductor pollicis brevis.

After completion of the surgery, the elbow and wrist were immobilized at 45° of flexion, with the thumb in the opposition position for a period of 4 weeks.

Postoperative Course

The patient was instructed to attempt finger and thumb flexion (with elbow flexion and forearm pronation) and extension with forearm supination when the splint was removed. He was scheduled to undergo physical examination and electrophysiological testing every 3 months for the first 2 years. During the postoperative period, he had no complications and did not report any impairment to forearm pronation, supination, or elbow flexion.

Three months after the first-stage operation, occasional motor unit potentials of the FPL, FDP/FDS, and extensor digitorum comminutus were detected. Additionally, 6 months after the first-stage surgery, finger extension strength was M3, and the patient could open his hand. At that time, early motion of the thumb and finger flexors was observed. At the final evaluation 30 months after the first-stage surgery, we observed flexion of M4 for the FPL (Fig. 2A) and FDP of the index finger (Fig. 2B) and M4 for the FDS of the middle and ring fingers (Fig. 2C and D). There was no recovery of little finger flexion (Table 1). The 4 radial digits could touch the palm (Fig. 2E and F and Video 1).

VIDEO 1. Good recovery of finger and thumb flexion and extension. Copyright Zhen Dong. Published with permission. Click here to view.

Finger and thumb extension strength were M4 (Fig. 3). After the second-stage operation, the patient regained thumb to index and middle finger opposition (Fig. 4 and Video 2).

VIDEO 2. Good recovery of thumb opposition. Copyright Zhen Dong. Published with permission. Click here to view.

Finally, grip strength tested using the Pablo System (Tyromotion) was determined to be 5.8 kg. With an increase in
muscle and grip strength, the patient could perform tasks that required strong finger flexion, including lifting a mop (Fig. 5A), grasping a water bottle (Fig. 5B), carrying a handbag (Fig. 5C), opening a door (Fig. 5D), and wringing a wet towel (Fig. 5E and Video 3).

**VIDEO 3.** The patient used his reconstructed hand to perform different daily life tasks. Copyright Zhen Dong. Published with permission. Click here to view.

**Discussion**

Several different nerve transfers have been attempted for finger flexion recovery in lower brachial plexus avulsions. Alternative donor nerves consist of the brachioradialis motor branch, 4 the extensor carpi radialis brevis branch, 1 and the PT branch. 10,12 However, the recipient nerve of these aforementioned transfers was the AIN, regardless of the donor nerve chosen. Classic anatomy textbooks state that the AIN innervates the FPL and the FDP of the index and middle fingers; hence, only the radial 3 digits might flex after reinnervation of the AIN. Additionally, another strong finger flexion muscle, the FDS, would not recover with these methods.

At our institution, we have transferred the brachialis motor branch to the posterior one-third portion of the median nerve in the upper arm—not to the AIN. We consider this portion of the median nerve to be the functional fascicles of finger flexion, consisting of the FPL, FDP, and FDS nerve fibers. 5 Patients have recovered flexion of not only the radial 3 digits but also the ring and little finger due to an expected FDS recovery. However, finger flexion strength could only reach MRC Grades M2–M3, and the relatively weak grip strength could not meet patient needs for daily use. We speculated that the causes of these unsatisfactory results were 1) an insufficiency of the donor nerve fibers compared with the full finger fascicles and 2) inaccuracy of the finger fascicle location in the upper arm.

To overcome these 2 main limitations, we designed combined nerve transfers for better restoration of finger flexion. We sought to transfer 2 feasible donor nerves to the AIN and the FDS branch. If accurate neurotization of the AIN and FDS branch could be achieved, then recovery of full finger flexors (FPL, FDP, and FDS) would be expected.

As mentioned previously, according to previous studies, feasible donor nerves for finger flexion recovery in lower brachial plexus injuries include the brachialis motor branch, 5 the brachioradialis motor branch, 4 the extensor carpi radialis brevis branch, 1 and the PT branch. 10,12 Considering that the brachioradialis muscle was used for thumb opposition in our proposed strategy and that the extensor carpi radialis brevis was an alternative donor muscle for intrinsic muscle function recovery if necessary, we selected the brachialis motor branch and PT branch as potential donor nerves. Because the FDP is more important than the FDS for finger flexion, the AIN should be the priority for neurotization. We transferred the PT branch to the AIN since it could be directly coapted to the AIN without tension. Furthermore, nerve grafting was needed to bridge the gap between the brachialis motor branch and the AIN. Therefore, our current strategy for finger flexion recovery in C7–T1 brachial plexus avulsions consisted of a combined nerve transfer: 1) transfer of the PT branch to the AIN for restoration of the FPL and FDP, and 2) transfer of the brachialis motor branch to the FDS branch with

<table>
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<tr>
<td>FPL (M1)</td>
<td>M1</td>
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<tr>
<td>FDP (index) (M0)</td>
<td>M0</td>
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<tr>
<td>FDS (index) (M0)</td>
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<tr>
<td>FDP (middle) (M0)</td>
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<td>FDP (ring) (M0)</td>
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<td>FDS (ring) (M0)</td>
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<td>FDP (little) (M0)</td>
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<td>FDS (little) (M0)</td>
<td>M0</td>
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<td>Grip strength (kg)</td>
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**FIG. 3.** Functional recovery of thumb and finger extension 30 months after the first-stage surgery. The patient could fully extend the metacarpophalangeal joints of the fingers (A) and thumb (B). He could successfully open his hand. Figure is available in color online only.
a nerve graft of the medial antebrachial cutaneous nerve for FDS restoration.

Unlike previous methods, we used 2 donor nerves and accomplished a combined nerve transfer instead of a single nerve transfer. Then, 2 groups of finger flexors (FPL/FDP and FDS) recovered after this combined nerve transfer. With this new strategy, we observed M4 strength for the FPL and the FDP of the index and middle fingers and M4 for the FDS of the middle and ring fingers in the present patient. The recovery of these 2 groups of muscles may work together to significantly improve expected finger flexion strength. Stronger finger flexion facilitated both grasp strength and practical value for this patient’s reconstructed hand.

However, there was no active flexion movement of the distal and proximal interphalangeal joints of the little finger. We supposed this was because we transferred the brachialis motor branch to only one FDS branch. A previous anatomical study has suggested that the FDS is usually innervated by 2 branches; thus, another FDS branch without neurotization may innervate the FDS of the little finger. Considering that the medial antebrachial cutaneous nerve had multiple distal branches near the elbow, we think it best to neurotize the 2 FDS branches (the proximal medial antebrachial cutaneous nerve is coapted to the brachialis motor branch, while the distal 2 branches of the medial antebrachial cutaneous nerve are coapted to 2 FDS branches) in future studies.

FIG. 4. Functional recovery of thumb opposition. The patient regained thumb to index (A and B) and middle finger (C and D) opposition. Figure is available in color online only.

FIG. 5. The patient was able to perform tasks that required strong finger flexion, including lifting a mop (A), grasping a water bottle (B), carrying a handbag (C), opening a door (D), and wringing a wet towel (E). Figure is available in color online only.
Conclusions
Transfer of the PT branch and brachialis motor branch can reliably restore stronger finger flexion for patients sustaining a C7–T1 brachial plexus injury. In combination with transferring the supinator motor branch for finger extension and transfer of the brachioradialis muscle for thumb opposition, this new strategy may improve functional recovery and practical usage of injured hands in this patient group.

Acknowledgments
This study was funded by Grant No. 124119a1001 from the Science and Technology Commission of Shanghai Municipality (STCSM), Grant No. 81371374 from the National Natural Science Foundation of China, as well as the Shanghai Key Laboratory of Peripheral Nerve and Microsurgery and the Key Laboratory of Hand Reconstruction, Ministry of Health.

References

Disclosures
The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

Author Contributions
Conception and design: Dong. Acquisition of data: Xu. Analysis and interpretation of data: Xu, Zhang. Drafting the article: Xu. Critically revising the article: all authors. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: Dong. Study supervision: Gu.

Supplemental Information
Videos

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