Contralateral C7 to C7 nerve root transfer in reconstruction for treatment of total brachial plexus palsy: anatomical basis and preliminary clinical results

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OBJECTIVE Contralateral C7 (CC7) nerve root has been used as a donor nerve for targeted neurotization in the treatment of total brachial plexus palsy (TBPP). The authors aimed to study the contribution of C7 to the innervation of specific upper-limb muscles and to explore the utility of C7 nerve root as a recipient nerve in the management of TBPP.

METHODS This was a 2-part investigation. 1) Anatomical study: the C7 nerve root was dissected and its individual branches were traced to the muscles in 5 embalmed adult cadavers bilaterally. 2) Clinical series: 6 patients with TBPP underwent CC7 nerve transfer to the middle trunk of the injured side. Outcomes were evaluated with the modified Medical Research Council scale and electromyography studies.

RESULTS In the anatomical study there were consistent and predominantly C7-derived nerve fibers in the lateral pectoral, thoracodorsal, and radial nerves. There was a minor contribution from C7 to the long thoracic nerve. The average distance from the C7 nerve root to the lateral pectoral nerve entry point of the pectoralis major was the shortest, at 10.3 ± 1.4 cm. In the clinical series the patients had been followed for a mean time of 30.8 ± 5.3 months postoperatively. At the latest follow-up, 5 of 6 patients regained M3 or higher power for shoulder adduction and elbow extension. Two patients regained M3 wrist extension. All regained some wrist and finger extension, but muscle strength was poor. Compound muscle action potentials were recorded from the pectoralis major at a mean follow-up of 6.7 ± 0.8 months; from the latissimus dorsi at 9.3 ± 1.4 months; from the triceps at 11.5 ± 1.4 months; from the wrist extensors at 17.2 ± 1.5 months; from the flexor carpi radialis at 17.0 ± 1.1 months; and from the digital extensors at 22.8 ± 2.0 months. The average sensory recovery of the index finger was S2. Transient paresthesia in the hand on the donor side, which resolved within 6 months postoperatively, was reported by all patients.

CONCLUSIONS The C7 nerve root contributes consistently to the lateral pectoral nerve, the thoracodorsal nerve, and long head of the triceps branch of the radial nerve. CC7 to C7 nerve transfer is a reconstructive option in the overall

management plan for TBPP. It was safe and effective in restoring shoulder adduction and elbow extension in this patient series. However, recoveries of wrist and finger extensions are poor.

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KEYWORDS contralateral C7; total brachial plexus palsy; nerve transfer; donor nerve

I N 1992, Gu et al.[11] reported the concept and clinical application of using a healthy contralateral C7 (CC7) nerve root as donor nerve in reconstruction of the brachial plexus for treatment of total brachial plexus palsy (TBPP). Since then CC7 nerve transfer has gained wider acceptability, with promising results reported from other centers.[6,26,28,29,31–34] Apart from TBPP, the utility of CC7 has also been expanded to the treatment of patients with central neurological injuries, such as cerebral palsy, traumatic brain injury, and stroke.[14,37,39]

The procedure's premise is that the harvest of C7 nerve root would not cause permanent functional loss in the healthy extremity. Following transection of the C7 nerve root, voluntary control over the muscles that it innervates appears to be preserved due to compensation by the adjacent nerve roots. For instance, apart from C7 innervation, the latissimus dorsi is also innervated by C6 and C8 roots; the triceps by C5, C6, C8, and T1; and the forearm extensors by C6 and C8. Previous studies in rodents and humans have shown that the C7 myotome contributes to the movements of the shoulder, elbow, wrist, and hand.[9,17] This is supported by the comprehensive functional improvement observed in the injured upper limb following CC7 to C7 transfer in patients with central neurological injury.[14] Some anatomical reports have revealed the structure of C7 and brachial plexus by cadaveric,[12,25] histochemical,[16,35] or electrophysiological studies.[9,18] However, the relative contribution of C7 innervation to the overall function of the upper limb remains unknown, as well as the recovery assessment of specific muscles.

In this study, cadaveric and clinical investigations were combined to delineate the neuroanatomy of C7 nerve fibers innervating the specific upper-limb muscles and to ascertain the extent of function(s) that can be regained by successful reanimation of the C7 myotome through CC7 nerve transfer in a completely paralyzed limb.

Methods

Anatomical Study

The brachial plexus specimens of 5 embalmed adult cadavers were bilaterally dissected in the Department of Anatomy, Histology, and Embryology at the Medical College of Fudan University. Dissection was performed using loupe magnification ×2.5. Particular attention was paid to the C7 nerve root, where the distal branches were dissected and followed until they reached a known muscle. The distances from the C7 root (transverse foramen) to the nerve entry point of target muscles were measured by a ruler.

Clinical Series

Patient Population

Between November 2012 and January 2014, 8 patients with TBPP underwent brachial plexus exploration and reconstruction. The preliminary diagnosis of TBPP was based on history, physical examination, and electromyography (EMG) and MRI findings. The final diagnosis of total root avulsion was confirmed during surgical exploration. All procedures were performed by the senior author (W.D.X.). All patients underwent CC7 to C7 nerve transfer, in addition to other nerve transfers, as part of the overall reconstructive plan. Of the 8 patients, 1 was lost to follow-up and 1 was excluded because of severe concomitant soft-tissue damage of the arm. Among the remaining 6 patients, 5 were male and 1 was female, and the mean age was 27.2 ± 9.0 years (range 18–43 years). The average interval from injury to operation was 2 ± 0.6 months (range 1–3 months) (Table 1).

Surgical Technique of CC7 to C7 Transfer

The patient was placed in the supine position with a sandbag under the interscapular region. The injured brachial plexus was exposed through a supraclavicular trans-

TABLE 1. General information for 6 patients with TBPP in case series

| Yr of Birth	Sex	Handedness	Age at Injury (yrs)	Cause	Past History	Affected Side	Time From Injury to Op (mos)	Intraop Diagnosis	Duration of FU (mos)
1990	M	Rt	23	Traffic accident	—	Lt	1	Lt TBPP	27
1989	M	Rt	24	Traffic accident	—	Lt	2	Lt TBPP	34
1969	M	Rt	43	Fall damage, multiple injuries	Smoking, hyperglycemia	Lt	2	Lt TBPP, lt scapula fracture, C4–5 disc resection	40
1995	F	Rt	18	Traffic accident, multiple injuries	—	Lt	2	Lt TBPP	30
1982	M	Rt	32	Traffic accident	—	Rt	3	Rt TBPP	28
1990	M	Rt	23	Traffic accident	—	Lt	2	Lt TBPP	26

FU = follow-up.
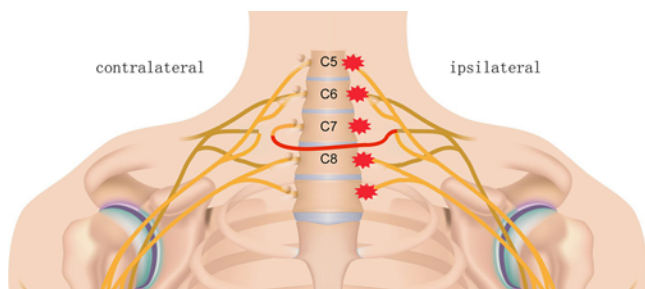
FIG. 1. Schematic drawing of the CC7 transfer procedure. Proximally, the scalenus anterior muscle was severed while protecting the PN. The CC7 nerve root was dissected up to the neural foramen. Distally, the nerve was dissected to the middle trunk as far as its anterior and posterior divisions, and it was transected at the distal end to the divisions. In the retrosternocleidomastoid muscle route, 3–4 strands of the autologous sural nerve grafts were used to bridge the gap between the recipient C7 nerve root and the donor anterior and posterior divisions of middle trunk. Copyright Su Jiang. Published with permission. Figure is available in color online only.

verse incision. Once the TBPP was confirmed, the target recipient nerves of C7 nerve root (i.e., the suprascapular nerve [SSN], musculocutaneous nerve, and axillary nerve [AN]) were isolated.

On the uninjured side, a similar supraclavicular incision was made. The CC7 nerve root was isolated and confirmed by intraoperative EMG. During the harvest of the CC7 root, the scalenus anterior muscle was divided while protecting the phrenic nerve (PN). To obtain maximal nerve length, the nerve root was mobilized up to the neural foramen. The CC7 nerve was then dissected as distally as its anterior and posterior divisions. The CC7 was transected at the distal end to the divisions after performing lidocaine blockade (1%, Squibb). The length of the donor nerve was measured.

The sternocleidomastoid muscles on both sides were retracted anteriorly and a tunnel was created by blunt dissection in front of the trachea. Three to four strands of the autologous sural nerve grafts were used to bridge the gap between the recipient and donor C7 nerve root through the retrosternocleidomastoid route, behind the posterior border of the sternocleidomastoid and in front of the trachea and common carotid artery sheath. Tension-free neurorrhaphy was achieved with 8–0 Ethicon PROLENE (Johnson & Johnson) under an operating microscope (Fig. 1). After the surgery, a prefabricated brace was used to hold the head in the neutral position, and the injured upper limb was immobilized for a period of 4 weeks.

Rehabilitation commenced at 4 weeks after the surgery. The patients were educated to perform shoulder adduction on the healthy side while undergoing passive exercises of shoulder adduction, elbow extension, and wrist/finger extension on the injured side. Five hundred cycles of exercises per day were recommended. Percutaneous electrical stimulation of the healthy C7 nerve root was used for at least 6 months postoperatively.

Concurrent Nerve Transfers

In all patients, the spinal accessory nerve (SAN) was transferred to the SSN, and the motor branches of 4 intercostal nerves (ICNs), III–VI, were transferred to the musculocutaneous nerve in different stages. In 3 patients, the PN was also harvested in full length via video-assisted thoracic surgery and transferred to the anterior branch of the AN.

Evaluation

All patients were reviewed clinically and underwent EMG testing every 3 months in the first postoperative year. After the first year, they were reviewed every 6 months. Muscle strength was assessed according to the modified British Medical Research Council (BMRC) scale. The grades M0 to M2 were regarded as poor, M2+ to M3 were fair, M3+ to M4– were good, and M4 to M5– were excellent. Any sensory or motor deficit on the contralateral side was documented.

Statistical Methods

Statistical analysis was performed with SPSS 15.0 statistical software (SPSS). Data were presented as the mean ± SD (range).

Results
Anatomical Study

In the cadaver study, there were consistent contributions of C7 nerve root to the lateral pectoral nerve (LPN), thoracodorsal nerve (TN), long thoracic nerve (LTN), and radial nerve, especially the long head of the triceps branch (LHTB) (Table 2, Fig. 2). The distances were recorded from the C7 root (transverse foramen) to the nerve entry point of target muscles. The supraclavicular and infraclavicular brachial plexus specimens were thoroughly explored and their branches were dissected and traced under loupe magnification ×2.5, whereas distal to the elbow, the attribution of individual nerve fibers from C7 became less reliable due to the repeated divisions and anastomoses of the fascicles.

TABLE 2. Cadaver study of C7 root trajectory and its detailed branches

Nerve	Muscle Innervated (C7 component)	C7 Component	Distance From C7 Nerve Root to Nerve Entry Point of the Muscle (cm, mean ± SD)
LPN	Clavicular part of the PM	Yes, & C7 source accounted for the main component	10.3 ± 1.38
TN	Latissimus dorsi	Yes, & C7 source accounted for the main component	21.7 ± 1.77
LTN	Lower part of the serratus anterior	Yes, C7 source accounted for minor component, & the nerve entry point of the muscle is below the 7th rib level	24.1 ± 3.26
LHTB	Long head of the triceps brachii	Yes	23.4 ± 1.82

FIG. 2. A: The LPN in this case arose from the anterior divisions of the upper and middle trunk, across the axillary artery and vein, entering the clavicular part of the PM. The LPN and medial pectoral nerve were connected immediately distal to the thoracoacromial artery. B: In this case, the LPN arose from the posterior division of the middle trunk and lower trunk, in which the branch from the middle trunk was thicker in diameter. C: In this case, the LTN came from C6 and C7, the C7 source component accounted for the minor proportion, and the nerve entry point to the muscle is below the level of the seventh ribs. The *yellow arrow* indicates the nerve component from C6 and the *white arrow* indicates the nerve component from C7. D: In this case, the LHTB came from the middle and lower trunk. The *white arrow* indicates the LHTB. ADMT = anterior division of the middle trunk; ADUT = anterior division of the upper trunk; AS = arteria subscapularis; LT = lower trunk; MT = middle trunk; PDLT = posterior division of the lower trunk; PDMT = posterior division of the middle trunk; Pm = pectoralis minor muscle; UT = upper trunk. Figure is available in color online only.

Clinical Series

All patients in our study were confirmed to have TBPP during surgical exploration and underwent CC7 to C7 nerve transfer by a single senior surgeon. In the procedure, the average length of dissected CC7 nerve root was 6.5 ± 0.7 cm (range 4.5–8 cm). The mean length of sural nerve

TABLE 3. Nascent EMG potentials in targeted muscles (months postoperatively) in 6 patients with TBPP

Case No.	Pectoralis Major	Latissimus Dorsi	Triceps Brachii	Extensor Carpi	Flexor Carpi	Extensor Digitorum & Pollicis
1	7	9	11	17	16	23
2	6	9	11	17	16	22
3	8	12	14	20	19	26
4	6	8	10	17	17	24
5	7	9	12	16	17	20
6	6	9	11	16	17	22
Mean	6.67	9.33	11.50	17.16	17.00	22.83
SD	0.82	1.36	1.38	1.47	1.10	2.04

graft was 9.5 ± 2.5 cm (range 7.5–11.5 cm). There were no major intraoperative complications. The mean length of postoperative follow-up was 30.8 ± 5.3 months (range 26–40 months). Three patients had concurrent surgery that attached full-length PN to the anterior branch of AN.

In EMG studies (Table 3), compound muscle action potentials were recorded. For shoulder movement, nascent EMG potentials on pectoralis major (PM) muscles were detectable at a mean of 6.7 ± 0.8 months postoperatively (range 6–8 months), and on latissimus dorsi at 9.3 ± 1.4 months (range 8–12 months). All patients reported noticeable shoulder adduction at a mean of 10 months postoperatively (range 9–12 months). For elbow movement, nascent EMG potentials on triceps long head were detectable at 11.5 ± 1.4 months (range 10–14 months). All patients reported noticeable elbow extension at a mean of 14 months (range 12–17 months). For wrist and finger movement, nascent EMG potentials in the wrist extension muscles were detectable at 17.2 ± 1.5 months (range 16–20 months) on extensor carpal radialis longus and extensor carpal radialis brevis in all patients, and 22.8 ± 2.0 months (range 20–26 months) for extensor digitorum and thumb extensors. Four were reported to have noticeable wrist extension and only 1 was reported with noticeable finger/thumb extension at the latest follow-up. In 3 patients, noticeable antagonistic movement of flexor carpi radialis (FCR) was recorded, and their nascent EMG potentials in FCR were detectable at 17.0 ± 1.1 months (range 16–19 months).

Regarding motor functional recovery assessment (Table 4), the average recovery at the latest follow-up was M2– for PM, M3 for latissimus dorsi, M3+ for triceps, M2 for wrist extensors, M1+ for FCR, and M1+ for digital extensors. All patients achieved a good or excellent result for shoulder adduction and elbow extension, with 5 of 6 achieving power of M3 or higher. The average shoulder abduction was 25°–30° in 3 patients, whereas 75°–90° was achieved in patients with the PN transfer. Elbow flexion was graded as excellent in 4 cases and good in 2 cases. Two patients obtained M3 for wrist extension, whereas the wrist flexion and finger extension were poor. Moreover, although there was long-lasting cocontraction of the C7 innervating muscles on both sides even 2 years postoperatively, independent movement on the injured side could still be strengthened, especially when firing muscles on the healthy side, which was estimated quantitatively as modified BMRC grade 1.

For sensory recovery (Table 5), all patients achieved S2 in the index finger on the side of the injured upper limbs at the latest follow-up (except for one patient, who achieved only S1). The average 2-point discrimination (2-PD) sensory function test result was 12 mm (range 10–15 mm). For complications, no permanent impairment of donor limb function was reported. All patients experienced numbness and decreased 2-PD of the thumb and index and middle finger pulp; 5 of them recovered within 3 months and the other one within 6 months. Three patients experienced pain on the index finger, which all resolved within 3 months. One patient experienced a decrease of triceps muscle strength to M3+, which fully recovered within 1 month.

Discussion
Anatomical Findings
The CC7 is a potential donor nerve in treating brachial plexus injury[6,11,28,34] and central neurological injuries.[14,37,39]

TABLE 4. Motor functional recovery on affected side in 6 patients with TBPP

Case No.	Pectoralis Major	Latissimus Dorsi	Triceps Brachii	Extensor Carpi	Flexor Carpi	Extensor Digitorum & Pollicis
1	M2+	M3	M4	M2–	M2	M1
2	M3	M3	M3+	M2+	M1	M1
3	M1	M3+	M3+	M1+	M2–	M1
4	M3	M3	M4	M1+	M2	M1
5	M1	M3+	M2	M3+	M1	M2+
6	M1	M4	M4–	M3–	M1	M1+

The modified BMRC scale was used for scoring.

TABLE 5. Sensory function on both sides in 6 patients with TBPP

	Affected Side			Unaffected Side	
Case No.	Index Finger	2-PD (mm)	Paresthesia When Touching Unaffected Index Finger	Duration of Numbness (mos)	Duration of Unbearable Pain (mos)
1	S2	11	Yes	3	NA
2	S2	11	Yes	3	1
3	S1	15	Yes	6	3
4	S2	10	Yes	3	1
5	S2	12	Yes	3	NA
6	S2	11	Yes	3	NA

NA = not applicable.

The C7 nerve root possesses 25,000–40,000 fibers,[16] providing a great source of nerve fibers.[4,10,11,23] Current understanding of the brachial plexus[1,12,19,25] would suggest that C7 myotome contributes to the movements of different muscles, and there does not appear to be an action that is controlled solely by C7. Hence there is the potential that the nerve root could be expendable, which is in accordance with the findings in our functional neuroanatomy study for C7 nerve distribution—that LPN, TN, LTN, and LHTB were all supplied mainly by the components of C7 nerve root. The anterior division of the C7 nerve makes its contribution in the median and musculocutaneous nerves, whereas the posterior division of the C7 root participates in the AN, TN, and radial nerves.

Therefore, the motor fibers of the C7 nerve root are dispersive. The C7 root is presumed to functionally innervate muscles of multiple joints such as shoulder (latissimus dorsi, PM); elbow (triceps); wrist (extensor carpi radialis); and hand (extensor digitorum)—the functional restoration of these joints is observed primarily in our clinical study. In our anatomy study, the pattern of C7 nerve root branching was predictable. The cadaver study results were in accordance with previous research overall, except for particular findings. For instance, a specimen study of 100 adult cadavers showed that the LPN mostly originated from the anterior division of the upper trunk proximal to the point of lateral cord formation (88 of 100 cases).[1] However, in our study the LPN mostly arose from the anterior divisions of the upper and middle trunk (8 in 10 sides) or as a single root from the lateral cord (2 in 10 sides), across the axillary artery and vein, and entering the clavicular part of the PM.

The distance measured from the C7 nerve root to the nerve entry point of the PM was 10.3 ± 1.38 cm (range 7.9–12.0 cm). Moreover, in the present study we found that the TN arose from the posterior division of the middle and lower trunk, in which the branch from the middle trunk became thicker in diameter under loupe magnification ×2.5. The distance from the C7 root to the TN entry point of the muscle was 21.7 ± 1.77 cm (range 18.5–25.0 cm). Lu et al.[18] published their prediction of the origin of the dominant nerve of latissimus dorsi muscle, which they determined by intraoperative electrophysiological examination. They put forth a similar conclusion that the amplitude ratios suggested that the middle trunk exerted the greatest influence over the latissimus dorsi muscle (41.3% ± 2.56%), and their conclusion has been further supported by histochemical staining, which showed that approximately 52% of motor fibers in the TN came from C7.[19,35]

Regardless of research techniques, Lu et al. also proposed that TN fibers originate from each of the three trunks, whereas in our study TN arose from the middle trunk mainly and also the lower trunk. The anatomy of the LTN has not been fully elucidated. In our study it was found that the LTN was formed by branches arising from the C5, C6, and C7 nerve roots, and that the distance between the C7 nerve root and the LTN entry of the muscle was 24.1 ± 3.26 cm (range 20.5–30.0 cm). In the present study, the C5 and C6 branches joined beneath the scalenus muscles to form the upper division, and the branch from C7 contributed to the lower part of LTN, whereas Hamada et al.[12] found that the upper part was supplied mainly by the C5 nerve root, and the C4, C6, or C7 nerve roots also had multiple branches in 64 of 70 dissections. For the LHTB, it came from the middle and lower trunk. The distance from the C7 root to the nerve entry point of triceps muscle was 23.4 ± 1.82 cm (range 19.5–26.0 cm).

The different lengths of the nerve branches, which indicate the distance and time of nerve reinnervation, were particularly recorded in this study (Table 2). The time and order of recovery in specific target muscles could be estimated given the routes of the nerve transfer. Because the LPN had the shortest distance from the nerve root to nerve entry point of the clavicular part of the PM, it is presumed to be the first reinnervated muscle, which would be further supported by first emergence of the Tinel sign and EMG recording signals clinically. In other words, the PM or LPN function can be used as the first observation and assessment after the CC7 surgery to determine nerve reinnervation, to assess the effect of the surgery, and to achieve early intervention and rehabilitation.

From the cadaver study, the fact that there were consistent degradations of components from the C7 nerve root to the LPN, TN, LTN, and LHTB (Table 2, Fig. 2) would be solid evidence to support the hypothesis that a comprehensive functional recovery of the upper limb could be achieved on successful C7 regeneration. TBPP results in the most catastrophic prognosis,[3] and current concepts for treatment are primarily focused on neurotization. Therefore, based on anatomical studies, we designed the procedure of CC7 transfer to repair the avulsed C7 nerve root, and we combined electrophysiological and functional measures to explore the utility of C7 nerve as a recipient for TBPP. The CC7 transfer route is another important factor. Here, the feasibility of the retrosternocleidomastoid muscle route with cabled sural nerve grafts was tried and applied, because one of the major aims of the CC7 transfer deals with providing a route that is both short and safe to the maximum extent. As a matter of fact, several routes for CC7 transfer have been stated. Mcguiness and Kay[21] (2002) transferred the nerve through the retropharyngeal space. Xu et al.[36] (2008) accomplished the transfer through a tunnel posterior to the scalenus anterior muscle. Chuang and Hernon[6] (2012) performed a subcutaneous transfer for monitoring the progression of Tinel sign, although the

nerve route was longer than the prevertebral route. Similarly, Zhang and Gu[38] (2011) used a cross-chest subcutaneous tunnel. In the current investigation, based on the anatomical study, the retrosternocleidomastoid approach was used with the average nerve graft of 9.5 cm, which made a tension-free suture and a relatively short graft distance as compared to subcutaneous tunnel, and it was easy to perform the procedure and follow the Tinel sign compared with the prespinal route.

Clinical Series

As a result of the anatomical findings, comprehensive functional improvements were achieved on the injured upper limbs, especially for shoulder adduction and elbow extension functions. These functions—with a grade of M3 or greater attained by 5 of 6 patients—implied that the C7 nerve root commanded a stable and dominant role over the latissimus dorsi, PM, and triceps brachii. It showcased consistency with our anatomical study wherein the muscle branches of the C7 components were confirmed. Besides, according to the EMG study the PM that was dominated by LPN had an earlier recovery. Soon after, successful reinnervation of latissimus dorsi guaranteed a stronger shoulder adduction. This recovery time and the order of restoration of specific muscles could also be estimated by the distances measured from the C7 nerve root to the nerve entry point of related muscles. Regarding motor recovery, our results seem superior to previous researches. For instance, Gao et al.[8] discovered that the effective recovery rate, which was classified as a muscle grade of M3 or higher, was 56% in the study of ICN transfer to the nerve of the triceps long head in TBPP. Arnal et al.[2] included 21 patients with TBPP in their study, in which they grafted C5 root on the nerve of the triceps long head and, at a mean follow-up of 22 months, 62% of their patients had achieved M3 or higher.

Besides shoulder adduction, shoulder abduction and external rotation also play an important role for a comprehensive shoulder function, for which the muscles were innervated by SSN and AN. Various reconstructive procedures have been developed. Available donors include the SAN, ICN, PN, proximal C5–6 stump, CC7, and the triceps branch of the radial nerve. Sammer et al.[24] proposed hemi-CC7 as a neurotizer for shoulder function, and attained only 23% acceptable shoulder abduction. Chuang and colleagues[5,7] reported 8 different combinations of neurotization procedures for shoulder reconstruction. They concluded that simultaneous neurotization to the SSN and AN obtained better results than just neurotization to the SSN. Tu et al.[31] also achieved a similar result by dual neurotization procedures (SAN-SSN combined with ICN-AN). In our case series dual neurotization procedures were applied (SAN-SSN combined with PN-AN). With this procedure significant shoulder abduction was achieved, together with strong shoulder adduction, which provided sound shoulder function.

The recovery of wrist and finger extension did not satisfy our expectations, even though the compound muscle action potentials had been recorded at 17.2 ± 1.5 months postoperatively on wrist extensors and at 22.8 ± 2.0 months on digital extensors. Moreover, finger extension recovered

with more difficulty than the wrist; the latest follow-up (average 30 months postoperatively) showed that just 2 patients achieved a grade of M3 for wrist extension, whereas only 1 received a grade of M2 for finger extension. Although the longest follow-up reached 40 months, patients' functions had not changed in the last 10 months. This demonstrates that the recovery of wrist and digital extension is not reliable and stable. The following reasons are likely to explain. 1) These patients mostly achieved a much better improvement in shoulder and arm function postoperatively (Table 4). It implies that the total number of fibers from the C7 nerve root to the shoulder and elbow is greater than that to the wrist and fingers. Experiments with different donor-to-target axon ratios in rabbits have demonstrated helpful motor recovery starting at a 1:3 ratio.[20] Research in rats also revealed that at least 30% of the original motor neurons were needed to achieve normal muscle strength.[30] In the present study, the difference in the number of fibers led to the different recoveries in target muscles, and it could predict that better recovery was unlikely to be achieved even in longer follow-up. 2) Persistent strong wrist flexion antagonism may be another reason for the unsatisfactory wrist recovery. Anatomy and EMG studies have shown that FCR also shared a proportion of fibers from the C7 nerve root, thus causing ineffective wrist movement after regeneration, because there was antagonism of wrist extension and flexion. For these patients with Tinel sign at the supinator tunnel, the neurolysis for the deep branch of the radial nerve was done by opening the supinator tunnel; however, it was found that the finger extension recovered but the wrist did not, which further implied that the antagonism of wrist flexion led to the poor recovery of wrist movement.

Cocontraction movement is proposed to be another interesting phenomenon—patients could obtain more improvement in shoulder and elbow functions by simultaneous firing of shoulder adduction or elbow extension on the healthy side, which was especially so with the same movement on the injured side. This phenomenon may be attributed to the fact that the CC7 nerve delivers the nerve fibers connecting both sides, and in this procedure the reshaping of the two hemispheres is easier.[13,15,27] With regard to the similarity of diameters and fibers between CC7 and avulsed C7 nerve roots, neural connection was easily established, which was favorable for the functional recovery of the limb[22] and brain plasticity.[39]

There are some limitations in this study; it lacks high statistical power on account of the small number of samples. Because 2 cases were excluded from the initial 8 patients in this study, which might affect the results, special cautions should be taken for patients with severe concomitant soft-tissue damage, and more cases are needed for further research. Moreover, it was apparent in the anatomical study that the LTN got proportional fibers from the C7 nerve root. However, it was not practical for us to study the serratus reinnervation because all the nerve roots were avulsed, making it infeasible to repair the LTN at the C7 nerve root level.

Conclusions

The C7 nerve root contributes consistently to the LPN,

the TN, and the LHTB of the radial nerve. CC7 to C7 nerve transfer is a reconstructive option in the overall management plan for TBPP. It was safe and effective in restoring shoulder adduction and elbow extension in this patient series. However, recoveries of wrist and finger extensions were poor.

Acknowledgments

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Disclosures

Author Contributions

Conception and design: WD Xu, GB Wang, Yu, Gu, JG Xu, Jiang. Acquisition of data: Yu, XM Wang, Feng, Li, Chen, He, Ding, Cui. Analysis and interpretation of data: GB Wang, Jiang. Drafting the article: WD Xu, GB Wang, Yu, Jiang. Critically revising the article: WD Xu, GB Wang, Yu, Jiang. Critically revising the article: Ng, Lei, He, Ding, Cui, Gu, JG Xu. Reviewed submitted version of manuscript: Ng. Statistical analysis: Yu, Lei, Qiu. Administrative/technical/material support: Ng, Qiu. Study supervision: WD Xu, Jiang. Anatomy study: WD Xu, GB Wang, Qiu.

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