Results of Nerve Transfer Techniques for Restoration of Shoulder and Elbow Function in the Context of a Meta-analysis of the English Literature

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We report the results of 15 patients who underwent nerve transfer for restoration of shoulder and elbow function at our institution for traumatic brachial plexus palsy. We present these results in the context of a meta-analysis of the English literature, designed to quantitatively assess the efficacy of individual nerve transfers for restoration of elbow and shoulder function in a large number of patients. One thousand eighty-eight nerve transfers from 27 studies met the inclusion criteria of the analysis. Seventy-two percent of direct intercostal to musculocutaneous transfers (without interposition nerve grafts) achieved biceps strength ≥ M3 versus 47% using interposition grafts. Direct intercostal transfers to the musculocutaneous nerve had a better ability to achieve ≥ M4 elbow strength than transfers from the spinal accessory nerve (41% vs 29%). The suprascapular nerve fared significantly better than the axillary nerve in obtaining ≥ M3 shoulder abduction (92% vs 69%). At our institution 90% of intercostal to musculocutaneous transfers (n = 10) achieved ≥ M3 bicep strength and 70% achieved ≥ M4 strength. Four of seven patients achieved ≥ M3 shoulder abduction with a single nerve transfer and 6 of 7 regained ≥ M3 strength with a dual nerve transfer. This study suggests that interposition nerve grafts should be avoided when possible when performing nerve transfers. Better results for restoration of elbow flexion have been attained with intercostal to musculocutaneous transfers than with spinal accessory nerve transfers and spinal accessory to suprascapular transfers appear to have the best outcomes for return of shoulder abduction. We conclude that nerve transfer is an effective means to restore elbow and shoulder function in brachial plexus paralysis. (J Hand Surg 2001;26A:303–314. Copyright © 2001 by the American Society for Surgery of the Hand.)

Key words: Brachial plexus, neurotization, nerve transfer, nerve surgery, intercostal nerves.

While the prognosis for recovery from traumatic brachial plexus palsy has historically been guarded,[1–5] pioneering advances in microsurgery since the 1960s have demonstrated unequivocal support for surgical reconstruction of these devastating injuries.[6–10] The detachment of a functioning motor nerve from a donor muscle and reattachment to the distal end of a disrupted peripheral nerve (nerve transfer) has been reported in several series to be an effective means of restoring denervated muscle function, particularly in cases involving avulsion of spinal roots.[11–14] Critical analysis of the outcomes of these techniques, how-

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ever, remains challenging. The number of patients reported in each series is frequently small. The differences in degree and description of injury, elapsed time since injury, surgical reconstruction techniques, and reporting of outcomes vary considerably. In addition, studies have been published in a number of surgical disciplines and languages.

In this study we report the functional outcomes of nerve transfers that we performed for restoration of elbow and shoulder function in 15 consecutive patients. To critically evaluate the results of these techniques in a larger sample size, we undertook a meta-analysis of the English literature on brachial plexus reconstruction. The purpose of the meta-analysis was to establish and define landmarks by which we and other investigators could assess surgical results in the context of the previously published experience. We attempted to answer the following questions:

- Does the use of interposition nerve grafts affect the outcome of nerve transfers?
- Is there a significant improvement in outcome with the use of 2 versus 3 or 4 intercostal nerves in terms of restoration of biceps strength?
- Does the choice of donor or recipient nerves for restoration of elbow flexion and shoulder abduction significantly influence functional outcome?
- Finally, does restoration of shoulder function compare favorably with the results for restoration of biceps function?

Materials and Methods

Case Series

Between October 1991 and November 1999 we performed surgical exploration and repair on 35 patients (age range, 4 months to 67 years) with brachial plexus injuries. Of these, 29 had nerve transfers. Fifteen patients with nerve transfers met the inclusion criteria for the study, which included surgery within 12 months of injury and a minimum follow-up period of 1 year. All 15 patients were male. Perinatal brachial plexus palsies were excluded from the analysis. The dominant extremity was involved in 8 of the 15 patients. Median age at the time of surgery was 28 years (range, 7–67 years). Average time from injury to surgery was 5 months (range, 4–8 months). Diagnosis of root, trunk, cord, or distal nerve injury was determined by clinical evaluation, preoperative neurodiagnostic studies, computed tomography myelogram,[15] and surgical exploration. The average follow-up period was 37 months (range, 12–86 months). Recovery was assessed using the Medical Research Council grading scheme (range, M0–M5).[4]

Of the 15 patients studied, 11 received intercostal to musculocutaneous nerve transfers for restoration of elbow flexion. One patient underwent medial pectoral nerve transfer to the musculocutaneous nerve. All 15 patients underwent nerve transfer for restoration of shoulder function using either the spinal accessory nerve or intercostal nerves as the donor. The 2 recipient nerves were the suprascapular and axillary nerves. Two of the 15 patients ultimately had shoulder arthrodesis for symptomatic instability. Two patients underwent Steindler flexoplasty procedures for augmentation of elbow flexion power; 1 was performed concurrently during brachial plexus reconstruction and 1 was performed subsequently. The patient who had the concurrent procedure was excluded from biceps analysis due to the inability to determine the contribution of flexion provided by each procedure.

Surgical Procedure

Two surgeons jointly performed all the surgical procedures. Complete brachial plexus exploration was performed through an extensile surgical incision. The supraclavicular dissection was performed though an incision paralleling the sternocleidomastoid muscle (12 patients) or through a transverse supraclavicular approach 1 cm cephalad and parallel to the clavicle (3 patients).[16] Priorities for functional restoration were elbow flexion, shoulder abduction, and external rotation. The caudal fascicles of the spino-accessory nerve were always transferred to the suprascapular nerve, unless the nerve required only neurolysis or had segmental disruption precluding reinnervation. When sufficient donor nerves were available, we reinnervated both the deltoid and supraspinatus for shoulder power. If the medial pectoral nerve was functional, 1 major branch was directly coapted to the axillary nerve. In all but 1 case, 3 intercostal nerves were then transferred to the musculocutaneous nerve (Fig. 1). All intercostal to musculocutaneous nerve transfers were performed by direct coaptation without intercalated nerve grafts. The decision to use 2 nerves in 1 case was due to technical difficulty transferring the third nerve without use of an interposition nerve graft. In another case, due to an anatomic variation that would have required us to use intercalated grafts, intercostal nerves were transferred to the axillary nerve and the medial pectoral nerve was transferred directly to the musculocutaneous nerve. Fibrin glue was used as an adjunct for nerve suture in 12 of the 15 patients.[17] Surgical principles for nerve reconstruction are de-

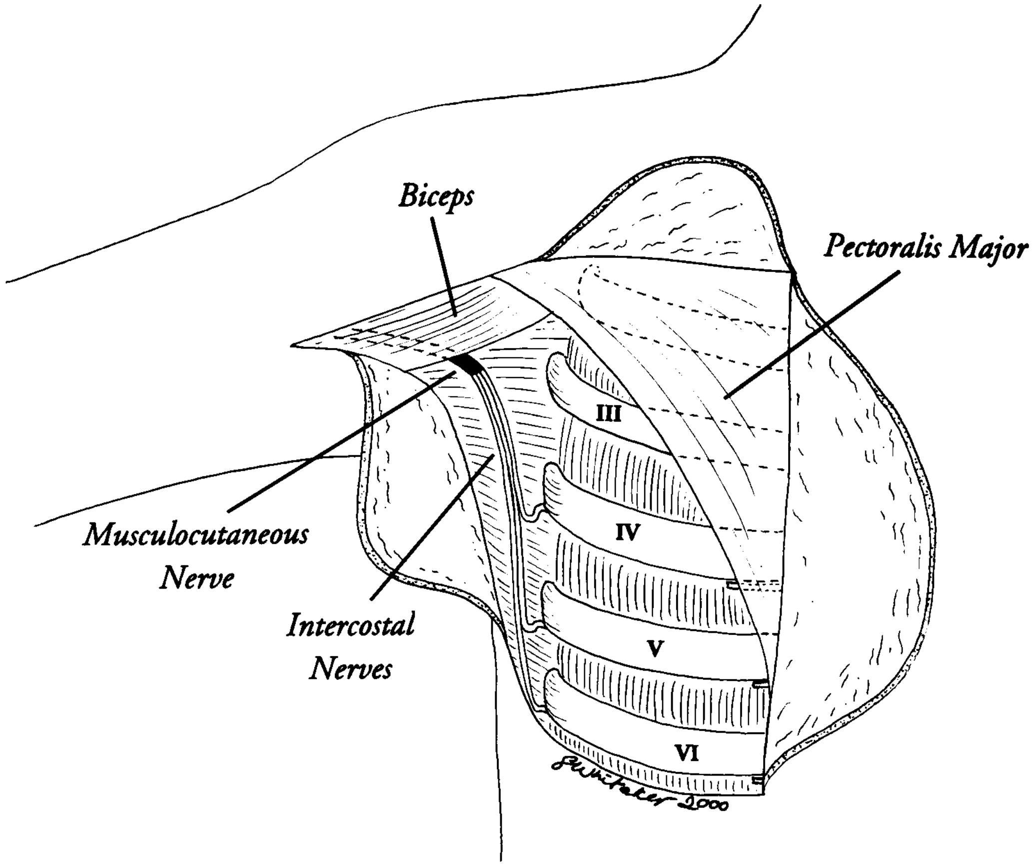

Figure 1. Intercostal to musculocutaneous nerve transfer.

scribed extensively in the literature and will not be further elaborated.[18–20]

Meta-analysis

A Medline search was conducted to identify all English reports that refer to the use of nerve transfers for restoration of either elbow or shoulder function in patients with traumatic brachial plexus avulsion injury. A cross-reference bibliography check was performed to ensure a complete list of potential studies. Seventy-eight studies were identified that contained follow-up data on nerve transfers. Only those patients who underwent surgery within 12 months of injury and who had a minimum 1-year follow-up period were included. Perinatal brachial plexus palsies were excluded. Of the 78 studies, 27 met the inclusion criteria (Tables 1 and 2). In studies that reported results by individual case, only those patients who met the inclusion criteria were analyzed.[8,21–25] A patient with a dual nerve transfer to either the shoulder or elbow was excluded because it would be difficult to assess the relative contribution of each transfer (eg, spinal accessory nerve to suprascapular nerve and intercostal nerve to axillary nerve, both transfers being for restoration of shoulder function). If the investigators assessed outcomes by a method other than the Medical Research Council grading scheme,[4] these methods were examined and results were translated into the corresponding Medical Research Council grade.[14,26–28] Of the 51 studies excluded, reasons for exclusion were based on failure to meet the inclusion criteria ($n = 26$), lack of sufficient information to determine whether the inclusion criteria were met ($n = 14$), and duplications of results published by the same investigators ($n = 11$).

A semiquantitative meta-analysis was conducted by a pooling of proportional outcomes data.[29–31] Outcomes were treated as ordinal data (Medical Research Council grade). Hypothesis testing was performed by use of the chi-square statistic for proportional data. Statistical significance was set at alpha = .05. For comparisons that did not achieve statistical difference, power was calculated using accepted equations for determination of power (see Appendix).[32]

Table 1. Studies and Outcomes Data Meeting Inclusion Criteria

Source	Year	No. of ICs Used	Donor Nerve	Recipient Nerve	Interposition Graft for IC	No. of Cases	% ≥ M4	% ≥ M3
Results for restoration of elbow flexion								
Bentolila et al[47]	1999		XI	MC		6	NA	83
Berger and Becker[36]	1994	1–4	IC	MC	NA	58	17	31
Celli et al[53]	1988	2	IC	LC	No	1	0	0
Celli et al[53]	1988	3	IC	LC	No	3	33	33
Celli et al[53]	1988	1	IC	MC	No	1	0	100
Celli et al[53]	1988	2	IC	MC	Yes	2	0	50
Celli et al[53]	1988	3 or 4	IC	LC	Yes	2	0	0
Chuang et al[52]	1993		PH	MC		1	100	100
Chuang et al[52]	1993		XI	MC		1	100	100
Chuang et al[11]	1992	3	IC	MC	No	34	79	79
Chuang et al[11]	1992	3	IC	MC	Yes	3	0	0
Chuang et al[11]	1992	2	IC	MC	No	29	59	59
Dai et al[23]	1990		TD	MC		1	100	100
Kawai et al[50]	1994	2–4	IC	MC	No	6	83	100
Kline and Hudson[14]	1995		IC	MC	Yes	37	46	57
Kline and Hudson[14]	1995		XI	MC		1	0	0
Krakauer and Wood[21]	1994	2	IC	MC	No	8	50	75
Leechavengvongs et al[33]	1998		Ulnar	MC		32	94	97
Malessy et al[51]	1999		Hypoglossal	MC		1	100	100
Malessy et al[42]	1998	3	IC	MC	No	17	47	59
Malessy et al[42]	1998	2	IC	MC	No	2	50	50
Malessy et al[42]	1998	4	IC	MC	No	2	100	100
Malessy et al[42]	1998	3	IC	MC	Yes, in 1 of 3 ICs	4	75	75
Minami and Ishii[44]	1987	2	IC	MC	No	17	71	100
Nagano et al[9]	1989	2	IC	MC	No	149	70	73
Oberlin et al[24]	1994		Ulnar	MC		4	29	100
Ochiai et al[26]	1993	NA	IC	MC	No	21	0	76
Ogino and Naito[49]	1995	2	IC	MC	No	10	75	90
Okinaga and Nagano[48]	1999	2	IC	MC	No	11	NA	100
Richardson et al[22]	1997		MP	MC		1	60	0
Richardson et al[22]	1997		TD	MC		3	60	100
Richardson et al[22]	1997		XI	MC		6	67	50
Ruch et al[43]	1995	3	IC	MC	No	13	0	46
Ruch et al[43]	1995	2	IC	MC	No	2	67	100
Ruch et al[43]	1995	2	IC	MC	Yes	2	50	0
Samardzic et al[28]	1992	2 or 3	IC	MC	Yes	7	15	43
Samardzic et al[28]	1992		MP, TD, or LT	MC		7	100	86
Samardzic et al[28]	1992		XI	MC		8	67	57
Sedel[8]	1982	1–4	IC	MC	Yes	7	67	57
Simesen and Haase[45]	1985	2	IC	MC	Yes	4	57	0
Songcharoen et al[12]	1996		XI	MC		216	14	73
Tonkin et al[46]	1996	2	IC	MC	No	17	0	65
Waikakul et al[13]	1999	3	IC	MC	No	75	0	64
Waikakul et al[13]	1999		XI	MC		130	33	85
Yamada et al[25]	1996		C3–4	UT		9	20	89
Results for restoration of shoulder function								
Celli et al[53]	1988	3	IC	PC	No	2	0	50
Celli et al[53]	1988	1	IC	AX	No	1	0	0
Celli et al[53]	1988	2	IC	AX	No	1	100	100
Celli et al[53]	1988	4	IC	AX	No	1	0	0
Celli et al[53]	1988	1	IC	SS	No	1	0	100
Celli et al[53]	1988	2	IC	SS	No	1	0	100
Celli et al[53]	1988	3	IC	PC	Yes	1	0	0
Celli et al[53]	1988	2	IC	AX	Yes	1	0	0
Celli et al[53]	1988	3 or 4	IC	PC	Yes	2	0	50
Chuang et al[27]	1995		PH	SS		5	NA	100
Chuang et al[27]	1995		PH	AX		6	NA	0

Table 1. *Continued*

Source	*Year*	*No. of ICs Used*	*Donor Nerve*	*Recipient Nerve*	*Interposition Graft for IC*	*No. of Cases*	*% ≥ M4*	*% ≥ M3*
Chuang et al[27]	1995		XI	SS		24	NA	100
Chuang et al[27]	1995		XI	AX		23	NA	100
Chuang et al[27]	1995	2	IC	AX	No	4	NA	100
Dai et al[23]	1990		TD	AX		2	100	100
Kline and Hudson[14]	1995	NA	IC	AX	Yes	6	0	33
Kline and Hudson[14]	1995		XI	SS		1	100	100
Kline and Hudson[14]	1995		XI	AX		1	0	0
Malessy et al[51]	1999		Hypogloss	AX		3	0	0
Malessy et al[51]	1999		Hypogloss	SS		4	0	25
Oberlin et al[24]	1994		XI	SS		1	0	100
Samardzic et al[28]	1992		TD, MP, or LT	AX		12	58	83
Samardzic et al[28]	1992	NA	IC	AX	Yes	11	27	64
Yamada et al[25]	1996		C3/4	UT		6	33	50
Yamada et al[25]	1996		C3/4	UT		3	0	66

AX, axillary; IC, intercostal; LT, long thoracic; MP, medial pectoral; SS, supraspinatus; TD, thoracodorsal; UT, upper trunk; PC, posterior cord; LC, lateral cord; MC, musculocutaneous; PH, phrenic; NA, not available; XI, spino-accessory.

Results

Case Series

In the series of patients from our institution we achieved restoration of ≥M3 bicep strength in 9 of the 10 intercostal to musculocutaneous nerve transfers. Seven of the 10 patients achieved M4 biceps recovery. One medial pectoral nerve to musculocutaneous nerve transfer was performed that obtained M3 biceps strength (Table 3).

For restoration of shoulder abduction 3 of 6 patients who underwent spinal accessory to suprascapular nerve transfer achieved ≥M3 shoulder abduction and 2 of these achieved M4 power. One patient received a spinal accessory to axillary nerve transfer with no return of function (M0). One patient underwent an intercostal nerve to axillary nerve transfer, achieving M4 shoulder abduction. Seven patients were excluded from analysis as they had transfers to both recipient nerves for shoulder abduction. Importantly, 6 of the 7 patients achieved M3 or better return of shoulder function (Table 3).

Meta-Analysis: Restoration of Elbow Flexion

Twenty-six studies with 965 transfers met the inclusion criteria for restoration of elbow flexion. Worldwide, 71% of transfers to the musculocutaneous nerve, independent of donor nerve, achieved ≥M3 elbow flexion and 37% achieved ≥M4. The 2 most common donors to the musculocutaneous were the intercostal nerves (54%) and the spinal accessory nerve (39%). Results for restoration of elbow flexion will focus on the use of interposition grafts with intercostal transfers, the number of intercostal nerves transferred, and the outcomes of intercostal versus spinal accessory nerve transfers. Reported data did not permit multivariate analysis of age, gender, or other demographic variables.

Intercostal to musculocutaneous nerve transfers without interposition grafts achieved ≥M3 results in 72% of patients. Only 47% of nerve transfers for biceps function performed with an interposition graft achieved ≥M3 strength ($p < .001$). While no difference in M4 biceps strength was demonstrated between the 2 groups (41% vs 32%), the number of transfers in this analysis was insufficient to exclude a potential difference between groups (power <50%; Fig. 2).

Of the 418 patients who had intercostal to musculocutaneous nerve transfers without interposition grafts, 59% had 2 nerves transferred and 34% had 3 or 4 intercostal nerves transferred. Seven percent of the intercostal to musculocutaneous transfers either did not identify the number of nerves transferred or grouped results for transfers of 1 to 4 nerves. While no difference could be detected between groups, the analysis lacked sufficient power (<50%) to exclude a potential difference in using 2 versus 3 or 4 intercostal nerves for restoration of elbow flexion to ≥M3 (75% vs 66%) or ≥M4 (42% vs 38%).

Spinal accessory nerve to musculocutaneous nerve transfers for restoration of elbow flexion resulted in 77% of patients with bicep strength of ≥M3 and 29% with ≥M4. Results comparing intercostal nerve

Table 2. Excluded Studies

Source	*Year*	*Reason for Exclusion*
Berger et al[84]	1991	A
Friedman et al[41]	1990	A
Kotani et al[7]	1972	A
Nagano et al[81]	1992	A
Nagano[93]	1998	A
Samardzic et al[73]	1986	A
Samardzic et al[92]	1989	A
Samardzic et al[39]	1990	A
Sedel[74]	1984	A
Sedel[88]	1987	A
Tsuyama and Hara[6]	1972	A
Azze et al[71]	1994	B
Brandt and Mackinnon[66]	1993	B
Dolenc[69]	1984	B
Dolenc[72]	1987	B
Iob et al[63]	1996	B
Matsuda et al[67]	1981	B
Millesi[65]	1988	B
Narakas[82]	1978	B
Narakas[37]	1981	B
Narakas[68]	1984	B
Narakas[18]	1991	B
Narakas and Hentz[64]	1988	B
Songcharoen[70]	1995	B
Thomeer and Malessy[91]	1993	B
Allieu et al[75]	1982	C
Allieu et al[76]	1984	C
Allieu et al[77]	1988	C
Allieu and Cenac[38]	1988	C
Brunelli[85]	1987	C
Brunelli and Brunelli[86]	1988	C
Friedman[90]	1991	C
Gilbert et al[89]	1988	C
Gu et al[80]	1989	C
Gu et al[59]	1990	C
Gu et al[57]	1992	C
Gu and Ma[60]	1996	C
Gu et al[56]	1998	C
Hentz and Navakas[79]	1988	C
Kanaya et al[58]	1990	C
Kawai et al[35]	1988	C
Mehta et al[83]	1993	C
Millesi[10]	1977	C
Millesi[20]	1984	C
Millesi[78]	1987	C
Narakas[61]	1985	C
Ploncard[40]	1982	C
Rutowski[55]	1993	C
Solonen[62]	1984	C
Terzis et al[87]	1987	C
Terzis et al[54]	1999	C

A, duplicated in another report by the same investigator; B, lack of information to determine inclusion criteria; C, did not meet inclusion criteria.

transfers without interposition grafts to spinal accessory nerve transfer for restoration of elbow flexion were comparable at $\geq$M3 biceps strength (72% vs 77%). Intercostal nerve transfers, however, were significantly improved relative to the spinal accessory nerve for biceps strength at $\geq$M4 (41% vs 29%; $p < .001$; Fig. 2). Although only small numbers were available for review, transfers using other donors, including Oberlin's transfer of 2 fascicles of the ulnar nerve[18,33] (97% $\geq$ M3, 94% $\geq$ M4), showed promising results for restoration of elbow flexion.

Meta-analysis: Restoration of Shoulder Abduction

Eight studies consisting of 123 transfers met the inclusion criteria for restoration of shoulder abduction. Worldwide, 73% of patients who underwent nerve transfer for restoration of shoulder abduction achieved $\geq$M3 and 26% achieved $\geq$M4 strength. Results will focus on comparison of donor nerve outcomes and recipient nerve outcomes.

The 2 major donor nerves were the spinal accessory nerve (41%) and intercostal nerves (26%). Twenty-two percent of the nerve transfers for restoration of shoulder abduction used multiple donor nerves and were excluded. In looking specifically at donor nerves for restoration of shoulder function, the spinal accessory nerve (98%) was significantly better than intercostal nerves (56%) in obtaining $\geq$M3 shoulder abduction ($p < .001$; Fig. 3). The numbers reported for shoulder strength of $\geq$M4 were too small to draw any meaningful conclusions for the spinal accessory nerve ($n = 3$) and the intercostal nerve ($n = 28$).

In analyzing recipient nerves, the axillary nerve was used in 58% of the cases and the suprascapular nerve in 30%. Transfers to 2 or more recipient nerves (13% of the patients) were excluded from the study. In evaluating restoration of shoulder function by recipient nerve, reinnervation of the suprascapular nerve (92%) demonstrated significantly better outcomes for $\geq$M3 shoulder abduction than the axillary nerve (69%; $p < .008$; Fig. 3). Thirty-four percent of the axillary nerve transfers ($n = 38$) and 13% of the suprascapular nerve transfers ($n = 8$) achieved $\geq$M4 shoulder abduction. The numbers reported for shoulder outcomes to $\geq$M4 were too small to draw any conclusions regarding recipient nerves.

Discussion

The functional outcomes of our 15 patients who underwent nerve transfer for restoration of shoulder and elbow function mirror the results of the English literature and provide additional support for this reconstruction option in these severely injured patients.

Table 3. Results of Case Series

Case No.	*Age (yr)*	*Gender*	*Dominant Hand*	*Mechanism*	*Injury*	*Primary Intervention*	*Secondary Procedures*	*Interval to Surgery (mo)*	*Elbow Flexion*	*Shoulder Abduction*	*Follow-Up (mo)*
1	21	M	No	MCA	AV (C6-T1), Com (UT)	Ntf XI-SS, NG of UT	Shoulder fusion	6	NA	0	86
2	67	M	No	MVA	AV (C6-T1), Com (UT)	Ntf XI-SS; IC (3, 4, 5)-MC; NG C5-AX and RD 15 cm		5	0	3*	72
3	23	M	Yes	ATV	AV (C6-T1), Com (UT)	Ntf IC (3-6)-AX, MP, RD; NG UT-MC, SS		4	NA	4*	78
4	39	M	No	MVA	AV (C6-T1), Inc (UT)	Nly UT; Ntf IC (3-7)-MN, AX, and MC		4	3	0	34
5	32	M	No	Industrial	AV (C5, 6)	Ntf XI-SS, IC (3-5)-MC, Steindler		5	4†	4	37
6	32	M	Yes	MCA	AV (C6-8), Inc (UT)	Ntf XI-AX, IC (4-6)-MC; Nly SS		5	5	0	32
7	7	M	Yes	MVA	AV (C5-7)	Ntf XI-SS; IC (4-6)-MC		5	4	4	28
8	23	M	Yes	Moped	AV (C6, 7), Com (UT)	Ntf XI-SS, IC (4-6)-AX, MP-MC	Steindler	5	3‡	4*	**48**
9	48	M	Yes	MCA	AV (C5-T1)	Ntf XI-SS, IC (4-6)-MC	Shoulder fusion	5	4	0	**28**
10	28	M	Yes	MCA	AV (C6-8), Com (UT), Inc (MT)	Ntf XI-SS, IC (5-7)-MC		4	3	3	19
11	19	M	No	ATV	AV (C6-T1), Com (UT)	Ntf XI-SS, IC (4-6)-MC; NG UT-AX		8	4	3*	12
12	9	M	No	MVA	AV (C5-T1)	Ntf XI-SS, IC (3, 4)-MC, IC (5, 6)-AX		5	4	2*	19
13	26	M	No	MCA	AV (C5, 6), Com (MT)	Ntf XI-SS, IC (4-7)-MC, MP-AX		5	5	4*	18
14	31	M	Yes	MCA	AV (C5, 6), Inc (MT)	Ntf XI-SS, IC (4-6)-MC, MP-AX		7	4	3*	17
15	40	M	Yes	Explosion	AV (C5-T1)	Ntf XI-SS, IC (3-5)-Gracilis		6	NA	0	17

AV, avulsion; Com, complete; Inc, incomplete; UT, upper trunk; MT, middle trung; Ntf, nerve transfer; NG, nerve graft; XI, spinal accessory; SS, supraspinatus; IC, intercostal; MC, musculocutaneous; MP, medial pectoral; AX, axillary; RD, radial; Nly, neurolysis; MN, median nerve; NA, not available.

* Excluded from analysis of shoulder function because of multiple nerve transfers for shoulder function.

† Patient excluded from analysis of elbow flexion because of Steindler flexorplasty done at time of initial repair.

‡ Grade is pre-Steindler.

The results of the meta-analysis suggest that there is a disadvantage to using interposition nerve grafts when performing intercostal nerve transfers for restoration of biceps function. There are some theoretical advantages to interposition nerve grafting that have encouraged its use. Studies have demonstrated that intercostal nerves lose up to 10% of motor axons with each 10 cm of distal progression from the midaxillary line to the sternum.[19,34] A more proximal transection of the intercostal nerve has the potential to preserve more motor axons. Another theoretical advantage of interposition grafts is that they permit a more distal dissection of the musculocutaneous nerve into the muscle belly. This permits coaptation of the graft closer to the motor endplates.[8,14] Grafts also avoid tension on the nerve repair and may allow earlier restoration of passive shoulder motion. Opponents of interposition grafts counter that reinnervation is compromised by traversing 2 coaptation sites as opposed to 1.[9,11,21,22] We believe this is the first study to demonstrate statistical superiority in achieving ≥M3 biceps function with the use of direct coaptation of intercostal to musculocutaneous transfers (72%) compared with those performed with interposition grafts (47%; $p < .001$). Although there was insufficient power to determine a difference, there also was a trend toward improved restoration of M4 strength without the use of interposition grafts (41% vs 32%). Of the 516 intercostal to musculocutaneous nerve transfers reviewed in this meta-analysis, 53 used an interposition nerve graft. Although there are substantially more cases without interposition grafts, the results are unlikely to be a result of selection bias. From this analysis it appears that individual surgeons do or do not use interposition grafts as a fundamental technique rather than being

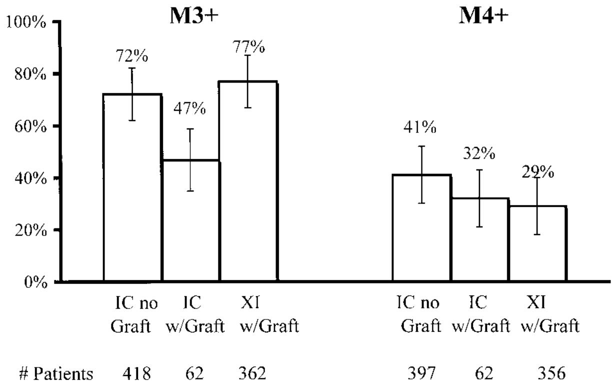

Figure 2. Nerve transfer for restoration of elbow flexion. The graph shows the percentage of patients achieving at least either M3 or M4 function. IC, intercostal; XI, spinal accessory.

based on specific characteristics of individual patients.

There is no consensus with regard to the optimum number of intercostal nerves necessary to transfer to the musculocutaneous nerve to obtain functional elbow flexion. With the numbers studied in this meta-analysis we were unable to demonstrate a difference when using 2 versus 3 or 4 intercostal nerves for restoration of elbow flexion to ≥M3 (75% vs 66%) or ≥M4 (42% vs 38%; power <50%) Further studies are needed to answer this question.

The results of this meta-analysis showed that intercostal transfers achieved a higher percentage of ≥M4 biceps flexion strength than use of the spinal accessory transfer ($p < .001$). This finding is in contrast to others who have reported superior results in obtaining elbow flexion using the spinal accessory nerve.[13] Waikakul et al,[13] in a prospective study that compared spinal accessory to intercostal nerve transfer, concluded that although the patients with spinal accessory nerve transfers had significantly better motor outcomes, patients with intercostal nerve transfers had significantly better protective sensation and pain relief. These investigators further point out that shoulder fusion was required more frequently in the group following spinal accessory transfer to control their unstable and subluxating shoulder. For these reasons, Waikakul et al[13] recommend intercostal transfer in patients with complete plexus palsy, particularly when deafferentation pain is a major issue, and prefer spino-accessory transfer for isolated biceps loss, particularly in female patients.

A powerful argument for using the spinal accessory nerve as a donor nerve is based on its axonal composition. The spinal accessory nerve contains a high number of motor fibers (1,500–3,000) and few sensory fibers. Conversely, an intercostal nerve contains a mixture of both motor and sensory fibers with only 500 to 700 motor fibers per nerve.[19,38–41] It makes sense that the axonal composition of the spinal accessory nerve could positively affect outcome. A clear disadvantage of using the spinal accessory nerve for transfer to the musculocutaneous nerve, however, is the need for an interpositional nerve graft. In interpreting our results one could surmise that the advantage gained due to axonal composition inherent in the spinal accessory nerve is more than offset by the negative effect of an interposition nerve graft.

Although we focused only on the spinal accessory and intercostal nerves for restoration of elbow flexion, promising results have been reported with other donor nerves.[11,22–24,28,33] Leechavengvongs et al[33] reported excellent results in 32 patients using 2 fascicles of the ulnar nerve transferred to the musculocutaneous nerve; 97% of their transfers achieved M3 strength and 94% achieved M4 biceps strength. This transfer, however, is only applicable when the C8–T1 roots and the lower trunk uninjured.

In examining restoration of shoulder function, the results of the meta-analysis suggest that the best nerve transfer for restoration of shoulder abduction is the spinal accessory to suprascapular nerve transfer. The spinal accessory nerve (98%) was a significantly better donor nerve than intercostal nerves (56%) in obtaining ≥M3 shoulder abduction ($p < .001$). In evaluating restoration of shoulder function by recipient nerve, the suprascapular nerve (92%) was a

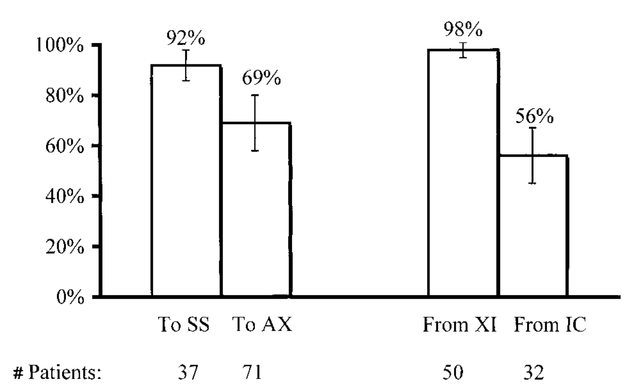

Figure 3. Nerve transfer for restoration of shoulder function. The graph shows the percentage of patients achieving M3 or greater outcomes. SS, suprascapular nerve; AX, axillary nerve; XI, spinal accessory nerve; IC, intercostal.

significantly better recipient nerve than the axillary (69%) in obtaining ≥M3 shoulder abduction ($p < .008$). Although unable to be examined from the data available in this meta-analysis, there is some suggestion that dual nerve transfers for shoulder restoration may be preferable. Chuang et al[27] achieved shoulder abduction of 20° to 90° (mean, 55°) in 21 of 21 patients using simultaneous phrenic to suprascapular and spinal accessory to axillary nerve transfers. Based on the data presented it was impossible to determine the numbers of patients with M4 recovery in their series. As 6 of the 7 patients in our case series with dual nerve transfers for shoulder restoration also achieved M3 or M4 recovery, we recommend that dual transfers for shoulder reinnervation be performed when adequate donors are available.

The quality of a meta-analysis is proportionate to the homogeneity and quality of the studies analyzed. Population bias is minimized by restricting our study to those patients with nonobstetric brachial plexus avulsion injuries who had sustained their injury within 12 months of surgery. Our goal was to isolate the effect of nerve transfer on outcome by eliminating as much confounding demographic variation as possible. It is noteworthy that the majority of patients included in this analysis underwent surgery less than 9 months after injury. Several investigators have stated that performing brachial plexus reconstruction within 9 months notably improves outcome.[9,12] As we included patients within a 12-month period it is possible that some transfers may not have performed as well due to a longer delay from injury. Finally, although we selected a minimum follow-up period of 1-year, it should be noted that the majority of patients had a follow-up period of several years (average, 42 months; range, 12–180 months). We acknowledge that motor recovery usually proceeds beyond 1 year. Therefore, it is possible that a small number of patients who were classified as having M3 strength could potentially achieve M4 with time. Because speed of nerve recovery should not differ among donor nerves it is unlikely that this would have an appreciable effect on our conclusions.

All meta-analyses are subject to detection and publication bias. Through an initially broad literature search and cross-reference check we attempted to minimize the number of relevant articles that were potentially not included. Lack of foreign language articles is a limitation; however, we believe this is minimized as a number of leading researchers report results in both non-English and English publications. A meta-analysis of case series is also subject to measurement bias. Each of the studies included had outcomes assessed by the surgeons or their staff rather than a blinded observer. We can only rely on the integrity of the investigators and the rigor of the peer review process to minimize this effect. We further acknowledge that other unrecognized, confounding variables also may impact the pooled results of this study.

Despite the difficulties in pooling the results of brachial plexus reconstruction outcomes we believe it is important to quantitatively assess previous results to determine the effectiveness of various surgical reconstructive techniques. It is recognized that the best study design for comparing 2 treatment methods is a randomized trial; however, in the absence of the availability of such studies and the considerable obstacles inherent in the design and execution of such a study, a meta-analysis provides insights from large numbers of patients that should be preferable to the alternatives of conjecture and personal experience. As such, the pooled data from this analysis, with its inherent methodologic flaws, and the additional analysis of our experience with these transfers suggest the following:

1. Nerve transfers are a viable treatment option in patients with traumatic brachial plexus injuries for restoration of elbow and shoulder function.
2. Nerve transfers from the intercostal to the musculocutaneous nerve using interposition grafts have a lower rate of functional return than similar transfers without interposition grafts.
3. As donor nerves to the musculocutaneous nerve, intercostal nerves have a higher rate of functional return than similar transfers using the spinal accessory nerve as a donor.
4. Shoulder restoration should focus on either a spinal accessory nerve to suprascapular nerve transfer or a dual nerve transfer to both suprascapular and axillary nerves.

Future efforts should be made to standardize both preoperative and postoperative assessment to assist in clinical decision making and to evaluate the efficacy of new procedures.

Appendix

Calculation of power by use of the equation

$$N = [(Za + Zb)^2 * 2p * (1—p)]/2d$$

solving for Zb. The corresponding value of beta was then derived from a table of Z scores[26] in which N = sample size of the smallest sample, Za = the corresponding z score for the alpha level chosen, Zb = the corresponding z score for the beta level, p = the mean of the success rates in the 2 groups, and d = the difference between success rates in the 2 groups.

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