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Background: In treating patients with brachial plexus injury, there are no comparative data on the outcomes of nerve grafts or nerve transfers for isolated upper trunk or C5-C6-C7 root injuries. The purpose of our study was to compare, with systematic review, the outcomes for modern intraplexal nerve transfers for shoulder and elbow function with autogenous nerve grafting for upper brachial plexus traumatic injuries.

Methods: PubMed, EMBASE, and the Cochrane Central Register of Controlled Trials were searched for studies in which patients had surgery for traumatic upper brachial plexus palsy within one year of injury and with a minimum follow-up of twelve months. Strength and shoulder and elbow motion were assessed as outcome measures. The Fisher exact test and Mann-Whitney U test were used to compare outcomes, with an alpha level of 0.05.

Results: Thirty-one studies met the inclusion criteria. Two hundred and forty-seven (83%) and 286 (96%) of 299 patients with nerve transfers achieved elbow flexion strength of grade M4 or greater and M3 or greater, respectively, compared with thirty-two (56%) and forty-seven (82%) of fifty-seven patients with nerve grafts ($p < 0.05$). Forty (74%) of fifty-four patients with dual nerve transfers for shoulder function had shoulder abduction strength of grade M4 or greater compared with twenty (35%) of fifty-seven patients with nerve transfer to a single nerve and thirteen (46%) of twenty-eight patients with nerve grafts ($p < 0.05$). The average shoulder abduction and external rotation was 122° (range, 45° to 170°) and 108° (range, 60° to 140°) after dual nerve transfers and 50° (range, 0° to 100°) and 45° (range, 0° to 140°) in patients with nerve transfers to a single nerve.

Conclusions: In patients with demonstrated complete traumatic upper brachial plexus injuries of C5-C6, the pooled international data strongly favors dual nerve transfer over traditional nerve grafting for restoration of improved shoulder and elbow function. These data may be helpful to surgeons considering intraoperative options, particularly in cases in which the native nerve root or trunk may appear less than optimal, or when long nerve grafts are contemplated.

Level of Evidence: Therapeutic Level IV. See Instructions to Authors for a complete description of levels of evidence.

Traumatic brachial plexus palsy is a devastating injury that affects predominantly young healthy individuals[1,2]. With the advent of high-energy motor sports and other recreational activities, the frequency of such injuries is increasing. Supraclavicular (root and/or trunk) stretch or contusion injuries occur in approximately 75% of the patients who have traumatic brachial plexus palsies[2]. Approximately 55% of the supraclavicular injuries involve all five roots (C5-T1), resulting in a flail limb[2]. Upper brachial plexus injuries, involving the C5-C6 and/or C7 roots, constitute approximately 45% of these injuries in adults[2]. Traumatic C5-C6 brachial plexus injuries cause denervation of the biceps, brachialis, deltoid, and rotator cuff muscles. Additional partial or complete C7 root involvement causes variable loss involving the triceps and forearm musculature.

Functionally, restoration of elbow flexion is the highest priority in these patients, followed by restoration of glenohumeral abduction, shoulder stability, and external rotation at the shoulder. The treatment options include nerve grafting, in which one or more of the nonavulsed roots is attached distally to the trunk, cord, or peripheral nerve by means of an autogenous graft, or nerve transfer, in which branches from an

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uninvolved nerve are microsurgically transferred to the distal peripheral nerves supplied by the injured roots. Many authors have described nerve transfer procedures for irreparable C5-C6 or C5-C6-C7 injuries with good results[3-5]. However, for proximal ruptures or upper trunk lesions in which some or all roots may be viable for nerve grafting, it is not clear whether it is beneficial to perform an autogenous nerve graft or to bypass the injured segment entirely and proceed with nerve transfers[6]. To evaluate the results of these procedures, we undertook a systematic review of the literature on brachial plexus reconstruction in isolated upper plexus traumatic injuries.

We hypothesized that the outcomes of modern nerve transfers for shoulder and elbow function in isolated upper trunk or C5-C6-C7 injury are improved compared with traditional nerve graft procedures.

Materials and Methods

We searched the literature on PubMed, the Cochrane Central Register of Controlled Trials, and EMBASE on April 10, 2010. The search strategy used the following terms: "brachial plexus" (MeSH term), "upper plexus," "C5, C6, C7," "wounds and injuries" (MeSH term), "nerve grafts," "neurotization," and "nerve transfers." We included all relevant English as well as non-English literature in the search. A cross-reference bibliography check was performed to ensure a complete list of potential studies. The search showed a total of 1461 articles. Of the 1461 articles on adult brachial plexus injury, 1058 abstracts were read and the remaining studies were excluded by reviewing the title. Eight hundred and ninety-four of the 1058 studies were excluded on the basis of the criteria listed below, leaving 164 full-text articles for the analysis. Patients with traumatic injury of the upper brachial plexus at the root (C5-C6-C7) or trunk level, who had reconstructive surgery with use of nerve grafts or nerve transfers within one year of injury, and who had a minimum follow-up of twelve months, were included.

Exclusion Criteria

Patients with perinatal brachial plexus injuries were excluded. Studies were excluded if the results for patients with isolated traumatic injury of the upper brachial plexus could not be independently assessed because of other injuries[1,7-46]. Studies that did not describe muscle strength for individual muscles and joint motion were excluded[11,21,27,41,47-55]. Studies that did not specifically describe the timing of surgical intervention or follow-up were excluded[17,32,56-62]. For evaluation of elbow function, we included only those studies or patients who had so-called plexoplexal or intraplexal nerve transfers (ulnar, median, medial pectoral, or thoracodorsal) to the biceps and/or brachialis branches of the musculocutaneous nerve. Specifically, so-called extraplexal transfers with use of intercostal, phrenic, or spinal accessory nerves for restoration of elbow flexion were excluded. Other exclusion criteria were studies involving complete brachial plexus palsy, contralateral C7 transfer, review articles, isolated case studies, duplicate publications, and patients with both nerve transfer and nerve graft for the same muscle[2,6,11,30,34,43,51,60,61,63-136].

Outcome parameters included strength and shoulder and elbow range of motion. Strength was evaluated with use of the British Medical Research Council grading scheme[137]. Strength measurement by the British Medical Research Council grading[138] and range-of-motion measurement[139,140] have demonstrated good interrater reliability such that pooling of these outcomes from various studies provides meaningful conclusions. The following methods were used to assess the active elbow flexion, shoulder abduction, and shoulder external rotation in various studies:

1. Elbow flexion was measured as the angle formed between the long axis of the arm and forearm by a goniometer.
2. Shoulder abduction was measured as the angle between the arm axis and the thoracolumbar spine by a goniometer.
3. Shoulder external rotation was measured in degrees from the resting position, which was defined as 90° of elbow flexion with the forearm resting on the abdomen (an internally rotated position). These measurements were made by a goniometer.

One study[141], which did not use the above methods for range-of-motion measurements, was excluded from range-of-motion analysis. Outcomes were treated as ordinal (strength) and scale (range-of-motion) data. The data were compared with use of the Fisher exact test (ordinal data) and an independent sample Mann-Whitney U test (scale data), with significance set at alpha = 0.05.

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There was no external source of funding.

Results

We found thirty-one studies that met the inclusion criteria in which modern so-called plexoplexal nerve transfers or nerve grafts for elbow function and single or dual nerve transfers or nerve grafts for shoulder function were described for traumatic upper brachial plexus palsy. The results of those studies are shown in Tables I, II, and III. It is important to note that all of the nerve grafts and 90% of the nerve transfers were performed within nine months of injury.

Elbow Function

Injury Patterns

A total of 299 patients had nerve transfers to the musculocutaneous nerve (see Appendix). Of those patients, 229 (77%) had C5-C6 lesions and seventy (23%) had C5-C6-C7 injuries. Root avulsions were found in 255 patients (85%), while forty-four patients (15%) had postganglionic injuries. Of the fifty-seven patients who underwent nerve grafts, fifty-one (89%) had C5-C6 lesions and six (11%) had C5-C6-C7 injuries. Forty-five (79%) had extraforaminal injuries of at least one of the roots, while twelve (21%) had root avulsions and received nerve grafts from the C3-C4 roots to the upper trunk.

Elbow Flexion Strength

Of the 299 patients who received nerve transfers, 247 (83%) achieved elbow flexion strength of M4 or greater compared with thirty-two (56%) of the fifty-seven patients with nerve grafts ($p < 0.05$). Elbow strength of M3 or greater was attained in 286 (96%) of 299 patients with nerve transfers compared with forty-seven (82%) of the fifty-seven patients with nerve grafts ($p < 0.05$). The comparison is summarized as a contingency table (see Appendix).

With regard to the outcomes of nerve transfers for patients with C5-C6 and C5-C6-C7 injuries, 201 (88%) of 229 patients with isolated C5-C6 injuries achieved strength of elbow flexion of M4 or greater compared with forty-six (66%) of seventy patients with C5-C6-C7 injuries ($p < 0.05$). This finding suggests that patients with upper brachial plexus injuries limited to C5-C6 have improved outcomes with nerve transfer for elbow flexion compared with those with C5-C6-C7 injuries.

The 229 patients with C5-C6 lesions who had a nerve transfer demonstrated improved elbow flexion strength (201 [88%] had strength of M4 or greater and 225 [98%] had

TABLE I Outcomes of Nerve Transfers and Nerve Grafting for Elbow Flexion

Study	Injury Pattern*	Donor Nerve	Recipient Nerve†	No. of Cases	Flexion Strength Grade (%) M4 or Greater	Flexion Strength Grade (%) M3 or Greater
Nerve transfers						
Leechavengvongs et al.[143] (2006)	Avulsion of C5-C6	Ulnar	MC	15	87	100
Teboull et al.[3] (2004)	Avulsion and/or rupture of C5-C6 (9) or C5-C6-C7 (20)	Ulnar	MC	29	69	83
Sungpet et al.[150] (2000)	Avulsion of C5-C6 (25) or C5-C6-C7 (11)	Ulnar	MC	36	83	94
Venkatramani et al.[151] (2008)	Avulsion of C5-C6 (13) or C5-C6-C7 (2)	Ulnar	MC	15	87	100
Nath et al.[152] (2006)	Avulsion of C5-C6	Median	MC	40	90	95
Liverneaux et al.[5] (2006)	Avulsion and/or rupture of C5-C6 (4) or C5-C6-C7 (2)	Median and ulnar	MC	6	100	100
Oberlin et al.[142] (1994)	Avulsion of C5-C6	Ulnar	MC	2	100	100
Leechavengvongs et al.[4] (1998)	Avulsion of C5-C6 (26) or C5-C6-C7 (4)	Ulnar	MC	30	93	96
Bertelli and Ghizoni[153] (2004)	Avulsion of C5-C6	Ulnar	MC	10	70	100
Mackinnon et al.[154] (2005)	Avulsion and/or rupture of C5-C6 (2) or C5-C6-C7 (2)	Median and ulnar	MC	4	100	100
Merrell et al.[146] (2001)	Avulsion of C6-C7	Medial pectoral	MC	1	0	100
Brandt and MacKinnon[62] (1993)	Avulsion of C5-C6	Medial pectoral	MC	2	100	100
Samardzic et al.[155] (2002)	Avulsion of C5-C6-C7	Medial pectoral	MC	10	60	90
Ferraresi et al.[156] (2004)	Avulsion of C5-C6 (28) or C5-C6-C7 (6)	Ulnar (30) and median (4)	MC	34	94	97
Sungpet et al.[157] (2003)	Avulsion of C5-C6	Median	MC	5	80	100
Samardzic et al.[158] (2005)	Avulsion of C5-C6	Thoracodorsal	MC	8	88	100
Bertelli and Ghizoni[159] (2004)	Avulsion of C5-C6 (8) or C5-C6-C7 (4)	Ulnar	MC	12	58	100
Bhandari et al.[160] (2009)	Avulsion and/or rupture of C5-C6 (12) or C5-C6-C7 (2)	Ulnar (4), ulnar and median (10)	MC	14	50	93
Goubier and Teboul[161] (2007)	Avulsion of C5-C6 (3) or C5-C6-C7 (2)	Ulnar and median	MC	5	100	100
Bertelli and Ghizoni[162] (2010)	Avulsion of C5-C6	Ulnar	MC	7	100	100
Kakinoki et al.[163] (2010)	Avulsion of C5-C6 (7) or C5-C6-C7 (1)	Ulnar	MC	8	88	100
Loy et al.[164] (1997)	Avulsion of C5-C6 (3) or C5-C6-C7 (3)	Ulnar	MC	6	67	100
Total				299	83	96
Nerve grafts						
Fogarty and Brennan[165] (2002)	Rupture of C5-C6	C5, C6; C5; and C6	C5, C6, and lateral cord	5	60	60
Sedel[166] (1982)	Avulsion and/or rupture of C5-C6 (2) or C5-C6-C7 (1)	C5 and C6	Upper trunk	3	67	100
Malessy et al.[167] (1999)	Avulsion and/or rupture of C5-C6 (2) or C5-C6-C7 (2)	C5, C6; C5; and C6	Upper trunk and MC	4	50	100
Malessy et al.[141] (2004)	Avulsion and/or rupture of C5-C6 (3) or C5-C6-C7 (3)	C5, C6; C5; and C6	Upper trunk, lateral cord, and MC	6	17	83
Yamada et al.[168] (2009)	Avulsion of C5-C6	C3 and C4	Upper trunk	6	100	100
Yamada et al.[169] (1996)	Avulsion of C5-C6	C3 and C4	Upper trunk	6	50	83
Jivan et al.[170] (2007)	Avulsion and/or rupture of C5-C6	C5 and C6	Upper trunk	27	55	77
Total				57	56	82

*The number of patients is given in parentheses. †Sural nerve graft used in nerve graft group. MC = musculocutaneous nerve.

TABLE II Shoulder Abduction Outcomes

Source	Injury Pattern*	Donor Nerve†	Recipient Nerve†	No. of Cases	Abduction Strength Grade *(%)*		Mean Range of Motion (Range) *(deg)*
					M4 or Greater	M3 or Greater	
Single nerve transfer							
Oberlin et al.[142] (1994)	Avulsion of C5-C6	SAN	SSN	1	0	100	NR
Venkatramani et al.[151] (2008)	Avulsion of C5-C6 (13) or C5-C6-C7 (2)	SAN	SSN	15	20	53	35 (0-90)
Samardzic et al.[158] (2005)	Avulsion of C5-C6	TDN	Axillary	10	50	100	NR
Samardzic et al.[155] (2002)	Avulsion of C5-C6 and sometimes C7	MP	Axillary	7	43	73	NR
Samardzic et al.[155] (2002)	Avulsion of C5-C6 and sometimes C7	MP and ICN	Axillary	4	100	100	NR
Merrell et al.[146] (2001)	Avulsion of C5-C6 or C5-C6-C7	SAN	SSN	2	100	100	NR
Bertelli and Ghizoni[171] (2007)	Avulsion and/or rupture of C5-C6-C7	LTN and SAN (4), SAN (3)	SSN	7	NR	NR	83 (70-100)
Malessy et al.[141] (2004)	Avulsion and/or rupture of C5-C6 (4) or C5-C6-C7 (6)	SAN	SSN	10	20	30	NR
Bhandari et al.[160] (2009)	Avulsion and/or rupture of C5-C6 (5) or C5-C6-C7 (3)	SAN	SSN	8	13	88	NR
Total				64	35‡	70‡	50 (0-100)
Dual nerve transfer							
Leechavengvongs et al.[143] (2006)	Avulsion of C5-C6	SAN, RN	SSN, axillary	15	87	100	115 (45-160)
Leechavengvongs et al.[144] (2003)	Avulsion of C5-C6	SAN, RN	SSN, axillary	7	100	100	124 (70-160)
Uerpairojkit et al.[172] (2009)	Avulsion of C5-C6	SAN, RN	SSN, axillary	5	80	100	134 (70-160)
Merrell et al.[146] (2001)	Avulsion of C5-C6 (2) or C5-C6-C7 (1)	SAN and MP (2) or ICN (1)	SSN, axillary	3	67	100	NR
Bertelli and Ghizoni[171] (2007)	Avulsion and/or rupture of C5-C6	SAN, RN	SSN, axillary	7	NR	NR	122 (80-170)
Bertelli and Ghizoni[153] (2004)	Avulsion of C5-C6	SAN, RN	SSN, axillary	10	30	100	92 (65-120)
Bertelli and Ghizoni[162] (2010)	Avulsion of C5-C6	SAN, RN	SSN, axillary	7	100	100	127 (85-169)
Bhandari et al.[160] (2009)	Avulsion and/or rupture of C5-C6	SAN, RN	SSN, axillary	7	57	100	NR
Total				61	74§	100§	122 (45-170)
Nerve graft							
Yamada et al.[169] (1996)	Avulsion of C5-C6	C3,C4	Upper trunk	6	50	67	NR
Yamada et al.[168] (2009)	Avulsion of C5-C6	C3,C4	Upper trunk	6	100	100	NR
Malessy et al.[141] (2004)	Avulsion and/or rupture of C5-C6 (3) or C5-C6-C7 (4)	C5,C7; C6; C5	SSN; SSN, axillary	7	14	14	NR
Malessy et al.[167] (1999)	Avulsion and/or rupture of C5-C6 (3) or C5-C6-C7 (3)	C5,C6; C5; C5,C5	Upper trunk; SSN, axillary	6	50	67	NR
Sedel[166] (1982)	Avulsion and/or rupture of C5-C6 (2) or C5-C6-C7 (1)	C5,C6	Upper trunk	3	0	67	NR
Total				28	46	61	NR

*The number of patients is given in parentheses. †Sural nerve graft used in nerve graft group. SAN = spinal accessory nerve, SSN = suprascapular nerve, LTN = long thoracic nerve, MP = medial pectoral nerve, ICN = intercostal nerve, TDN = thoracodorsal nerve, RN = radial nerve (nerve to long or lateral head of triceps), and NR = not reported. ‡Percentage is based on fifty-seven patients with single-nerve transfer for whom data were available. §Percentage is based on fifty-four patients for whom data were available.

TABLE III Shoulder External Rotation Outcomes

Source	Injury Pattern*	Donor Nerve†	Recipient Nerve†‡	No. of Cases	External Rotation Strength§ (%) M4 or Greater	External Rotation Strength§ (%) M3 or Greater	Mean Range of Motion (Range)§ (deg)
Single nerve transfer							
Venkatramani et al.[151] (2008)	Avulsion of C5-C6 (13) or C5-C6-C7 (2)	SAN	SSN	15	20	53	24 (0-95)
Bertelli and Ghizoni[171] (2007)	Avulsion and/or rupture of C5-C6-C7	LTN and SAN (4), SAN (3)	SSN	7	NR	NR	94 (30-140)
Malessy et al.[141] (2004)	Avulsion and/or rupture of C5-C6-C7 (6) or C5-C6 (4)	SAN	SSN	10	10	30	NR
Total				32	16#	44#	45 (0-140)
Dual nerve transfer							
Leechavengvongs et al.[143] (2006)	Avulsion of C5-C6	SAN and RN	SSN and axillary	15	60	86	97 (60-130)
Leechavengvongs et al.[144] (2003)	Avulsion of C5-C6	SAN and RN	SSN and axillary	7	86	100	NR
Uerpairojkit et al.[172] (2009)	Avulsion of C5-C6	SAN and RN	SSN and axillary	5	NR	NR	124 (70-140)
Bertelli and Ghizoni[171] (2007)	Avulsion and/or rupture of C5-C6	SAN and RN	SSN and axillary	7	NR	NR	118 (90-140)
Bertelli and Ghizoni[153] (2004)	Avulsion of C5-C6	SAN and RN	SSN and axillary	10	20	70	93 (80-120)
Bertelli and Ghizoni[162] (2010)	Avulsion of C5-C6	SAN and RN	SSN and axillary	7	71	100	121 (97-145)
Total				51	56††	87††	108 (70-140)
Nerve graft							
Yamada et al.[169] (1996)	Avulsion of C5-C6	C3 and C4	Upper trunk	6	50	67	NR
Yamada et al.[168] (2009)	Avulsion of C5-C6	C3, C4	Upper trunk	6	100	100	NR
Malessy et al.[141] (2004)	Avulsion and/or rupture of C5-C6 (3) or C5-C6-C7 (3)	C5, C7; C6; and C5	SSN; SSN and axillary	7	0	0	NR
Malessy et al.[167] (1999)	Avulsion and/or rupture of C5-C6 (3) or C5-C6-C7 (3)	C5, C6; C5; C5, C5	Upper trunk; SSN and axillary	6	0	33	NR
Total				25	36	48	

*The number of patients is given in parentheses. †SAN = spinal accessory nerve, SSN = suprascapular nerve, LTN = long thoracic nerve, and RN = radial nerve (nerve to long or lateral head of triceps). ‡Sural nerve graft was used in the nerve graft group. §NR = not reported. #Percentage is based on twenty-five cases for which data were available. ††Percentage is based on thirty-nine cases for which data were available.

strength of M3 or greater) compared with the fifty-one patients who received a nerve graft (twenty-nine [57%] had strength of M4 or greater and forty-two [82%] had strength of M3 or greater) ($p < 0.05$). For the seventy patients with a C5-C6-C7 injury treated by nerve transfer, forty-six (66%) regained elbow flexion strength of M4 or greater and sixty-one (87%) regained strength of M3 or greater. In the nerve graft group for C5-C6-C7 injury, three of the six patients regained elbow flexion strength of M4 or greater and five of the six patients regained elbow flexion strength of M3 or greater. Statistical comparison was not performed for this small patient sample.

Among the patients who had postganglionic injuries, elbow flexion strength of M4 or greater was achieved by thirty-four (77%) of forty-four patients treated with nerve transfers compared with twenty-three (51%) of forty-five patients treated with nerve grafts ($p < 0.05$).

On the basis of the number of nerves transferred, twenty-two (88%) of twenty-five patients with double (ulnar and median) nerve transfer to the biceps and brachialis motor branches achieved elbow flexion strength of M4 or greater compared with 225 (82%) of 274 patients with single (ulnar or median or medial pectoral or thoracodorsal) nerve transfer to the biceps ($p > 0.05$). The point estimate of the difference in proportions (6%) and the associated sample size (299) lacked sufficient power to state with certainty that there was not a significant difference.

Elbow range of motion was described in sufficient detail for only two of fifty-seven patients in the nerve graft cohort, so a meaningful statistical comparison could not be performed. Of note, the thirty-two patients in the nerve transfer group for whom range of motion was reported achieved a mean elbow flexion of 137° (range, 90° to 140°).

Shoulder Function

Injury Patterns

Of the sixty-four patients who underwent isolated nerve transfers to the suprascapular or the axillary nerve, thirty-four (53%) had C5-C6 or upper trunk injuries, nineteen (30%) had C5-C6-C7 lesions, and the remaining eleven (17%) were a mixed group with either C5-C6 or C5-C6-C7 injuries. Root avulsion was the injury pattern in fifty-one patients (80%), while thirteen (20%) had postganglionic injuries.

Of the sixty-one patients who had dual nerve transfers to the suprascapular and the axillary nerve (see Appendix), sixty (98%) had C5-C6 or upper trunk injuries. Root avulsions were present in forty-eight patients (79%), while thirteen (21%) had postganglionic injuries.

Of twenty-eight patients treated with nerve grafts to improve shoulder function, twenty (71%) had C5-C6 or upper trunk injuries and the remaining eight (29%) had C5-C6-C7 lesions (see Appendix). Postganglionic injuries were present in sixteen patients (57%), while the remaining twelve patients (43%) had root avulsions and received nerve grafts from the C3-C4 roots to the upper trunk.

Abduction Strength

Forty (74%) of the fifty-four patients who had dual nerve transfer had shoulder abduction strength of M4 or greater compared with thirteen (46%) of the twenty-eight patients with nerve grafts ($p < 0.05$) and twenty (35%) of the fifty-seven patients with single nerve transfers ($p < 0.05$) (see Appendix). Shoulder abduction strength of M3 or greater (see Appendix) was seen in fifty-four (100%) of the fifty-four patients who had dual nerve transfer compared with seventeen (61%) of the twenty-eight patients treated with nerve grafts ($p < 0.05$) and forty (70%) of the fifty-seven patients treated with single nerve transfers ($p < 0.05$). No difference in abduction strength was found between patients having nerve transfers to a single nerve and those with nerve grafts ($p > 0.05$ for both M4 and M3 strength). The point estimate of the difference in proportions (11%) and the associated sample size (eighty-five) lacked sufficient power to state with certainty that there was not a significant difference.

For patients with single nerve transfers, shoulder abduction strength significantly improved in the twenty-one patients who had medial pectoral or thoracodorsal nerve transfer to the axillary nerve (twelve [57%] had strength of M4 or greater and nineteen [90%] had M3 or greater) compared with the thirty-six patients treated with spinal accessory nerve transfer to the suprascapular nerve (eight [22%] had M4 or greater and twenty-one [58%] had M3 or greater) ($p < 0.05$). With respect to nerve transfers to the axillary nerve, nineteen (90%) of the twenty-one patients who had such a transfer achieved abduction strength of M3 or greater compared with seventeen (61%) of the twenty-eight patients with nerve grafts ($p < 0.05$). No difference was found for the M4 level of abduction strength between these two groups. The point estimate of the difference in proportions (11%) and the associated sample size (forty-nine) lacked sufficient power to state with certainty that there was not a significant difference.

For patients with C5-C6-C7 injuries, shoulder abduction strength of M4 or greater was found in eleven (48%) of the twenty-three patients who had single nerve transfers and two of the eight patients treated with a nerve graft. Sample sizes were too small to perform a statistical comparison.

External Rotation

Twenty-two (56%) of the thirty-nine patients undergoing dual nerve transfer had external rotation strength of M4 or greater compared with nine (36%) of the twenty-five patients with nerve grafts ($p < 0.05$) and four (16%) of the twenty-five patients with single nerve transfer ($p < 0.05$) (see Appendix). Similarly, external rotation strength of M3 or greater (see Appendix) was obtained for thirty-four (87%) of the thirty-nine patients with dual nerve transfers compared with twelve (48%) of the twenty-five patients treated with nerve grafts ($p < 0.05$) and eleven (44%) of the twenty-five patients treated with single nerve transfer ($p < 0.05$). No difference in external rotation strength was demonstrated between the patients having nerve transfer to a single nerve and those with nerve grafts ($p > 0.05$ for both M4 and M3). The point estimate of the difference in proportions (20%) and the associated sample size (fifty) lacked sufficient power to state with certainty that there was not a significant difference.

In patients with C5-C6-C7 injury, one of the eight patients treated with nerve transfer to a single nerve and none of the eight patients treated with a nerve graft achieved shoulder external rotation strength of M4 or greater. Statistical comparison was precluded by the small sample size.

Range of Motion (Abduction)

Thirty-four patients treated with nerve transfers to both axillary and suprascapular nerves had an average shoulder abduction of 122° (range, 45° to 170°) compared with 50° (range, 0° to 100°) for twenty-two patients who underwent nerve transfer to the suprascapular nerve alone ($p < 0.05$). There was a lack of sufficient range-of-motion data to compare outcomes for patients undergoing single nerve transfer to the axillary nerve.

Range of Motion (External Rotation)

Twenty-seven patients treated with transfers to both axillary and suprascapular nerves recovered an average external rotation of 108° (range, 60° to 140°). Twenty-two patients treated with single nerve transfers (to the suprascapular nerve) had an average external rotation of 45° (range, 0° to 140°), and this represented a significant reduction in motion ($p < 0.05$).

Discussion

Transfer of a part of the ulnar nerve to the motor nerve of the biceps was, to our knowledge, first reported by Oberlin et al.[142]. Since then, many studies have evaluated the transfer of a part of the ulnar and/or median nerve to the motor branch of the biceps and/or brachialis muscles[3-5,143]. No appreciable deficit has been reported in the ulnar or median nerve distribution after these transfers. In our analysis of patients with upper trunk or root level injuries, nerve transfers for elbow flexion achieved a higher percentage of elbow flexion strength of M4 or greater than did nerve grafts ($p < 0.05$).

Transfer of the spinal accessory nerve to the suprascapular nerve is commonly performed to restore shoulder function in patients with brachial plexus injuries. Transfer of a part of the radial nerve (nerve to long head of triceps) to the motor branch of the axillary nerve was, to our knowledge, first described by Leechavengvongs et al.[144]. For upper brachial plexus injuries, many surgeons now perform dual nerve transfers, in which the spinal accessory nerve is transferred to the suprascapular nerve and a part of the radial nerve is transferred to the axillary nerve. In our analysis of patients who had C5-C6 or upper trunk palsies, dual nerve transfers attained a higher shoulder abduction and external rotation strength compared with patients treated with autogenous nerve grafts or with patients who had single nerve transfers to either suprascapular or axillary nerves. Both shoulder abduction and external rotation were better in patients with dual nerve transfers than with transfers to a single (suprascapular) nerve ($p < 0.05$). The results demonstrate that patients with dual nerve transfers to the suprascapular and the axillary nerve have improved range of motion and strength compared with patients who have had single nerve transfers.

With the numbers available for patients with C5-C6-C7 injuries, the data are less conclusive. Without a normally functioning triceps, a powerful donor for axillary nerve transfer may not be available. There were insufficient numbers in this patient cohort to identify whether medial pectoral nerve transfer to the axillary nerve would produce better outcomes over a long nerve graft from C5. Because of the demonstrated superiority of dual reinnervation for shoulder function, it may be important that the surgeon explore the entire plexus to identify remaining viable roots for grafting or other potential donors for transfer to the axillary nerve in C5-C6-C7 injury.

Despite the encouraging results reported in the present study, recovery of external rotation of the shoulder continues to lag behind recovery of shoulder abduction. Whether the inclusion of the teres minor branch of the axillary nerve during distal nerve transfers or the use of the posterior approach for suprascapular nerve transfer[102] can improve the relatively modest results of external rotation strength and motion cannot be supported with the available data.

As demonstrated by our data for biceps recovery and shoulder abduction, it cannot be stated with certainty why the results for modern techniques of nerve transfer to a denervated muscle are improved over the results for nerve grafting from the native cervical nerve root of the muscle, but it is likely that several factors are involved. Bentolila et al.[145] showed that nerve grafts that are >7.2 cm long are associated with worse results compared with short grafts; consequently, long nerve grafts to the musculocutaneous or axillary nerves may be subject to attenuation of nerve regeneration potential, especially if performed greater than six months after injury[145]. Merrell et al.[146] demonstrated that use of interposed nerve grafts when nerve transfers were performed diminished outcomes compared with direct transfer to the denervated motor nerve. This suggests that the additional suture junction, the devascularized autogenous graft itself, and/or the additional regeneration distance required were all factors in diminished percentages of successful regeneration. Also, upper brachial plexus traction injuries represent a spectrum of pathology from stretch to avulsion and are invariably associated with some degree of intraneural fibrosis at the level of the trunk or root; intraoperative determination of suitable candidates for grafting can be subjective, and an incorrect decision can potentially subject the patient to a long and unsuccessful recovery period. The use of intraoperative histologic analysis[147] is time-intensive and does not yield a precise determination of viable motor axons but rather a percentage of satisfactory preservation of fascicular architecture. Similarly, the use of somatosensory evoked potential stimulation[50,148,149], while useful to rule out root avulsion in questionable cases, is only predictive of intact sensory pathways.

The benefits of modern nerve transfers include the close proximity of the donor peripheral nerve to the denervated muscle end plates and the assurance of a healthy donor source of viable motor axons. These factors are especially pertinent in patients who present six months or more following injury, as the reduced reinnervation distance for nerve transfers may provide an additional advantage over a long nerve graft for functional recovery.

Given the nature of brachial plexus injury and the rapidly evolving methods of treatment, it is evident that few centers have sufficient numbers of patients to perform a single-center prospective comparison of surgical reconstruction. The best study design to compare nerve grafts and nerve transfers would be a prospective, multicenter randomized trial of large numbers of patients, and perhaps our retrospective data analysis may be a catalyst for this type of study. Retrospective data comparison or the performance of prospective multicenter trials depends on a unified method for the reporting of data. The greatest challenge of this systematic review was the need to exclude potentially valid outcome data for hundreds of postoperative patients because of a lack of objective outcome parameters for motion and strength. Comparisons of data from different centers will be optimized if joint-specific range-of-motion data and manual muscle strength grading is reported in all studies.

The findings of this systematic review demonstrate that for patients with complete upper trunk palsy, without clinical or electromyographic evidence of recovery at three to six months after the injury, the functional outcomes for restoration of elbow flexion and shoulder function will be improved by the use of nerve transfers rather than autogenous nerve grafts. These findings call into question the advisability of upper trunk exploration and testing in isolated, complete C5-C6 or upper trunk injuries. In these patients, the advantages of direct nerve transfer may include decreased operative time, the avoidance of potential operative morbidity of a supraclavicular plexus exploration, as well as the avoidance of a second incision, the obligate sensory loss, and the morbidity of harvesting a nerve graft. With the numbers available for patients with C5-C6-C7 injuries, the data are less conclusive and a plexus exploration for potential nerve root donors is probably warranted to maximize restoration of shoulder function.

Appendix

eA Tables summarizing injury patterns and comparisons of elbow flexion strength, shoulder abduction strength, and shoulder external rotation strength across the groups are available with the online version of this article on our web site at jbjs.org. ■

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