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A Systematic Review of Outcomes of Contralateral C7 for the Treatment of Traumatic Brachial Plexus Injury: Part 1-Overall outcomes of contralateral C7 transfer for traumatic brachial plexus injury

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Abstract

Background—Contralateral C7 (CC7) transfer has been used for treating traumatic brachial plexus injury. However, the effectiveness of CC7 transfer remains a subject of debate. We performed a systematic review to study the overall outcomes of CC7 transfer to different recipient nerves in traumatic brachial plexus injuries.

Methods—A literature search was conducted using PubMed and EMBASE databases to identify original articles related to CC7 transfer for traumatic brachial plexus injury. The data extracted were study/ patient characteristics, and objective outcomes of CC7 transfer to the recipient nerves. We normalized modifications of MRC and other outcome measures into an MRC-based outcome scale for comparisons.

Results—Thirty-nine studies were identified. The outcomes were categorized based on the three major recipient nerves: median, musculocutaneous, and radial/triceps nerves. Regarding overall functional recovery, 11% of patients achieved MRC grade M4 wrist flexion and 38% achieved M3. Grade M4 finger flexion was achieved by 7% of patients whereas 36% achieved M3. Finally, 56% of patients achieved ≥S3 sensory recovery in the median nerve territories. In the musculocutaneous nerve group, 38% of patients regained elbow flexor strength to M4 and 37% regained to M3. In the radial/triceps nerve group, 25% regained elbow or wrist extension strength to an MRC grade M4 and 25% regained to M3.

Conclusions—Outcome measures in the included studies were not consistently reported to uncover true patient-related benefits from the CC7 transfer. Reliable and validated outcome instruments should be applied to critically evaluate patients undergoing CC7 transfer.

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Keywords

Traumatic Brachial Plexus Palsy; Contralateral C7 transfer

INTRODUCTION

Traumatic brachial plexus injuries are devastating, causing paralysis and loss of sensation in the affected limb. Nerve reconstruction consists of nerve transfer and nerve repair.[1, 2] In cases of total brachial plexus avulsion injuries when proximal nerves are not available for repair, nerve transfer is suggested to restore useful limb functions.[3] However, even with advanced microsurgery techniques, treatment of these injuries remains challenging.

Contralateral C7 (CC7) transfer was first introduced by Gu in 1986 to treat total brachial plexus avulsion injuries when donor nerves are in short supply.[4] In this surgical technique the whole or partial seventh cervical nerve on the uninjured side is transferred to neurotize the injured nerve on the injured side using nerve graft. Theoretically, C7-innervated muscles are cross-innervated by C6 and C8, with C5 and T1 contributing partially.[5] Therefore, the donor-site limb would most likely maintain satisfactory motor functions after C7 is harvested. The major advantage of CC7 transfer is that C7 nerve contains more myelinated nerve fibers than other available donor nerves, which can provide adequate power for neurotization.[6] On the other hand, the noticeable disadvantages of CC7 transfer are long distance over which nerve must regenerate and potential donor-site deficits.

CC7 transfer has been widely used for treating brachial plexus injuries, especially for total brachial plexus avulsion injury. However, current literature reports different results, and the effectiveness of CC7 transfer remains controversial. Some studies presented optimistic results and suggested CC7 transfer as an acceptable and desired treatment for total brachial plexus avulsion injury.[7, 8] Others reported unsatisfying outcomes and believed this technique was unreliable.[9, 10] High levels of evidence data may be difficult to obtain for rare conditions when clinical trials are ethically not possible and prospective outcomes studies may take years to obtain sufficient number of cases. Evidence may be collected via an ambitious multicenter study leveraging participation of high volume centers around the world, but studies such as this are costly and logistically difficult. Systematic review is a research method that can pool the highest level of evidence by scientifically collecting and analyzing relevant data from the conflicting studies.[11] Moreover, systematic review is the only possible method to quantitatively obtain the best evidence on the clinical question if a randomized controlled trial is not available.[12]

In this systematic review, we will focus on the overall outcomes of CC7 transfer to different recipient nerves. We strive to provide the best evidence on this controversial procedure, and then to help guide clinical decision-making and counsel patients on the use of this procedure for treatment of traumatic brachial plexus injury.

MATERIALS AND METHODS

Literature Search

Following the PRISMA guideline[13], we performed a systematic search of literature from January 1986 to April 2014 using PubMed and EMBASE databases to identify original articles related to CC7 transfer for traumatic brachial plexus injury. We searched with the following terms: “C7” or “C-7” or “seventh cervical nerve” and “brachial plexus” in abstract and title. After removing duplicates, two reviewers (G.Y. and K. W. C. C) who were trained in systematic review techniques screened the titles and abstracts according to the predetermined inclusion criteria and exclusion criteria. Studies in which content was unclear based on a review of the abstracts underwent the full-text review.

Inclusion and Exclusion Criteria

Inclusion criteria are indicated in Table 1. We excluded studies from review if they met any of the following exclusion criteria: (1) review articles, (2) without CC7 transfer to nerve report, (3) CC7 transfer for neonatal brachial plexus injuries, (4) surgical technique without primary outcome report, (5) electrophysiological study or anatomical study without outcome report, (6) data duplication from the same author, (7) lacking extractable data in the study.

Data Extraction and Analysis

Study patient demographic data and descriptive statistics included study published year, location, number of patients, gender, age, injury type, pre-operative period (interval between injury and surgery) and follow-up period. Although most of the available data were from case series and case reports with limited samples, we included the highest level of evidence possible. For articles presenting individual patient information tables, we collected the data and measured the pooled estimates of patients who met our inclusion criteria. If the individual patient demographic information was not available, we used the reported overall mean value. We also extracted the objective outcomes of CC7 transfer to the injured nerve, including motor and sensory functions with measurement scale at the final follow-up visit.

In this systematic review, we would like to study the overall CC7 transfer outcome as well as the outcomes of various recipient nerves (median, musculocutaneous, radial/triceps and other nerves). After reviewing the outcome measures reported in the literature, we found that the Medical Research Council (MRC) scale was used for reporting most of the median nerve, Musculocutaneous (MC) nerve, and radial/triceps nerve outcomes. However, results in other nerves were difficult to normalize because of variability in reporting outcome measures. Therefore, we normalized modifications of MRC and others into an MRC-based outcome scale for median nerve, MC nerve, and radial/triceps nerve (Table 2). For other recipient nerves, we reported study characteristics and patient demographic information.

In the median nerve group, we reported the hand motor functional outcomes (wrist flexion, finger flexion) and sensory recovery. Studies reporting hand and grip functions were categorized as finger flexion. Four studies[14–17] reported the finger flexor muscles (FDS or FDP) strength as motor outcomes, and we assigned them as finger flexion strength. Likewise, we categorized wrist flexor muscles (FCR, PL, FCU) strength reported into wrist flexion function. There were different areas of sensory recovery reported in the studies, and three studies did not define the sensory recovery area of CC7 transfer to median nerve.[14, 18, 19] These areas were combined as the median nerve area (Table 3). In the MC nerve group, biceps muscle power was assigned as elbow flexion for MC nerve outcome (Table 4). In the radial/ triceps nerve group, triceps and wrist extensor muscle power was assigned as elbow or wrist extension power respectively for radial/triceps nerve recovery (Table 5).

We assigned the MRC grade of M3 and S3 as the cut-off point for functional recovery. Motor functions were categorized into MRC grade of M4, M3, and lower than M3. If the primary reported outcomes only stated ≥M3 in the studies, we assigned them as M3. Sensory recoveries were categorized into greater and lower than S3 in the study tables.

Statistical Analysis

The data were categorized based on the recipient nerves: median nerve (Table 3), MC nerve (Table 4), radial/triceps (Table 5), and other nerves (Table 6). Study patient demographic information and descriptive statistics were summarized in Table 7. One-way ANOVA was applied for interval data (percentage of males, mean age, mean pre-op period, and follow-up period). Probability values less than 0.05 were considered statistically significant, and all statistical analyses were performed using SAS statistical software (version 9.2). We also reported the percentages of functional recovery (M4, M3 and/or ≥ S3) for median, MC, and radial/triceps nerves.

RESULT

Study and patient demographic characteristics

Database search and number of studies retrieved and excluded are presented in Figure 1 and all the included articles are presented in Supplemental Digital Content 1, Appendix I, INSERT LINK. Ultimately, 39 studies met the inclusion and exclusion criteria.[7, 10, 14–50] One prospective randomized control trial was identified,[47] and all others were retrospective studies. These studies were divided into 4 groups: median nerve group (n=25), MC nerve group (n=14), radial/triceps nerve group (n= 9) and other nerves group (n=18). Fourteen studies reported outcomes of multiple procedures.[7, 10, 17–19, 28, 30, 31, 37, 38, 40, 43, 46, 49]

The majority of the studies (n =21) were published in China and account for 54% of studies (Figure 2). A total of 754 patients underwent CC7 transfer for treatment of traumatic brachial plexus injury in this systematic review. Geographic distribution of the patients is presented in Figure 3. The largest series of 96 patients in one study was conducted by Waikakul.[21] Gu and his colleagues presented 181 out of 754 patients (24%) in 15 studies,[7, 14–18, 29, 30, 32, 33, 35, 39, 43–45] and other surgeons from China reported 170 out of 754 patients (23%) in 6 studies[25, 34, 37, 38, 42, 46].

The patients who underwent CC7 transfer had different brachial plexus injury types in the studies (Figure 4). Sixty-six percent of patients (499/754) had total brachial plexus avulsion

Supplemental Digital Content 1, Appendix I shows all included articles, INSERT LINK.

injuries, and 9% of patients (67/754) had total brachial plexus injuries with mixed root avulsion or rupture injury. Partial brachial plexus injury occurred in 8% of patients (62/754). Three studies mixed total brachial plexus injury with other types of injuries or only described the traumatic brachial plexus injury;[10, 40, 41] therefore the specified injury pattern in 17% of patients (126/754) could not be identified. Overall, 91% of patients were male, and mean age was 23 years, mean pre-operative period (interval between injury and surgery) was 6 months, and mean follow-up period was 43 months (Table 7). There were no significant differences in age, pre-operative period, or follow-up period among the four recipient nerve groups.

Median nerve outcomes

In total, 451 patients were treated with CC7 transfer to median nerve to improve wrist and hand functions. Considering the overall functional recovery of those with reported data and without subgroup analysis of various surgical techniques, 30 of 281 patients (11%) achieved an MRC grade of M4 and 106 (38%) achieved M3 in wrist flexion. Thirty-two of 429 (7%) patients achieved M4, and 156 patients (36%) achieved M3 in finger flexion, whereas 133 of 239 patients (56%) achieved ≥S3 sensory recovery in median nerve territories (Table 8).

MC nerve outcomes

Of the 151 patients who underwent CC7 transfer to the MC nerve for elbow flexion for treatment of brachial plexus injury, 57 patients (38%) regained elbow flexor strength of an MRC grade of M4 and 56 patients (37%) achieved M3, whereas 38 patients (25%) achieved less than a grade of M3 (Table 8).

Radial/triceps nerves outcomes

Seven studies reported the outcomes of CC7 transfer to radial or triceps nerve, and one study reported both radial and triceps nerves outcomes (Table 5). Twenty-five percent of 76 patients regained elbow or wrist extension strength of an MRC of M4 and M3 respectively, and the remaining 50% of patients had less than M3 (Table 8).

Other nerve outcomes

The CC7 nerves were also transferred to other nerves in total 218 cases, including upper trunk,[30, 32, 42] lower trunk,[33, 34, 46] lateral cord and posterior cord,[28, 32] thoracodorsal nerve,[7, 17, 18] axillary nerve,[10, 19, 20] suprascapular nerve[10, 20, 26, 48, 49] and ulnar nerve[25]. Outcomes of the included patients were quite variable and demonstrated in Table 6.

DISCUSSION

Traumatic injuries to the brachial plexus occurred in slightly more than 1% of adult multitrauma patients in a regional trauma facility in North America.[51] Motor vehicle accidents are the most frequent cause of these injuries, especially in developing countries, where motor vehicle is the primary transportation mode.[1, 52, 53] Approximately 60% of brachial plexus injuries in the literature are total five roots injuries that can cause flail arm.[2] Young men are most likely to sustain these disabling injuries.[1, 21, 40] Surgical reconstruction might be challenging when direct nerve repair is not applicable for avulsion injuries and prolonged denervation time causes irreversible atrophy of the muscle fibers, especially in hand muscles.[54] In the last decade, nerve transfer has been widely adopted and is considered as the only means of providing motor axons in treatment of total brachial plexus avulsion injuries.[2] Theoretically, this procedure can connect the donor nerve closer to the target nerve, which results in the reduction of distance and duration of axonal regrowth.[3, 55] Owing to this benefit, spinal accessory nerve,[56] intercostal nerve,[56, 57] and phrenic nerve[58, 59] have been successfully transferred to restore shoulder and elbow functions in brachial plexus injuries. However, the effectiveness of CC7 transfer is unproven.

CC7 was commonly transferred to the median nerve to restore the hand function in patients with brachial plexus injuries. In this review, two thirds of the studies reported the outcomes of CC7 transfer to median nerve, and 60% of the patients underwent this reconstruction procedure. Theoretically, C7 root provides 17,000 to 40,000 myelinated nerve fibers and contains both sensory and motor fibers, which are suitable for median nerve re-innervation.[6, 7, 47] Therefore, median nerve is considered as the first choice of the recipient nerve for CC7 transfer.

The motor recoveries of CC7 transfer to median nerve varied dramatically in the studies. In 1998, Gu and his colleagues reported 5 of 8 patients regained grade M3 or greater wrist and finger flexor strength at average of 3 years follow-up period.[18] In their latest case series in 2013, they reported wrist and finger flexors recovered to M3 or greater in 25 of 51 patients at a mean of 7 years follow-up period.[44] Reinnervation of thenar muscle had been reported in 5 out of 32 patients with total brachial plexus avulsion injury at mean 5 years after CC7 transfer to median nerve.[39] However, in a large series with 96 patients underwent anterior part of CC7 transfer to median nerve, only 20% to 30% of all patients regained significant hand function at 3 years follow-up perios.[21] In Sammer's report, none of the 15 patients achieved a functional composite grip at a mean of 40 months postoperatively.[10] Our findings indicated less than half of patients achieved an MRC grade of M3 or greater in wrist (11% of M4 and 38% of M3) and finger flexion (7% of M4 and 36% of M3). For sensory recovery, our results indicated more than half of patients (56%) had S3 or greater. Potential confounders that could affect treatment outcome, including patient age, denervation time, and different surgical techniques of CC7 transfer, were not studied in this systematic review.

Anatomy could explain the various motor recovery outcomes. It has been found that adult denervated muscles atrophy and motor end plates lost their restorative ability after 12 to 18 months.[60] In CC7 to median nerve transfer, axons must regenerate for over 30 centimeters distance before they reach the target muscles.[37] It will take approximately 10 months for axons at a regenerate rate of 1mm/day to reach 30 centimeters, except the time for crossing nerve suture lines. Another difficulty is that although the CC7 have almost twice the number of nerve fibers as median nerve, the numbers of myelinated nerve fibers that grow across the nerve graft are still limited by the nerve graft size and some fibers might not contribute to recovery.

More importantly, even if patients regain wrist and finger flexion strength to grade M3 or M4, whether this provides patients with functional hand usage is questionable. First, finger flexion against gravity, especially in the absence of intrinsic muscles, is not sufficient for basic hand functions.[23] Secondly, most patients could not achieve independent active movement of the injured hand without simultaneous activation of the contralateral muscles innervated by the CC7 nerve. Cortical reorganization from contralateral shoulder or elbow motion to ipsilateral hand function is a difficult and time-consuming process. Therefore, simply measuring a patient's motor function recovery does not represent meaningful recovery of the involved hand.

As for the CC7 transfer to MC nerve outcomes, our data demonstrated that 75% of patients regained elbow flexor strength of M3 and M4. This recovery rate is similar to the phrenic nerve transfer to the MC nerve (mean recovery rate of 78%).[58] Regaining elbow flexion is useful for patients to maintain some control over the involved limb, and be able to use their normal contralateral arm for daily activities instead of stabilizing the flail limb.[37] On the other hand, elbow and wrist extension functions are not as critical for the patients with total brachial plexus injury; therefore, only a few reports of CC7 transfer to radial or triceps nerve, which contained a small number of patients.[7, 17–19, 38, 43, 49] In our study, 66% of the included patients had total brachial plexus avulsion injuries; spontaneous recovery innervated with the other root is very unlikely. The short distance between CC7 and biceps and triceps muscles could possibly contribute to these enhanced recoveries. Another factor may be that their innervated muscles are larger and the atrophy rate is slower.

Additionally, CC7 has been rarely transferred to other nerves using modified techniques. Wang et al. reported CC7 transfer to lower or upper trunks via the prespinal route with motor recovery rates of M3 or greater in the different innervated muscles over 50% out of 116 cases.[42, 46] In a case series, 3 cases were treated by shortening the upper arm to perform CC7 coaptation to the ulnar nerve without nerve graft.[25] Amr et al. applied CC7 to repair brachial plexus injures by end-to-side or side-to-side grafting neurorrhaphy.[27] Although satisfactory results were indicated in these reports, these techniques were immature or unconventional and patients might be unwilling to undergo these procedures.

This review is not without limitations. First, we limited the search in only PubMed and EMBASE databases. Some non-English studies might not be included in these databases and elimination of those studies may reduce the power of this review. Furthermore, most included studies were retrospective uncontrolled studies. The results in this review could also be affected by the inconsistency and variability in outcome reports. We normalized the outcomes by each joint using MRC scale to provide a clearer overview of the outcomes. There might be potential confounders such as patient age, targeted muscles and different CC7 procedures, which are out of the scope of this review. Lastly, there might be publication bias in that studies with positive outcomes were more likely to be published and these studies might not represent the general outcomes. About one-fourth of the published cases in this study were reported by Dr. Gu and his colleagues with favorable outcomes, which might be attributed to their experience with CC7 transfer procedure. These limitations make reliable analysis difficult. Without consistent use of outcomes measures, statistical power was lacking to support the comparison between studies. Therefore, we used descriptive statistics in this systematic review to investigate the overall outcome of CC7 transfer.

Despite some limitations, we screened and summarized the data in the most rigorous way to provide the best available evidence on CC7 transfer. However, outcomes measures in the included studies were not consistent and specific enough to uncover true patient-related benefits from the CC7 transfer. Reliable and validated outcomes instruments should be created to evaluate patients undergoing CC7 transfer. Other than overall outcomes, aspects such as motor and sensory donor-site morbidity should also be investigated, which we will discuss in the second part of this paper.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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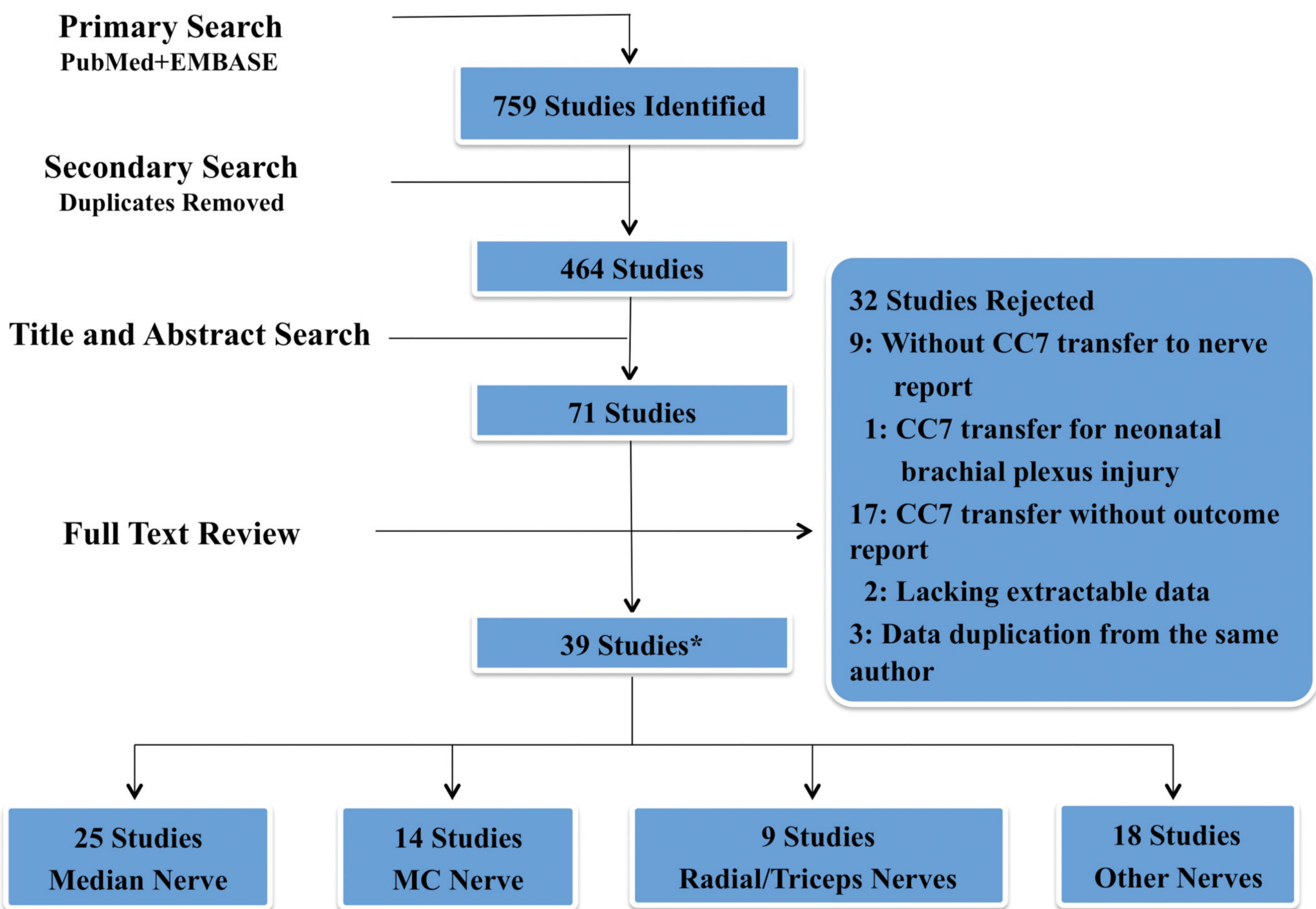

Figure 1.

Flow diagram of database search and number of studies retrieved and excluded from review.
* See Supplemental Digital content 1, Appendix I, INSERT LINK, for all included articles; 14 studies had multiple procedures and were added more than once for the analysis.

Figure 2.

Geographic distribution of 39 studies in the systematic review (n, patient number)

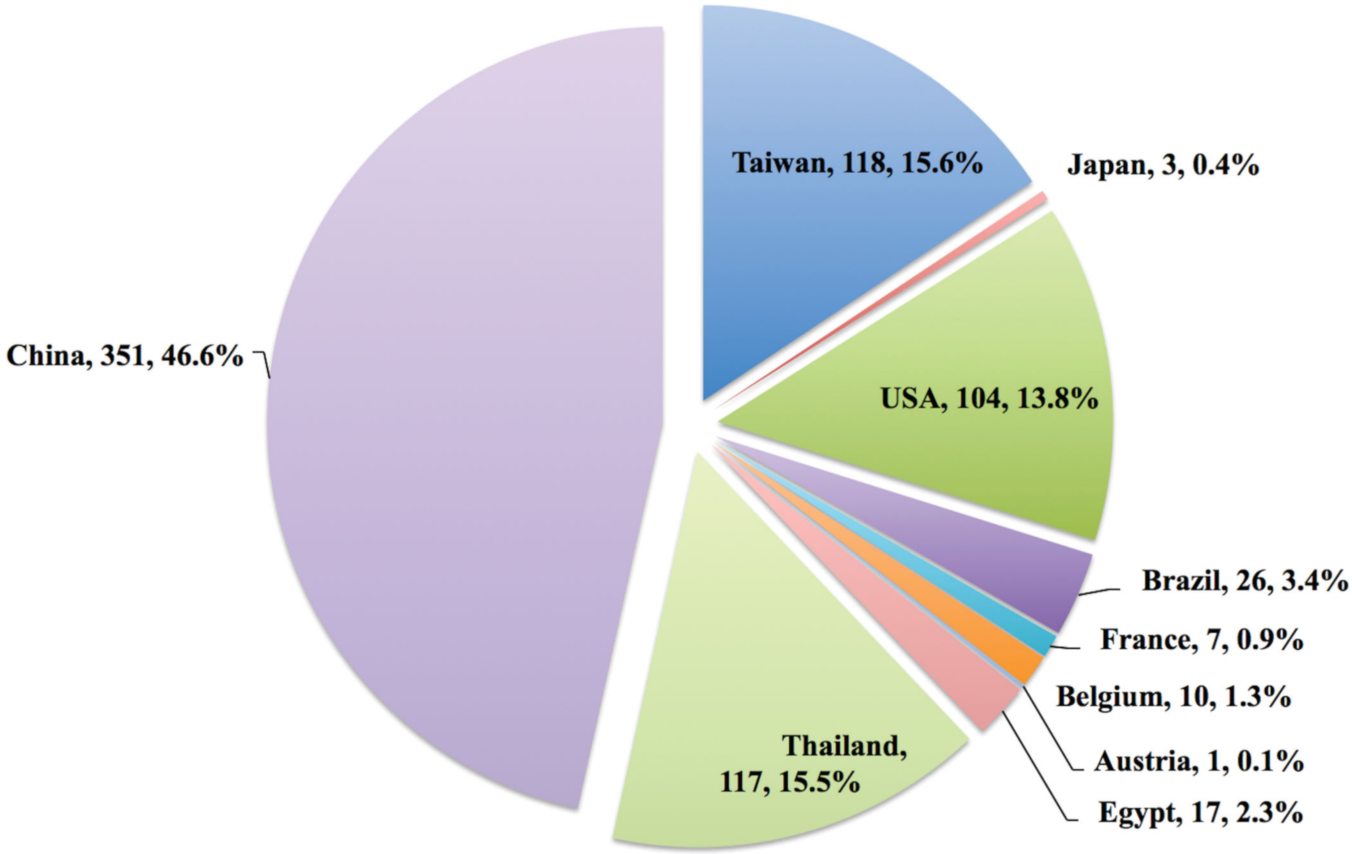

Figure 3.
Geographic distribution of 754 patients in the systematic review (Location, patient number, %); percentages added up to 99.9% because of rounding.

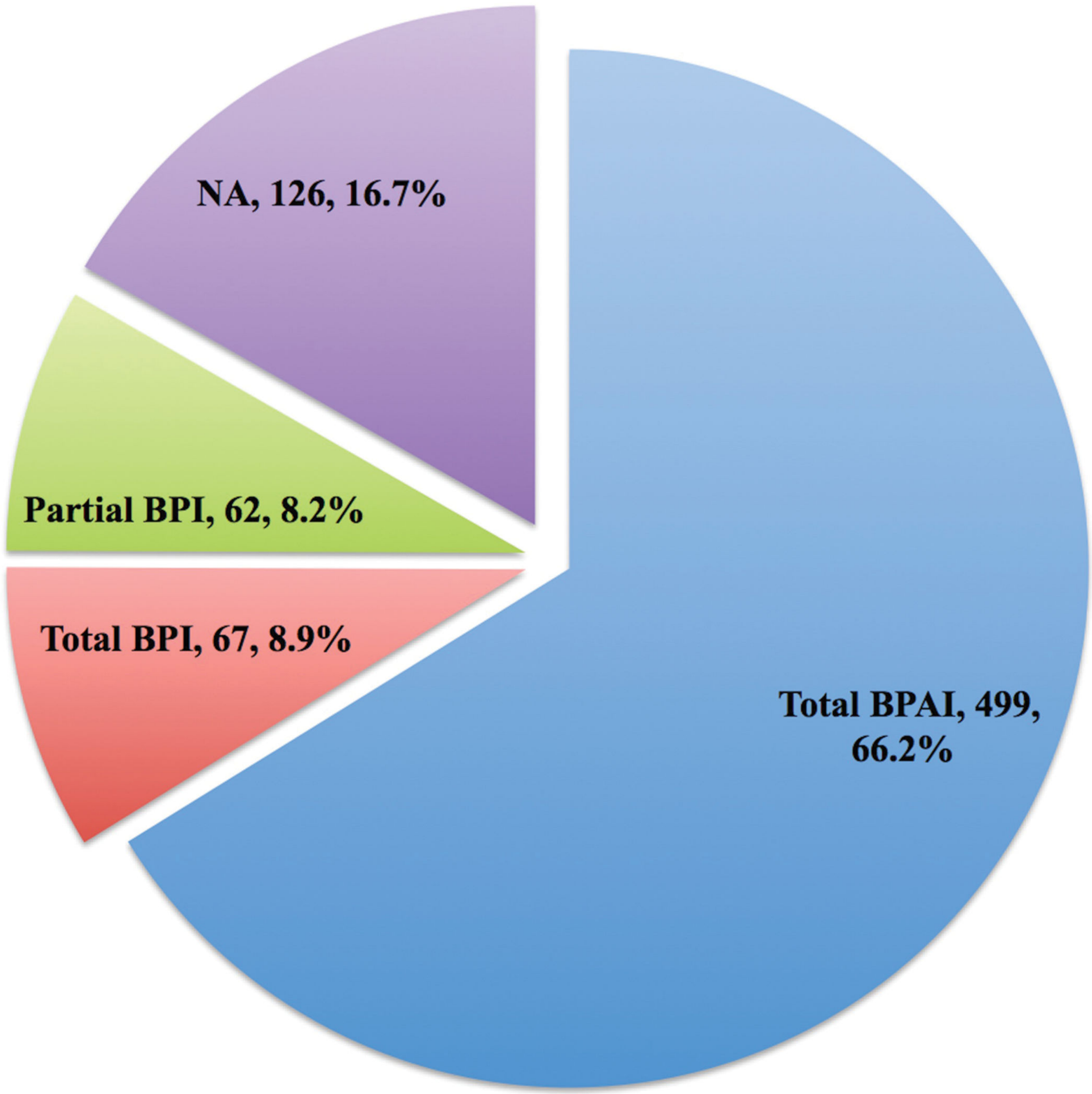

Figure 4.

Distribution of injury types of 754 patients in the systematic review (Injury type, patient number, %) * BPI, brachial plexus injury; BPAI, brachial plexus avulsion injury.

Table 1

Inclusion criteria

Literature style
Original article
Human subjects
Published from Jan 1, 1986 to April 1, 2014
Treatment option
Contralateral C 7 transfer to the injured nerves for treating traumatic brachial plexus injury
Report of objective functional outcomes (at least 1 of following)
Recipient nerves innerved motor strength evaluation
Recipient nerves sensory recovery evaluation

Table 2

Muscle and sensory function grading scales

Grade System and Measurement	Study	Range and Definition
Motor function		
MRC [£]		M0–M5
		M0, no contraction; M1, flick or trace of contraction; M2, active movement with gravity eliminated; M3, active movement against gravity; M4, active movement against gravity and resistance; M5, normal strength.
Modified MRC		M0–M5
	Chen 2007[30], Lin 2011[37]	M0, no contraction; M1, flick or trace of contraction; M2, active movement with gravity eliminated; M2+, active movement partially against gravity (≥ one half range); M3, active movement against gravity; M4, active movement against gravity and resistance; M5, normal strength. For M2+, we assign grade M2 in MRC; for other grades, we assign in corresponding grade in MRC.
	Sammer 2012[10]	M0, no contraction; M1, palpable or visible contraction; M2, full range of motion with gravity eliminated; M3, full range of motion against gravity; M4, full range of motion against resistance but with decreased strength; M5, normal. We assign the reported grades to corresponding grades in MRC.
	Terzis 2009[19], Terzis 2012[41], Wang 2013[46]	MRC expanded further with intermediate grade of + and − (e.g. M2, M2+, M3−, M3). Poor, M0 to M2; Fair, M2+ to M3; Good, M3+ or M4 −; Excellent, M4 to M5−. For poor, we assign grade M2 in MRC; fair, M3; good and excellent, M4.
Sunderland's Muscle Power Test		M0–M5
	Waikakul 1999[21], Gu 2002[7]	M0, no palpable or visible contractions and no movement attributable to the muscle; M1, feeble contractions, no voluntary movement; M2, feeble movement but not against resistance or gravity. In this state the muscle may maintain a part in a position into which it has been passively moved; M3, movement against gravity and some resistance. M4, movement against gravity and strong resistance. M5, normal power and range of movement. For M0 to M2, we assign grade <M3 in MRC; M3–M5, we assign the corresponding grades in MRC.
Functional Primitive Grip	Hierner 2007[31]	We assign the functional primitive grip to grade M3 in MRC.
Sensory function		
MRC		S0–S4
		S0, no sensation; S1, deep pain; S2, superficial pain and some touch; S2+, grade S2 without over-response; S3, grade S2 with some two-point discrimination; S4, normal.
Highet's Scale		S0–S4
	El-Gammal 2002[23], El-Gammal 2003[24]	S0, no recovery of sensibility in the autonomous zone of the nerve; S1, recovery of deep cutaneous pain sensibility within the autonomous zone of the nerve; S1+, recovery of superficial pain sensibility; S2, recovery of superficial pain and some touch sensibility; S2+, as in S2, but with over-response; S3, recovery of pain and touch sensibility with disappearance of over-response; S3+, as in S3, but location of the stimulus is good and there is imperfect recovery of two-point discrimination; S4, complete recovery. For S0 to S3, we assign < S3 in MRC; S3+ and S4, ≥ S3 in MRC.
Protective sensibility	Chen 2004[14], Hattori 2005[49]	We assign protective sensibility to grade S2in MRC.

[£]MRC, Medical Research Council

Table 3

Study and patient demographics, CC7 transfer to median nerve[§]

Study	Location	N	M	Age, y	Injury Type	Pre-op Period, mo	Follow -up, mo	Motor Measures	Motor Recovery: Wrist Flexion M4	Wrist Flexion M3	Wrist Flexion < M3	Finger Flexion M4	Finger Flexion M3	Finger Flexion < M3	Sensory Area	Sensory Recovery ≥ S3	Sensory Recovery < S3
Gu 1992[17£]	Shanghai, China	4	3	27	Total BPAI	11	35	FCR/FDS	2	0	1	1	0	3	1–3 palmar digits	3	1
Gu 1998[18]	Shanghai, China	8	NA	26	Total BPAI	12	41	WFF	3	2	3	3	2	3	NA	6	2
Waikakul 1999[21]	Bangkok, Thailand	96	96	27	Total BPAI	3	36	WF and FF	0	28	68	0	20	76	NA	NA	NA
Songcharoen 2001[22]	Bangkok, Thailand	21	19	25	Total BPAI	5	42	WFF	0	6	15	0	6	15	Median nerve area	10	11
Ei-Gammal 2002[23]	Assiut, Egypt	7	7	26	Total BPAI	4	35	NA	NA	NA	NA	NA	NA	NA	Palm	0	7
Gu 2002[7]	Shanghai, China	14	NA	26	Total BPAI	10	24	WF or FF	NA	NA	NA	NA	NA	NA	Median nerve area	12	2
Ei-Gammal 2003[24]	Assiut, Egypt	2	2	9	Total BPAI/ Total BPI	5	60	Hand function	NA	NA	NA	0	0	2	Palm	0	2
Chen 2004[14]	Shanghai, China	1	1	25	Total BPAI	11	18	FCR, PL/FDS	1	0	0	0	1	0	NA	0	1
Hattori 2005[49]	Ogori, Japan	1	0	4	Total BPI	4	49	NA	NA	NA	NA	NA	NA	NA	Median nerve area	0	1
Sun 2005[15]	Shanghai, China	8	6	28	Total BPAI	6	21	FDP	NA	NA	NA	1	4	3	Median nerve area	4	4
Xu 2006[29]	Shanghai, China	2	2	27	Total BPAI	7	29	WFF	0	2	0	0	2	0	Median nerve area	2	0
Chen 2007[30]	Shanghai, China	3	NA	6	Total BPAI/ Total BPI	5	46	WFF	3	0	0	3	0	0	Median nerve area	3	0
Hierner 2007[31]	Leuven, Belgium	4	NA	NA	Total BPI	NA	60	Primitive grip	NA	NA	NA	0	1	3	NA	NA	NA
Terzis 2009[19]	Norfolk, USA	29	NA	23	NA	30	73	WFF	10	8	11	10	8	11	NA	12	17
Zuo 2010[35]	Shanghai, China	8	8	25	Total BPAI	5	68	WFF	4	4	0	4	4	0	NA	NA	NA
Lin 2011[37]	Shanghai, China	10	6	26	Total BPAI	4	39	WFF	0	5	5	0	5	5	Thumb, index and middle finger tips	7	3
Muhetidier 2011[38]	Urumqi, China	16	16	33	Total BPAI	6	18	WF and FF	3	7	6	1	6	9	Median nerve area	11	5
Wang 2011[39]	Shanghai, China	5	5	17	Total BPAI	9	57	WFF	0	2	3	0	2	3	Median nerve area	NA	NA
Chuang 2012[40]	Taoyuan, Taiwan	78	NA	26	NA	4	48	FF	NA	NA	NA	0	39	39	Fingers	NA	NA
Hua 2012[16]	Shanghai, China	1	1	30	Total BPAI	NA	48	FCR, FCU, FPL/Digitorum	1	0	0	1	0	0	NA	NA	NA

Study	Location	N	M	Age, y	Injury Type	Pre-op Period, mo	Follow -up, mo	Motor Measures	Motor Recovery: Wrist Flexion M4	Wrist Flexion M3	Wrist Flexion < M3	Finger Flexion M4	Finger Flexion M3	Finger Flexion < M3	Sensory Area	Sensory Recovery ≥ S3	Sensory Recovery < S3
								muscles of all 4 fingers muscles of all 4 fingers									
Sammer 2012[10]	Rochester, USA	15	14	27	NA	5	40	Composite grip	NA	NA	NA	0	0	15	NA	NA	NA
Gao 2013[43]	Shanghai, China	22	20	26	Total BPAI	5	76	WFF	0	15	7	0	15	7	Median nerve area	10	12
Gao 2013[44]	Shanghai, China	51	46	29	Total BPAI	NA	83	WFF	0	25	26	0	25	26	1–3 palmar digits	32	19
Hua 2013[45]	Shanghai, China	5	5	25	Total BPAI	2	71	WFF	3	2	0	3	2	0	NA	NA	NA
Tu 2014[47]	Tainan, Taiwan	40	36	27	Total BPAI	4	72	Hook-grip	NA	NA	NA	5	14	21	Hand	21	19

[§]N, patient number; M, male; y, year; Pre-op, pre-operative; mo, month; BPAI, brachial plexus avulsion injury; FDS, flexor digitorum superficialis; NA, not available; WFF, wrist and finger flexion; WF, wrist flexor; FF, finger flexor; BPI, brachial plexus injury; FCR, flexor carpi radialis; PL, palmaris longus; FDP, Flexor digitorum profundus; FCU, flexor carpi ulnaris; FPL, flexor pollici slongus.

[£]One patient did not report wrist function.

Table 4

Study and patient demographics, CC7 transfer to MC nerve[§]

Study	Location	N	M	Age, y	Injury Type	Pre-op Period, mo	Follow-up, mo	Motor Measures	Motor Recovery		
									M4	M3	< M3
Gu 1992[17]	Shanghai, China	3	3	23	Total BPAI	11	33	Biceps	2	0	1
Gu 1998[18]	Shanghai, China	6	NA	26	Total BPAI	12	41	Biceps	2	2	2
Gu 2002[7]	Shanghai, China	10	NA	26	Total BPAI	10	24	Biceps	1	7	2
Beaulieu 2006[28]	Paris, France	5	5	32	Total BPAI	4	20	Biceps	2	0	3
Chen 2007[30]	Shanghai, China	1	NA	3	Total BPAI	4	63	Biceps	1	0	0
Hierner 2007[31]	Leuven, Belgium	6	5	NA	Total BPI	6	60	Elbow flexion	5	1	0
Terzis 2009[19]	Norfolk, USA	23	NA	23	NA	30	73	Biceps	12	5	6
Beisteiner 2011[50]	Vienna, Austria	1	1	6	Total BPI	5	78	Elbow flexion	1	0	0
Bertelli 2011[36]	Santa Catarina, Brazil	1	1	20	Total BPAI	4	20	Elbow flexion	0	1	0
Lin 2011[37]	Shanghai, China	10	6	26	Total BPAI	4	39	Biceps	2	4	4
Muhetidier 2011[38]	Urumqi, China	3	3	33	Total BPAI	6	18	Elbow flexion	1	1	1
Chuang 2012[40]	Taoyuan, Taiwan	23	NA	28	NA	4	48	Elbow flexion	0	19	4
Gao 2013[43]	Shanghai, China	12	NA	26	Total BPAI	5	76	Elbow flexion	0	8	4
Wang 2013[46]	Beijing, China	47	NA	NA	Total BPAI	4	57	Elbow flexion	28	8	11

[§]N, patient number; M, male; y, year; Pre-op, pre-operative; mo, month; BPAI, brachial plexus avulsion injury; NA, not available;

Table 5

Study and patient demographics, CC7 transfer to radial nerve and triceps nerve[§]

Recipient Nerve	Study	Location	N	M	Age, y	Injury Type	Pre-op Period, mo	Follow-up, mo	Motor Measures	Motor Recovery (Elbow or wrist extension)		
										M4	**M3**	**< M3**
Radial Nerve												
	Gu 1992[17]	Shanghai, China	2	1	37	Total BPAI	11	31	Triceps/ECRL	1	0	1
	Gu 1998[18]	Shanghai, China	4	NA	26	Total BPAI	12	41	Triceps	2	0	2
	Gu 2002[7]	Shanghai, China	6	NA	26	Total BPAI	10	24	Wrist or finger extension	2	2	2
	Hattori 2005[49]	Ogori, Japan	1	1	5	Total BPI	5	54	Elbow extension	0	0	1
	Terzis 2009[19£]	Norfolk, USA	10	NA	23	NA	30	73	Wrist and finger extension	2	2	6
	Muhetidier 2011[38]	Urumqi, China	2	2	33	Total BPAI	6	18	Wrist extension	0	1	1
Triceps Nerve												
	Terzis 2009[19£]	Norfolk, USA	21	NA	23	NA	30	73	Triceps	7	5	9
	Terzis 2012[41]	New York, USA	20	NA	26	NA	17	56	Triceps	5	7	8
	Gao 2013[43]	Shanghai, China	10	NA	26	Total BPAI	5	76	Elbow extension	0	2	8

[§] N, patient number; M, male; y, year; Pre-op, pre-operative; mo, month; BPAI, brachial plexus avulsion injury; ECRL, extensor carpi radialis longus; NA, not available; PD, posterior division.

[£] The study (Terzis 2009[19]) reported two procedures.

Table 6

Study and patient demographics, CC7 transfer to other nerves§

Study	Location	N	M	Age, y	Injury Type	Pre-op Period, mo	Follow -up, mo	Target Nerve	Procedure	Stage	Outcomes
Gu 1992[17]	Shanghai, China	1	1	27	Total BPAI	11	35	Thoracodorsal nerve	CC7 root transfer to thoracodorsal nerve and MC nerve via ulnar nerve graft with ulnar artery and vein	2	Latissimus dorsi: M2-1
Gu 1998[18]	Shanghai, China	2	NA	26	Total BPAI	12	41	Thoracodorsal nerve	CC7 transfer to thoracodorsal nerve via ulnar nerve graft	2	Latissimus dorsi: M4 in one case
Bertelli 1999[20]	Santa Catarina, Brazil	1	1	26	Partial BPAI	4	24	Axillary and suprascapular nerves	Motor rootlets of CC7 transfer to axillary and suprascapular nerves via sural nerve graft	1	The patient was capable of 120° of active should abduction and hold an 800-g weight at 90°.
Gu 2002[7]	Shanghai, China	2	NA	26	Total BPAI	10	24	Thoracodorsal nerve	CC7 transfer to thoracodorsal nerve by using sural nerve graft	1	Latissimus dorsi: M4 in one case; M0 in another case
Doi 2003[48]	Ogori, Japan	1	1	6	Total BPI	NA	24	Suprascapular nerve	CC7 transfer to suprascapular nerve by using ulnar graft	1	Shoulder abduction: 40°; external rotation: 60°
Yu 2003[25]	Shanghai, China	3	3	25	Total BPAI	6	32	Ulnar nerve	CC7 was coaptated to ulnar nerve after upper arm shortening	1	Hand sensation ≥ S3 and FCU ≥ M3 in all cases
Bertelli 2004[26]	Santa Catarina, Brazil	24	23	22	Total BPAI/Partial BPI	4	36	Suprascapular nerve	Total or partial CC7 motor rootlet transfer to suprascapular nerve by a sural nerve graft	1	The mean recovery in shoulder abduction was 90° and 92° in external rotation.
Amr 2005[27]	Cairo, Egypt	8	7	27	Total/Partial BPI/BPAI	3	26	Roots, trunks, cords or braches	CC7 transfer to roots, trunks, cords or braches by end-to-side,	1	Different level functional recovery was found in the deltoid and triceps, biceps, pronator teres, FCU, FDP,

Study	Location	N	M	Age, y	Injury Type	Pre-op Period, mo	Follow -up, mo	Target Nerve	Procedure	Stage	Outcomes
									side-to-side grafting side-to-side grafting		wrist extensors and extensor digitorum longus.
Hattori 2005[49]	Ogori, Japan	1	1	5	Total BPI	5	54	Suprascapular nerve	CC7 transfer to suprascapular nerve via free vascularized ulnar nerve graft	1	Shoulder abduction: 30°; external rotation: 60°
Beaulieu 2006[28]	Paris, France	2	2	25	Total BPAI	4	20	Lateral cord	CC7 transfer to lateral cord by using sural nerve graft	1	Reinnervated musecle: M2
Chen 2007[30£]	Shanghai, China	2	NA	2	Total BPAI/Total BPI	3	23	Upper trunk	PD or whole CC7 transfer to upper trunk via conventional nerve graft	1	One case: Biceps, M4; Median nerve, S3+. Deltoid, M2+; another: Biceps, M4; WFF, M4; Median nerve, S3+.
Xu 2008[32]	Shanghai, China	8	8	30	Total BPAI/Total BPI	4	12	Upper trunk or lateral and posterior cords	CC7 transfer to the upper trunk or lateral and posterior cords via a prespinal and tetropharyngeal route by using sural nerve graft	1	Shoulder abduction and elbow flexion were found in all cases.
Terzis 2009[19£]	Norfolk, USA	10	NA	23	NA	30	73	Axillary	Selective CC7 transfer to axillary nerve	1	Deltoid: M3+ or M4− in 2 cases; M2+ to M3 in 3 cases; M0 to M2 in 5 cases
Feng 2010[33]	Shanghai, China	4	3	26	Total BPAI	2	32	Lower trunk or C8-T1 spinal nerves	CC7 repair the lower trunk or the C8-T1 spinal nerves via the subcutaneous tunnel across the anterior surface of the chest and neck	1	Digital flexion: M1–M3; carpal flexion: M2–M4; hand sensation S1–S3 in all cases
Wang 2010[34]	Beijing, China	20	16	13	Total BPAI/Total/Partial BPI	5	27	Lower trunk	CC7 transfer to lower trunk directly through the prespinal route	1	Muscle strength of finger flexion: M4, in 18 cases, M2 in 2 cases; thumb flexion: M4 in 10 cases; M3 in 8 cases, M2 in 2 cases; intrinsic muscles M3 in 2 cases

Study	Location	N	M	Age, y	Injury Type	Pre-op Period, mo	Follow -up, mo	Target Nerve	Procedure	Stage	Outcomes
Sammer 2012[10]	Rochester, USA	13	11	25	NA	5	27	Axillary and/ or suprascapular nerve	Hemi-CC7 transfer to axillary or suprascapular nerve via sural nerve grafts	1	Only 3 patients achieved M3 or greater shoulder abduction.
Wang 2012[42]	Beijing, China	41	37	29	Total/Partial BPAI	3	47	Upper trunk	CC7 transfer to upper trunk or C5/C6 nerve roots via the modified prespinal route	1	Muscle strength was graded M4 or M3 for the biceps muscle in 85.4% of patients, for the deltoid muscle in 82.9% of patients, and for the upper parts of pectoral major in 92.7% of patients.
Wang 2013[46]	Beijing, China	75	70	28	Total BPAI	4	57	Lower trunk	CC7 transfer via the modified prespinal route and direct coaptation with the lower trunk	1	Motor function with a grade of M3 or greater was attained in 60% of the patients for elbow flexion, 64% of the patients for finger flexion, 53% of the patients for thumb flexion, and 72% of the patients for wrist flexion.

[§]N, patient number; M, male; y, year; Pre-op, pre-operative; mo, month; BPAI, brachial plexus avulsion injury; NA, not available; FCU, flexor carpi ulnaris; FDP, Flexor digitorum profundus; BPI, brachial plexus injury; PD, posterior division; WFF, wrist and finger flexion

[£]These outcomes were reported in modified MRC.

Table 7

Patient demographics summaries[§]

	Overall	Median Nerve	MC Nerve	Radial/ Triceps Nerve	Other Nerves [€]	P-value
Study N	39[£]	25	14	9[¥]	18	-
Patient N	754[‡]	451	151	76	218	-
Male% (N)	91% (531/585)	93% (293/315)	83% (24/29)	80% (4/5)	91% (184/202)	0.35
Mean age± SD, y	23±8	24±7	23±9	25±9	22±9	0.65
Mean pre-op period± SD, mo	6±5	7±6	8±7	14±10	7±7	0.05
Mean follow-up period± SD, mo	43±20	48±19	46±22	50±22	34±15	0.12

[§]N, number; y, year; Pre-op, pre-operative; mo, month.

[€]Other nerves include upper trunk, lower trunk, lateral cord and posterior cord, thoracodorsal nerve, axillary nerve, suprascapular nerve and ulnar nerve.

[£]One study (Terzis 2009[19]) reported 5 procedures; three studies (Gu 1992[17], Gu 1998[18], Gu 2002[7]) reported 4 procedures; four studies (Hattori 2005[49], Chen 2007[30], Muhetidier 2011[38], Gao 2013[43]) reported 3 procedures; six studies (Beaulieu 2006[28], Hierner 2007[31], Lin 2011[37], Sammer 2012[10], Chuang 2012[40], Wang 2013[46]) reported 2 procedures; thus, there are 39 reference studies.

[¥]One study (Terzis 2009[19]) reported 2 procedures; thus, there are 8 reference studies.

[‡]There are 56 patients underwent CC7 transfer to 93 target nerves. In addition, 46 patients underwent CC7 transfer to both MC and median nerves, 47 patients underwent CC7 transfer to both MC nerve and lower trunk, 10 patients underwent CC7 transfer to both median and triceps nerves, 1 patient underwent CC7 transfer to both radial and suprascapular nerves, and 1 patient underwent CC7 transfer to both MC and thoracodorsal nerves; thus actually there are 754 patients included in this systematic review.

Table 8

Outcome summaries of CC7 transfer to median, MC and radial/triceps nerves[§]

	Study N	Elbow or Wrist Extension N (%)			Elbow Flexion N (%)			Wrist Flexion N (%[†])			Finger Flexion N (%)			Sensory Recovery N (%)	
		M4	M3	<M3	M4	M3	<M3	M4	M3	<M3	M4	M3	<M3	≥S3	<S3
Median Nerve	25		-	-		-	-	30 (11%)	106 (38%)	145 (52%)	32 (7%)	156 (36%)	241 (56%)	133 (56%)	106 (44%)
MC Nerve	14		-	-	57 (38%)	56 (37%)	38 (25%)		-	-		-	-	-	-
Radial/Triceps Nerve	9	19 (25%)	19 (25%)	38 (50%)											

§ N, number

† Because of rounding, percentages do not equal 100%