The Impact of Different Degrees of Injured C7 Nerve Transfer: An Experimental Rat Study

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Background: Ipsilateral C7 nerve transfer is an available procedure in C5C6 2-root avulsion injury of the brachial plexus. However, concomitant injury of a normal-looking C7 cannot be ruled out. The efficiency of a concomitant injury of C7 transfer was investigated.

Methods: Forty-two Sprague-Dawley rats were randomly assigned to 5 groups. They all underwent a 2-stage procedure. In the first stage from dorsal spine approach, left C5 and C6 roots were avulsed and C7 was crushed with jeweler’s forceps with different degrees: group A (n = 6), C7 not injured; group B (n = 10), C7 crushed for 10 seconds; group C (n = 10), C7 crushed for 30 seconds; group D (n = 10), C7 doubly crushed for 60 seconds; and group E (n = 6), C7 transected and not repaired. Four weeks later in the second stage, the C7 was reexplored via volar approach, transected, and coapted to the musculocutaneous nerve. At 12 weeks following the nerve transfer, functional outcomes were assessed.

Results: Grooming test, muscle weight, electromyography, and muscle tetanic contraction force all showed that the biceps muscles were significantly worse in group C (moderate crush) and group D (severe crush). Group B (mild crush) and group A (uninjured) showed no difference. Group E (C7 cut and not repaired) was the worst.

Conclusions: An injured but grossly normal-looking ipsilateral C7 can be used as a motor source but with variable results. The result is directly proportional to the severity of injury, potentially implying that better results will be achieved when longer regeneration time is allowed. (Plast Reconstr Surg Glob Open 2014;2:e230; doi: 10.1097/GOX.0000000000000198; Published online 9 October 2014.)

In brachial plexus injury, ipsilateral C7 is quite often used to transfer to the upper trunk in C5C6 2-root avulsion for shoulder and elbow restoration.1-3 C7 transfer brings a vast number of myelinated nerve fibers. Its anterior division contains 29.8% of median and 23.7% of musculocutaneous nerves (MCNs), and the posterior division comprises 22% axillary, 45% radial, and 53% dorsal...
thoracodorsal nerves. In addition, loss of a C7 spinal nerve is mostly compensable, resulting in no impairment of original function. C7 spinal nerve can be used as a neurotizer (motor and sensory) for transfer contralaterally or ipsilaterally. However, ipsilateral C7 transfer does not always work well. The health of a C7 donor nerve is a critical determining factor for success of nerve transfer. Clinically, the C7 root is involved more often than any other root in brachial plexus injury, from stretching to avulsion injury. It is difficult for a surgeon to decide if a macroscopically normal-looking C7 is suitable for transfer. The purpose of this study was to assess the impact of different degrees of injured C7 when used as a donor nerve for transfer.

PRELIMINARY STUDY

To see the phenomenon of the nerve regeneration after different crush injuries, and to determine when is the suitable time for nerve transfer and for nerve evaluation after crush injury, 20 Sprague-Dawley rats underwent the preliminary study. The rats, approximately 250 g each in weight, were randomly separated into 4 groups (A–D). From the back spine approach, the C5 and C7 were avulsed, and the C6 was crushed by microneedle holder (curved one, 8/150 mm with lock, Prima, Germany) and by the same person (T.N.-J. Chang) with different degrees: group A, crushed for 10 seconds; group B, for 30 seconds; group C, for 60 seconds; and group D, doubly crushed by 2 same needle holders for 60 seconds. Functional outcomes of the biceps muscle were evaluated with grooming test, electromyogram-muscle action potential (stimulated the MCN at its origin from the lateral cord and recorded the biceps muscle), muscle (biceps) tetanus contraction force, and muscle (biceps) weight at 1, 2, 4, 8, and 12 weeks postoperatively.

Results are shown in Figure 1. At 4 weeks after nerve crush, all 4 evaluation methods showed that all the crushed nerves seemed to reach a point to start to activate the denervated biceps muscle. At 12 weeks postoperatively, all 4 methods showed that the 4 groups have reached their individual plateau of functional recovery.

In conclusion, by this preliminary investigation, 4 weeks after nerve crush injury will be a suitable time to perform the nerve transfer. Functional evaluation of the upper extremity was usually performed at 12 weeks after nerve surgery in rats.

MATERIALS AND METHODS

Forty-two Sprague-Dawley male rats, weighing approximately 250 g each, were randomly separated into 5 groups (A–E) and underwent a 2-stage procedure (Fig. 2). Left brachial plexus was used as the experimental site, C6 spinal nerve the motor neurotizer, and MCN and biceps muscle the targets to be neurotized. All animals were cared for in accordance with established principles for the care of research animals approved by Chang Gung Memorial Hospital Animal Care Committee. Postoperatively, the rats were housed in a light-controlled and temperature-controlled environment and given water and standard chow ad libitum until they were humanely killed for further investigation.

In the first stage, from the back cervical spine approach, the C5 and C6 were avulsed, and C7 was crushed by No. 5 jeweler's forceps (Venus 5, Micro forceps, Regine, Switzerland) performed by the same surgeon (C.-H.J. Tzou) to exert different degrees of injuries simulating the clinical trauma: group A (n = 6, control), C7 was uninjured; group B (n = 10), C7 was crushed for 10 seconds (simulating Sunderland I injury); group C (n = 10), C7 was crushed for 30 seconds (simulating Sunderland II injury); group D (n = 10), C7 was doubly crushed by 2 forceps for 60 seconds (simulating Sunderland III injury); and group E (n = 6, negative control), C7 was completely transected (simulating Sunderland V injury). The proximal end was sutured to the nearby ligament. To change the crush tool from microneedle holder in the preliminary study to the No. 5 jeweler forceps in this study, the microneedle holder was considered not strong enough for nerve crush. In addition, to decrease the number of killed rats, group A (positive control) and group E (negative control) were all 6 rats in contrast to n = 10 in the study groups. The relationship of severity of the nerve crush injury and

Disclosure: The authors have no financial interest to declare in relation to the content of this article. This study was supported by the grant of the Chang Gung Memorial Hospital, Linkou, Taiwan (CMRP-G3B1211), and the Erwin Schrödinger Fellowships scholarship (J3254-B09) of the Austrian Science Fund (FWF) awarded to the first author (C.-H.J. Tzou). The Article Processing Charge was paid for by the Austrian Science Fund.
Sunderland classification was a hypothesis based on the preliminary study and clinical experience.

In the second stage, 4 weeks later, from the volar neck approach, left brachial plexus was explored. The distal C7, close to the MCN, was transected. The MCN was transected too. The proximal C7 stump was coapted to the nearby distal MCN stump, end-to-end directly without tension (Fig. 2).

Regeneration for 12 weeks following nerve transfer was allowed. Biceps muscle was evaluated with behavioral (grooming test), electromyogram-muscle action potential, muscle tetanus contraction force, and muscle weight at 1, 2, 4, 8, and 12 weeks postoperatively (see text). The y-axis in the graphs: "mV" for electromyogram; "mg" for muscle weight; "g" for muscle contraction force; "an average score" for the grooming test (scores 0–5).

**Surgical Procedures**

**First Stage: Crush Injury**

All surgical procedures were performed under sterile conditions and anesthesia by inhalation of isofluorane (Halocarbon Laboratories, River Edge, N.J.). The animals were placed in the prone position, hair was shaved, and skin was washed with antiseptic solution. Under an operating microscope, the left brachial plexus was exposed via a vertical incision in the paravertebral region, and the nerve trunks were identified using a nerve stimulator (Vari-Stim handheld nerve locator/stimulator, Medtronic Xomed, Minneapolis, Minn.). The C5 and C6 roots were avulsed, and C7 was crushed for various durations (10 seconds, 30 seconds, and double crushes 60 seconds) using jeweler’s forceps. The crush site was marked with one 10-0 nylon suture. The wound was closed with nylon 4-0 sutures.

**Second Stage: Nerve Transfer**

After 4 weeks, the animal was put in supine position. The left brachial plexus was reexposed via an incision from the supraclavicular to the cubital region. The C7 was identified and transected at distal to the crush site but close to the MCN. The MCN was cut right after its bifurcation from the lateral cord. Coaptation of C7 and MCN was performed with 11-0 nylon sutures. The terminal MCN distal to the bi-
ceps muscle was cut and transferred back into the biceps muscle to avoid loss of regenerated axons. The wound was closed with 4-0 nylon sutures. To obtain postoperative immobilization, the left arm was immobilized to the chest with adhesive bandage for 1 week. Animals were rewarmed and returned to their cage.

**Third Stage: Outcomes Evaluation**

Twelve weeks after the second stage of nerve transfer, all experimental limbs were checked with grooming test, muscle electrophysiological study, tetanus contraction force, and weight (Table 1). To avoid animals’ weight-dependent result discrepancies, each animal’s experimental side was also expressed in ratio (%) of experimental/healthy site (E/H) in parentheses (Table 2). Axon counts of the MCN distal to the nerve coaptation site were also performed (Table 3).

**Behavioral Analysis**

Function of the upper extremity was analyzed at 12 weeks after surgery using the grooming test developed by Bertelli and Inciong, which assessed shoulder abduction and elbow flexion. Water (1–3 ml) was applied over the animal’s snout to provoke a reproducible grooming response: attempting to remove drops of water from their heads, animals raised and elevated their forelimbs behind the ears, then brought them down to the snout to be licked. Digital video recordings were assessed in slow motion to categorize the forelimb function on a 5-point scale: 5 points if the paw reached behind the ear, 3 points if the paw passed the snout but did not reach the eye, and 1 point if the paw moved but did not reach the snout. Multiple assessments were performed, and the best score was recorded.

**Electromyogram**

At 12 weeks, after the grooming test, animals were prepared again under general anesthesia. The left C7, MCN, and biceps muscle were exposed. A recording electrode was placed in the biceps muscle.
and a subcutaneous ground electrode positioned adjacent in the electromyogram setup. Two small hook-shaped stimulating electrodes (2 mm apart) held MCN gently. Stimulation was delivered for each trial by an electrical stimulator (Biopac System, BSL Software Installation Package, Windows, Goleta, Calif.), fixed at 1 millisecond at a constant current between 10 mA and 10 A. The muscle action potentials were recorded.

**Muscle Tetanus Contraction Force Measurement**

After electrophysiological study, the biceps muscle contraction force was assessed with a force displacement transducer and computerized recording software (FT03 Force Displacement Transducers, Grass Instruments, Quincy, Mass.). Force measurement followed a modified protocol based on Terzis's and Shibata's procedure. Resting muscle length of biceps was determined, and its insertion was detached from the cubital region and then reattached with the muscle resting length to the force transducer. The shoulder, elbow, and wrist joints were immobilized with fixation pins to avoid motion artifacts during muscle-contraction measurements. Stimulating current was applied with a bipolar platinum electrode distal to the repaired side. The threshold stimulus was defined as the stimulus that was required to produce an observable muscle twitch. Stimulation of the MCN was performed for activation of the biceps muscle at different thresholds (1 to 10 times

| Table 1. Comparison of Muscle Weight, Muscle Electromyography, and Muscle Contraction Force among Groups |
|---------------------------------------------------------------|
| **Groups**         | **Outcomes**                           |             |
|                   | Muscle Weight (g) | Biceps Muscle Action Potential (mV) | Biceps Muscle Tetanus Contraction Force (g) |
| A (C7 intact and transfer, n = 6) | 0.30 ± 0.02 | 4.05 ± 0.37 | 36.40 ± 3.79 |
| B (C7, 10″ crush and transfer, n = 10) | 0.29 ± 0.03 | 3.81 ± 0.90 | 32.65 ± 12.40 |
| C (C7, 30″ crush and transfer, n = 10) | 0.25 ± 0.02 | 2.82 ± 0.58 | 30.72 ± 9.76 |
| D (C7, 60″ double crush and transfer, n = 10) | 0.26 ± 0.03 | 2.38 ± 0.89 | 17.88 ± 14.16 |
| E (C7 and MCN cut without transfer, n = 6) | 0.38 ± 0.04 | 5.56 ± 0.82 | 50.29 ± 12.65 |
| H (control, right side of upper limb) | <0.001 | <0.001 | <0.001 |

**P** value (KW test, ABCD, and control) <0.001 <0.001 <0.001

Significant difference by post hoc Dunn test AB (1.000), BC (0.020), AC (0.012), BD (0.224), AD (0.019), CD (1.000)

The values given in parentheses followed by mean ± SD are the valid sample sizes.

**Dunn test (pairwise comparison) was performed if P** value by Kruskal-Wallis test was <0.05 (significant).

**Bold indicates significant value.**

KW, Kruskal-Wallis test; MCN, musculocutaneous nerve; NA, not applicable.

| Table 2. Comparison of Experimental Side with Nonoperative Side among Groups with % |
|---------------------------------------------------------------|
| **Groups**         | **Outcomes**                           |             |
|                   | Muscle Weight Ratio (E/H) and % | Bimuscle Action Potential Ratio (E/H) and % | Bimuscle Tetanus Contraction Force Ratio (E/H) and % |
| A (C7 intact and transfer, n = 6) | 0.88 ± 0.07 (88%) | 0.83 ± 0.05 (83%) | 0.72 ± 0.14 (72%) |
| B (C7, 10″ crush and transfer, n = 10) | 0.76 ± 0.08 (76%) | 0.64 ± 0.05 (64%) | 0.70 ± 0.16 (70%) |
| C (C7, 30″ crush and transfer, n = 10) | 0.69 ± 0.06 (69%) | 0.50 ± 0.10 (50%) | 0.55 ± 0.18 (55%) |
| D (C7, 60″ double crush and transfer, n = 10) | 0.67 ± 0.05 (67%) | 0.44 ± 0.03 (44%) | 0.32 ± 0.25 (32%) |
| E (C7 and MCN cut without transfer, n = 6) | 0.002 | 0.099 | 0.001 |

**P** value (KW test) AB (0.460), BC (0.408), AC (0.005), BD (0.054), AD (<0.001), CD (1.000)

Significant difference by post hoc Dunn test AB (0.828), BC (0.531), AC (0.017), BD (0.035), AD (0.001), CD (1.000)

The values given in parentheses followed by mean ± SD are the valid sample sizes.

**Dunn test (pairwise comparison) was performed if P** value by Kruskal-Wallis test was <0.05 (significant).

**Bold indicates significant value.**

E/H, ratio of experimental side/healthy side; KW, Kruskal-Wallis test; MCN, musculocutaneous nerve.

| Table 3. Comparison of Axon Counts of Musculocutaneous Nerve Distal to the Nerve Coaptation among Groups |
|---------------------------------------------------------------|
| **Group**         | **Axon Count** |
|                   | (in average) |
| A (C7 intact and transfer) | 826.4 ± 165.4 |
| B (C7, 10″ crush and transfer) | 529.0 ± 169.2 |
| C (C7, 30″ crush and transfer) | 425.0 ± 284.5 |
| D (C7, 60″ double crush and transfer) | 603.6 ± 191.8 |
| Normal C7 | 1413 ± 380.0 |

**Muscle Tetanus Contraction Force Measurement**

After electrophysiological study, the biceps muscle contraction force was assessed with a force displacement transducer and computerized recording software (FT03 Force Displacement Transducers, Grass Instruments, Quincy, Mass.). Force measurement followed a modified protocol based on Terzis’s and Shibata’s procedure. Resting muscle length of biceps was determined, and its insertion was detached from the cubital region and then reattached with the muscle resting length to the force transducer. The shoulder, elbow, and wrist joints were immobilized with fixation pins to avoid motion artifacts during muscle-contraction measurements. Stimulating current was applied with a bipolar platinum electrode distal to the repaired side. The threshold stimulus was defined as the stimulus that was required to produce an observable muscle twitch. Stimulation of the MCN was performed for activation of the biceps muscle at different thresholds (1 to 10 times...
the threshold), different voltages (range, 0.6–1.2 V), and different frequencies (range, 1.0–60 Hz). With various stimuli, the maximal tetanic strength was determined at 1 V and 60 Hz and recorded as grams/weight. The mean maximal isometric muscle contraction of the repeated muscle contraction forces (5 times with a pulse duration of 1.0 millisecond) was recorded. All data were controlled, analyzed, and recorded by MacLab Systems (AD Instruments, Colorado Springs, Colo.).

**Muscle Weights**

After the above measurements, animals were euthanized by additional pentobarbital administration. Biceps muscles (operative and nonoperative sites) were harvested and weighed immediately.

**Axon Counts**

Nerve specimens (3–5 mm in length) were obtained from MCN before its entry into the biceps muscle and from the C7 proximal to the coaptation site. Samples were fixed in 2.5% glutaraldehyde and postfixed in 2% osmium tetroxide. Each nerve was embedded in 100% Epon. One-micrometer-thick transverse sections were made from the nerve to obtain successive sections in 1-mm intervals, which were stained with 2% toluidine blue. The axon count per se is not a reliable measurement. The selected section was photographed under a light microscope (from original magnification 400× enlarged to 1000×). Under further magnification, the axons were counted by hand in each specimen.

**Statistical Analysis**

Data were expressed as mean ± SD values in each group. The Kolmogorov-Smirnov test was used to check for normal distribution of the data, and the Kruskal-Wallis test was performed to compare performances of each group in grooming test, muscle force and weight, and electromyography. Dunn’s test was used as a post hoc test when groups were significantly different (P < 0.05). A Mann-Whitney test was used to compare the axon counts between groups. A P value < 0.05 was considered statistically significant. Statistical analysis was performed with IBM SPSS Statistics software, version 20.0 (IBM, released 2011, Armonk, N.Y.) by the Biostatistical Center for Clinical Research, Chang Gung Memorial Hospital, Linkou, Taiwan.

**RESULTS**

**Behavioral Analysis/Grooming Test**

The rat’s operative and nonoperative sides for all groups were evaluated carefully. The grooming test on the right (nonoperated side) showed that the paw could pass at least the eyes and scored on average 4.17±0.51 in all groups. However, the experimental side (left) all showed only elbow flexion with mean score of 1, except the group E (complete division without repair), which had no movement at all.

**Electrophysiologic Testing**

Electromyography of the biceps muscle after stimulation of the MCN on the operative and nonoperative sides was performed (Table 1). In the operative side, it showed low amplitudes in groups C and D, with an average of 2.82±0.58 mV (50% of healthy side, Table 2) and 2.38±0.89 mV (44% of healthy side, Table 2), respectively, but high amplitudes in group B (average, 3.81±0.90 mV, 64% of healthy side, Table 2) and group A (average, 4.05±0.37 mV, 83% of healthy side, Table 2). These results of those rats who had crush injury and nerve transfer (groups B, C, and D) were statistically significant (<0.05) compared with those of the healthy side (group H, average, 5.56±0.82 mV). Statistically significant differences between the experimental groups were observed between groups A and C, groups A and D, and groups B and D (Table 1).

**Muscle Tetanus Contraction Force Measurement**

Biceps muscle tetanus contraction force decreased with more injury of the C7 nerve: group A with an average elbow flexion strength 36.40±3.79 g (72% of healthy side, Table 2), group B 32.65±12.40 g (70% of healthy side, Table 2), group C 30.72±9.76 g (55% of healthy side, Table 2), and group D 17.88±14.16 g (Table 1) (32% of healthy side, Table 2). Statistically significant differences (P < 0.001) could be seen when compared to the healthy side (average, 50.29±12.65 g). Statistically significant differences between the experimental groups were seen between groups A and C, groups A and D, and groups B and D.

**Muscle Weight**

Muscle weight evaluation presented the heaviest muscle weight in the healthy group (average, 0.38±0.04 g), followed by group A (average, 0.30±0.02 g, 88% of healthy side), group B (average, 0.29±0.03 g, 76% of healthy side), group C (average, 0.25±0.02 g, 69% of healthy side), and then group D with the lowest (average, 0.26±0.05 g, 67% of healthy side) (Tables 1 and 2). Statistically significant differences (P < 0.001) were observed between the experimental and healthy groups. Statistically significant differences between the experimental groups were seen between groups A and C, groups A and D, and groups B and C.
Axon Counts

Axon counts of healthy C7 spinal nerves (Table 3) were 1413 ± 380.0 on average. Axon counts of the MCN distal of the coaptation site showed average in group A 826 ± 163.4, group B 529 ± 169.2, group C 425 ± 284.5, and group D 603 ± 191.8. Group D showed the highest. Perhaps a double crush injury serves a double stimulation of the donor nerve, but only resulted in a greater number of dysfunctional axons. Although substantial differences existed between the groups, they are not statistically significant (P = 0.055).

Statistically significant correlation was only observed between axon counts and muscle contraction (P = 0.024).

DISCUSSION

Classification of Nerve Injuries

Seddon,20 in 1943, classified the nerve injuries into 3 different types: neurapraxia, axonotmesis, and neurotmesis. Sunderland,15 in 1951, expanded the Seddon classification of nerve injuries into 5 degrees: Sunderland I, segmental demyelination; Sunderland II, disrupted axon with intact endoneurium; Sunderland III, disrupted axon and endoneurium; Sunderland IV, disrupted endoneurium and perineurium, neuroma in continuity; and Sunderland V, complete transection of nerve. When C5 and C6 are avulsed, the nearby C7 has high tendency to have concomitant injuries, although it may show macroscopically normal appearance with positive nerve stimulation (Sunderland I to III injury). This might be the main reason why reconstruction with ipsilateral C7 transfer results in different outcomes clinically.

Crushed by Jeweler’s Forceps

In our preliminary study, we used microneedle holder. In this study, we used jeweler forceps. People may wonder how to standardize the pressure control. The whole nerve crush process was performed by the same surgeon and used the same jeweler’s forceps to avoid potential difference of the pressure applied.

Timing of the Ipsilateral C7 Nerve Transfer

Muscle tetanus contraction force in this study shows strong force in group A, 72% of the healthy limb (Table 2), and group B, 70%. However, unacceptable functional recovery is noted in group C, 55%, and group D, 32%, showing significantly lower than group A (P < 0.035). These findings are also confirmed by electromyography of the biceps muscle action potentials and muscle weights (Table 2). Statistically significant correlation of axon counts with data of muscle contraction force is observed (Table 3) in groups B and C, but not in group D. Axon counts of group D show around 12% more axons than group B and 42% more than group C.

Perhaps a double nerve crush serves as a double stimulation with more axon sprouting, but most of them are immature and functionless. The time point for nerve transfer in group D was just not optimal.

The more severely the nerve is crushed, the more axon sprouting with an immature pattern will be observed, which needs more time for maturation. At a period of 4 weeks following a more severe C7 crush injury, the C7 donor nerve might not have reached an optimum time point either of nerve regeneration or for nerve transfer. Early nerve transfer in more severe crushing injured nerve might downgrade the final functional results. Further investigation is necessary to determine whether the timing of a partially injured donor nerve for transfer has any effect on the outcome. Statistical analysis on the data from the preliminary study is valuable, which can give some clue. What will be the results at 16 weeks to conclude the optimal time for final evaluation? What will be the results if groups B–D are all allowed a 12 weeks regeneration period and then transferred? All of these questions need to be answered for us to determine whether a late transfer of a partially injured donor nerve has an advantage in terms of the outcome.

CLINICAL IMPLICATIONS

For a closed injury of the brachial plexus, the general recommendation for timing of exploration is still under debate. Some authors recommend an urgent exploration and nerve repair simultaneously to avoid a difficult dissection at a later stage.21,22 However, judgment of the degree and extent of a normal-looking donor nerve in a traction injury in the acute stage is difficult and doubtful. Selection of a healthy stump is very crucial for a successful repair. A close supervision of the patient for a period of 3–6 months14,23,24 seems logical and practical based on this experimental study. The benefits of such waiting will outweigh the advantage of early surgery. How early can a transfer downgrade the final outcome? How late can a transfer upgrade the final outcome? Further investigations are necessary too.

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ACKNOWLEDGMENTS

We thank Pei-Ju Chen and Ruby Yih-Ru Chang for their professional and continuous technical assistance throughout this study and Ms. Hsiao-Jung Tseng, M.P.H., from the Department of Biostatistical Center for Clinical Research, Chang Gung Memorial Hospital, Taoyuan, Taiwan, for her statistical support and analysis of the data.

REFERENCES

1. Xu JG, Hu SN, Wang H, et al. A study of the clinical application of ipsilateral selective C7 transfer. Chin J Hand Surg. 1999;15:151–153.
2. Gu YD, Cai PQ, Xu F, et al. Clinical application of ipsilateral C7 nerve root transfer for treatment of C5 and C6 avulsion of brachial plexus. Microsurgery 2003;23:105–108.
3. Song J, Chen L, Gu Y. Effect of ipsilateral C7 nerve root transfer on restoration of rat upper trunk muscle and nerve function after brachial plexus root avulsion. Orthopedics 2010;33:886.
4. Chuang DC, Wei FC, Noordhoff MS. Cross-chest C7 nerve grafting followed by free muscle transplantations for the treatment of total avulsed brachial plexus injuries: a preliminary report. Plast Reconstr Surg. 1993;92:717–725; discussion 726–727.
5. Liu J, Pho RW, Kour AK, et al. Neurologic deficit and recovery in the donor limb following cross-C7 transfer in brachial-plexus injury. J Reconstr Microsurg. 1997;13:237–242; discussion 242–243.
6. Gu YD, Shen LY. Electrophysiological changes after severance of the C7 nerve root. J Hand Surg Br. 1994;19:69–71.
7. Chuang DC, Cheng SL, Wei FC, et al. Clinical evaluation of C7 spinal nerve transaction: 21 patients with at least 2 years’ follow-up. Br J Plast Surg. 1998;51:285–290.
8. Gu YD, Zhang GM, Chen DS, et al. Seventh cervical nerve root transfer from the contralateral healthy side for treatment of brachial plexus root avulsion. J Hand Surg Br. 1992;17:518–521.
9. Gu YD. Contralateral C7 root transfer over the last 20 years in China. Chin Med J (Engl). 2007;120:1123–1126.
10. Chuang DC. Contralateral C7 transfer (CC-7T) for avulsion injury of the brachial plexus. Tech Hand Up Extrem Surg. 1999;3:185–192.
11. Chuang DC, Cartherine H. Minimum 4-year follow-up on contralateral C7 nerve transfers for brachial plexus injuries. J Hand Surg Am. 2012;37:270–276.
12. Castaldo JE, Ochoa JL. Mechanical injury of peripheral nerves: fine structure and dysfunction. In: Terzis JK, ed. Microreconstruction of Nerve Injury. Philadelphia, Pa.: WB Saunders; 1987:15–31.
13. Chuang DC. Adult brachial plexus injuries. In: Mathes SJ, Hentz VR, eds. Plastic Surgery. Volume 7. Philadelphia, Pa.: Saunders Elsevier; 2006:515–538.
14. Bridge PM, Ball DJ, Mackinnon SE, et al. Nerve crush injuries—a model for axonotmesis. Exp Neurol. 1994;127:284–290.
15. Sunderland S. A classification of peripheral nerve injuries producing loss of function. Brain 1951;74:491–516.
16. Bertelli JA, Mira JC. Behavioral evaluating methods in the objective clinical assessment of motor function after experimental brachial plexus reconstruction in the rat. J Neurosci Methods 1993;46:203–208.
17. Inciong JG, Marrocco WC, Terzis JK. Efficacy of intervention strategies in a brachial plexus global avulsion model in the rat. Plast Reconstr Surg. 2000;105:2059–2071.
18. Terzis JK, Sweet RC, Dykes BW, et al. Recovery of function in free muscle transplants using microneurovascular anastomoses. J Hand Surg Am. 1978;3:37–59.
19. Shibata M, Breidenbach WC, Ogden L, et al. Comparison of one- and two-stage nerve grafting of the rabbit median nerve. J Hand Surg Am. 1991;16:262–268.
20. Seddon HJ, Medawar PB, Smith H. Rate of regeneration of peripheral nerves in man. J Physiol. 1943;102:191–215.
21. Narakes A. Surgical treatment of traction injuries of the brachial plexus. Clin Orthop Relat Res. 1978;133:71–90.
22. Birch R. Brachial plexus injury: the London experience with supraclavicular traction lesions. Neurosurg Clin N Am. 2009;20:15–23, v.
23. Millesi H. Brachial plexus injuries. Nerve grafting. Clin Orthop Relat Res. 1988;237:36–42.
24. Terzis JK, Papakonstantinou KC. Management of obstetric brachial plexus palsy. Hand Clin. 1999;15:717–736.