Reconstruction of Pediatric Brachial Plexus Injuries With Nerve Grafts and Nerve Transfers

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Purpose To review the demographics and injury patterns in consecutive pediatric patients with traumatic brachial plexus injury presenting to a single center over a 16-year period and to review the outcomes of nerve grafting and nerve transfers for reconstruction of shoulder abduction and elbow flexion in these patients.

Methods Forty-five pediatric patients presented for treatment of traumatic Brachial plexus injury from 1996 to 2012. Subgroup analysis of patients who had nerve grafting or nerve transfers for restoration of shoulder abduction and elbow flexion was carried out to compare outcomes of Medical Research Council (MRC) motor grading.

Results The mean age of patients was 13.8 years (range, 3–17 y). Panplexal injuries (62%) and upper plexus injuries (16%) were particularly common. There was a very high proportion of preganglionic injuries (91%). Six of the 10 of patients who underwent intraplexal nerve grafting only for restoration of shoulder abduction achieved grade 3 or better power compared with 42% (5/12) of patients who had nerve transfers. When contralateral C7 was used as a donor for nerve transfer in restoration of shoulder abduction, 1 of the 5 patients achieved grade 3 or better shoulder abduction. All 4 patients who had nerve grafts for restoration of elbow flexion achieved grade 3 or better power, compared with 11 of 12 patients who had nerve transfers. There was no statistical difference in outcome (MRC grade 3 or 4) between patients who had nerve grafts and those who had nerve transfers.

Conclusions This study shows that nerve grafts can result in similar outcomes (MRC grading) to nerve transfers for restoration of shoulder abduction and elbow flexion in traumatic pediatric BPI. The findings of this study do not support the use of contralateral C7 as a donor for nerve transfer in reconstruction of shoulder abduction in this age group. *(J Hand Surg Am. 2014;39(9):1771–1778. Copyright © 2014 by the American Society for Surgery of the Hand. All rights reserved.)*

Type of study/level of evidence Therapeutic IV.

Key words Brachial plexus injury, contralateral C7, nerve graft, nerve transfer, pediatric brachial plexus.

Traumatic brachial plexus injuries (BPIs) in children are rare. Boome[1] reported an incidence of 1% of pediatric injuries out of all brachial plexus lesions in his series. Most reports consist of case series of fewer than 25 patients often accrued over 10 years or longer.[2–7] Thus, there is no consensus on the best treatment for these patients, with most surgeons adopting techniques used for adult brachial plexus reconstruction to pediatric patients.

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A particular characteristic of pediatric patients is the high incidence of root avulsion injuries[4,5,8] and a lack of deafferentation pain. These patients also have a higher incidence of associated skeletal injuries and exhibit a shorter time to recovery of shoulder and elbow function following plexus reconstruction. Data from the National Pediatric Trauma Registry of the United States has demonstrated an incidence of 0.1% of BPIs in pediatric patients with multitrauma.[9] This contrasts markedly with a reported incidence of 1.2% BPIs in adult multitrauma patients.[10]

An unanswered question is which technique, nerve graft or nerve transfer, is superior in the pediatric traumatic BPI population. Because of the high prevalence of root avulsion injuries in children, nerve transfers are often the only option for treatment.[8] Two recent systematic reviews have highlighted the superiority of nerve transfers over nerve grafting for reconstruction of shoulder and elbow function in adult traumatic upper BPIs.[11,12] These findings may not be true for children owing to their enhanced potential for regeneration and recovery compared to adults.

The primary aim of this study was to review the demographics and patterns of injury in consecutive pediatric patients with BPIs presenting to a single tertiary referral center between 1996 and 2012. A secondary aim was to review the outcomes of nerve grafting and nerve transfers for reconstruction of shoulder abduction and elbow flexion in these patients.

TABLE 1. Demographic Data of Pediatric Patients With Traumatic BPIs (n = 45)

Age (y)*	13.8 ± 3.4 (3−17)
Sex	
Male	35
Female	10
Time from injury to surgery (mo)*	6 ± 3 (2−55); median, 6
Early (≤ 9 mo)	39
Late (> 9 mo)	6
Mechanism of injury	
Automobile	16
Snowmobile/snowboarding/skiing	8
Motorcycle/motorcross	5
ATV	6
Ped struck	5
Sports-related	2
Other (eg, gunshot wound, falling from bicycle, hit by falling tree)	3

ATV, all-terrain vehicle; Ped struck, pedestrian struck by vehicle.
*Values are mean and SD, with range in parentheses.

MATERIALS AND METHODS

Patients

Following approval by our institutional review board, a retrospective chart review of all pediatric patients with BPIs between 1996 and 2012 was performed. Inclusion criteria included all patients 17 years of age or younger at the time of surgery who had sustained a traumatic BPI confirmed by clinical examination and electromyogram and subsequently underwent brachial plexus exploration and reconstruction. All patients were evaluated by the senior authors of the study (R.J.S., A.T.B., A.Y.S.) in a multidisciplinary brachial plexus clinic and underwent an electromyogram and computed tomography myelogram and/or magnetic resonance imaging study to confirm the level and extent of the injury. The final decision for the type of surgical reconstruction was made during surgery after exposure of the brachial plexus and performance of electrodiagnostic studies. An exception to this was when the decision to use a free functioning muscle transfer (FFMT) was made prior to surgery. Subgroups of patients who underwent nerve grafting and nerve transfers for restoration of shoulder abduction and elbow flexion were identified from this cohort. Patients who had at least 9 months of postoperative follow-up were included in this subgroup analysis.

Forty-five patients were identified who met the inclusion criteria. Demographic data of patients are presented in Table 1.

Outcome measures

Patients were evaluated after surgery to assess recovery of muscle strength with the modified grading system of the British Medical Research Council (MRC).[13]

Approach to brachial plexus reconstruction

For patients with C5−6 injuries, the brachial plexus was explored through a supraclavicular approach. An infraclavicular exposure was occasionally used either when scarring extended into the retroclavicular region or specifically to explore the musculocutaneous (MCN), axillary, or suprascapular (SSN) nerves. In the presence of a functional C5 nerve as confirmed through intraoperative electrophysiological testing, nerve grafts to the posterior division of the upper trunk (PDUT), axillary nerve, or SSN were used to reinnervate the shoulder. In patients presenting more than 6 months after injury or without a functional C5 nerve, our preference was to perform a double nerve transfer if donor nerves were both available (spinal accessory nerve [SAN] to SSN and triceps branch to the anterior division of the axillary nerve). For recovery of elbow function, either a single or a double fascicular nerve transfer was performed (ulnar nerve fascicle to biceps motor branch and/or median nerve fascicle to brachialis motor branch). Alternatively, nerve grafts were used if a defined injury to the MCN was present (ie, proximal and distal portions of the MCN were viable).

In patients with panplexus injuries, our priorities were restoration of elbow flexion followed by shoulder abduction/external rotation. The brachial plexus was explored through supraclavicular and infraclavicular approaches. In the presence of functional nerves (at nerve, trunk, or division level) in the upper plexus, nerve grafts were used to reinnervate the axillary nerve and SSN. We tried to graft to at least 2 shoulder targets, SSN and PDUT or axillary nerve, if possible. If additional donor nerves were available, nerve grafts were used to restore elbow flexion through the anterior division of the upper trunk (UT). Extraplexal donors such as the SAN and intercostal nerve (ICN), may be used to restore shoulder and elbow function, either as nerve transfers (SAN or ICN) or with a bridging nerve graft (SAN to distal targets), if required. In children nearing skeletal maturity, FFMT innervated by ICNs may be used to restore elbow flexion together with adjunctive nerve transfers or grafts for restoration of shoulder abduction.

We relied on intraoperative electrodiagnostic studies for decision making. These include nerve action potentials, somatosensory and motor evoked potentials, and compound muscle action potentials. In the presence of a nerve action potential recording across a lesion (indicating preserved axons with potential for regeneration and a good prognosis,[14] we typically performed only a neurolysis. The presence of somatosensory and motor evoked potentials signified continuity of the roots and the spinal cord and served to distinguish postganglionic lesions from preganglionic ones (root avulsions). In cases in which the electrophysiological studies were inconclusive, the findings of all studies were considered, and we made a team decision to choose the optimal surgical procedure.

Statistical analysis

Data, which consisted of categorical variables, were analyzed and evaluated using the Fisher exact test. Two-sided tests were used, and the threshold of significance was set at *P* less than .05.

TABLE 2. Injury Pattern of Pediatric Patients With Traumatic BPIs

	Number of Injuries (%)
Injury pattern (n = 45)	
Complete (C5−T1)	28 (62)
Incomplete	
Upper (C5−6)	7 (16)
Upper + C7	4 (9)
Lower + C7	2 (4)
Lower (C8−T1)	1 (2)
UT	1 (2)
Division/cord	2 (4)
Root level lesions (n = 42)	
Preganglionic	38 (91)
Postganglionic	4 (10)
Surgical intervention (n = 45)	
Nerve transfers/nerve grafts	25 (56)
Neurolysis only	1 (2)
FFMTs with adjunctive procedures	18 (40)
Tendon transfers only	1 (2)

RESULTS

The injury patterns and levels and surgical interventions are available in Table 2.

Thirty-six patients had at least 9 months of postoperative follow-up and met criteria for subgroup analysis for outcomes following surgery to restore shoulder abduction or elbow flexion. The mean duration of follow-up was 37 months (range, 9−152). Two patients had follow-up less than 1 year. There were 22 patients who had nerve grafts or nerve transfers for restoration of shoulder abduction. Data are summarized in Table 3. Of these, 10 had nerve grafts alone, with targets for reinnervation inclusive of axillary nerve (n = 8), SSN (n = 7), UT (n = 1), and posterior division of upper trunk (PDUT) (n = 1). Ten patients had nerve transfers for shoulder abduction. A number of patients had SAN to SSN (n = 4) or nerve to triceps branch transfer to the anterior division of the axillary nerve (n = 3), alone or in combination. Other patients had nerve transfers using the contralateral C7 (CC7) as the donor nerve (n = 5). Two patients had a combination of nerve grafts and nerve transfers. Of patients who had nerve grafts alone, 3 out of 10 achieved MRC grade 4 or

TABLE 3. Nerve Grafts and Transfers for Shoulder Abduction

Number	Age/Sex	Mechanism of Injury	Injury Pattern	Avulsed Nerve Root	Time to Surgery Postinjury (mo)	Last Follow-Up (mo)	Procedures Performed (Length of Nerve Graft [cm])	Postoperative Shoulder Abduction (MRC Grade)
Nerve Grafts								
1	14/male	ATV	Complete	C6–8	3	30	C5 to axillary (13); C5 to SSN (6)	2+
2	11/male	Automobile	Complete	C7–T1	2	55	C5 to axillary (12); C5 to SSN (6)	3
3	6/male	Automobile	Complete	C7–T1	6	32	C5 to axillary (9); C5 to SSN (6)	0
4	12/male	Motorcycle	Complete	C7–8	NA	44	C6 to UT (3.5)	4
5	14/male	Snowmobile	UT	None	6	17	C5 to axillary (15); C5 to SSN (7)	4
6	15/female	Automobile	Complete	C7–T1	4	33	PDUT to axillary (14)	3
7	15/male	Automobile	C5–7	C6	6	9	C5 to SSN (7); C5 to PDUT (7)	3
8	6/female	Automobile	Complete	C5–8	4	10	SAN to axillary (NA)	0
9	8/male	Snowmobile	PDUT, SSN	None	4	23	PDUT to axillary (6); PDUT to SSN (6)	4
10	10/male	Motorcycle	C5–7	C6–7	6	21	C5 to axillary (11); C5 to SSN (9)	0
Nerve Transfers								
1	9/male	Snowmobile	Complete	C8–T1	3	52	SAN to SSN	3
2	16/male	Automobile	C5–6	C5–6	6	118	SAN to SSN, nerve to triceps to axillary	5–
3	11/female	Sledding	Complete	C5,7	8	82	SAN to SSN	2
4	16/male	Ped vs vehicle	C5–6	C5–6	4	44	SAN to SSN, nerve to triceps to axillary	4+
5	17/female	Automobile	C5,6	None	10	25	Nerve to triceps to axillary	2
6	15/male	Car vs bicycle	Complete	C5–T1	3	28	CC7 to axillary (24); CC7 to SSN (21)	1
7	17/male	Football	Complete	C5–T1	3	22	CC7 to SSN (20); CC7 to PDUT (20)	2
8	8/male	Automobile	Complete	C5–T1	5	27	CC7 to axillary (NA); CC7 to SSN (NA)	1
9	14/female	Sledding	Complete	C5–7	2	28	CC7 to axillary (22); CC7 to SSN (16)	3
10	3/male	Ped vs vehicle	Complete	C5–T1	6	69	CC7 to SSN (NA); CC7 to PDUT (NA)	2
Combination								
1	16/male	Ped vs vehicle	C5–7	C7	6	35	SAN to SSN; C5 to PDUT (8)	3–
2	13/male	ATV	C5–7	C6–7	5	24	SAN to SSN; C5 to PDUT (5.5)	3+

ATV, all-terrain vehicle accident; Ped, pedestrian; NA, not available.

better shoulder abduction, and 6 out of 10 achieved MRC grade 3 or better. For patients who underwent nerve transfers alone or in combination with nerve grafts, 2 out of 12 achieved MRC grade 4 or better shoulder abduction, and 5 out of 12 achieved MRC grade 3 or better. In patients with CC7 as a donor for nerve transfer, 1 out of 5 achieved MRC grade 3 or better shoulder abduction. There was no statistical difference in outcome (MRC grade 3 or 4) between patients who had nerve grafts and those who had nerve transfers for restoration of shoulder abduction.

Sixteen patients had nerve grafts or nerve transfers for restoration of elbow flexion. Data are summarized in Table 4. Of these, 4 had nerve grafts alone, either to reconstruct defects of the musculocutaneous nerve or as a bridge between a nerve transfer from the SAN. Twelve patients had reconstruction with nerve transfers. In patients receiving nerve grafts alone, 3 out of 4 achieved MRC grade 4 or better elbow flexion, and 4 out of 4 achieved MRC grade 3 or better. Nerve transfers used included (1) ICNs to MCN or biceps motor branch (n = 4), (2) single fascicular (Oberlin transfer[15]) (n = 4), (3) double fascicular transfer (n = 3) for elbow flexion, (4) SAN to biceps motor branch (n = 1). For patients with nerve transfers, 9 out of 12 achieved MRC grade 4 or better elbow flexion, and 11 out of 12 achieved MRC grade 3 or better. There was no statistical difference in outcome (MRC grade 3 or 4) between patients who had nerve grafts and those who had nerve transfers for restoration of elbow flexion.

DISCUSSION

The characteristics of pediatric patients with BPIs presenting to our institution over a 16-year period were similar to other reported series.[2–6,16] Like others, we found that the most common mechanism of injury was as a result of motor vehicle accidents with children either as passengers or pedestrians struck by vehicles. This is in concordance with the literature.[16] Similarly, there was an extremely high proportion of preganglionic injuries in our series, necessitating nerve transfers for reconstruction in 55% of patients for shoulder abduction and 75% for elbow flexion.[8] Despite the high incidence of preganglionic injuries, often not all nerve roots were avulsed, allowing reconstruction of shoulder abduction through nerve grafting in many of our patients (Table 3).

Our results suggest that nerve grafting for reconstruction of elbow flexion and shoulder abduction can achieve good results in children, similar to that achieved with nerve transfers. Failures following nerve grafting can still occur, as evidenced by 3 out of 10 patients who had nerve grafts for shoulder abduction and did not exhibit any recovery. This differs from pooled data analyzed through systematic reviews in adults,[11,12] which supports nerve transfers over nerve grafts. It also differs from comparative studies that support nerve transfers over nerve grafting in adults for reconstruction of shoulder and elbow function.[17,18] An explanation for this may be the enhanced regenerative capacity of nerves and the shorter distances for regeneration in children. Experimental studies in animals have shown that, whereas fetal nerve regeneration occurs at a rate equivalent to the adult, the number of larger myelinated fibers crossing the repair site is superior to that in adult animals, with a higher total percentage of remyelinated nerves at the experimental endpoint.[19,20] This may allow regenerating nerve axons to reach the target muscle even in the presence of long (> 7 cm) nerve grafts, which were used in many patients.

We found that the use of the CC7 as a donor for nerve transfers in shoulder abduction resulted in very poor outcomes, with 1 out of 5 patients achieving M3 or greater power. This is similar to our experience with the use of hemi-CC7 transfers in adults, where we had very poor outcomes in restoration of shoulder and median nerve function.[21] The advantages of CC7 as a donor include little donor site morbidity and a large number of myelinated fibers in C7 (25,000), which is far more than other nerves used in reconstruction of the brachial plexus.[22] However, the reported outcomes of CC7 transfer for restoration of shoulder abduction have been mixed. Hentz and Doi[23] reported 2 CC7 transfers to the SSN with restoration of M2 and M3 shoulder function. In other studies, CC7 transfer was performed together with other nerve transfers, such as SAN to SSN, making outcomes of CC7 transfer in isolation difficult to interpret.[24–26] Based on our findings and experience, we would not recommend the use of CC7 as a donor for nerve transfers for restoration of shoulder abduction.

Our approach to children with traumatic BPIs is divided into 3 groups based on age. In children younger than 4 years, the focus is on restoring and maximizing hand function, similar to patients with obstetric brachial plexus palsies. Later efforts are aimed at restoration of elbow and shoulder function. In our brachial plexus clinic, we have arbitrarily decided to treat children older than 12 years as adults. The priorities for restoring function, in order of importance, are elbow flexion, shoulder abduction and/or stability, hand sensation, wrist extension and

TABLE 4. Nerve Grafts and Transfers for Elbow Flexion

Number	Age/Sex	Mechanism of Injury	Injury Pattern	Avulsed Nerve Root	Time to Surgery Postinjury (mo)	Last Follow-Up (mo)	Procedures Performed (Length of Nerve Graft [cm])	Postoperative Shoulder Abduction (MRC Grade)
Nerve Grafts								
1	16/male	Tree fall	Post cord, MCN	None	4	30	MCN graft (15)	4+
2	14/male	Skiing	Complete	C8–T1	15	152	SAN to MCN (12.5)	5–
3	15/female	Automobile	Complete	C7–T1	4	33	Anterior division to MCN (17)	4
4	3/male	Ped vs vehicle	Complete	C5–T1	6	69	SAN to biceps branch MCN (14)	3+
Nerve Transfer								
1	16/male	Snowmobile	Complete	C6–T1	5	34	ICN to MCN	4+
2	9/male	Snowmobile	Complete	C8–T1	3	52	ICN to MCN	5–
3	14/male	Snowmobile	UT	None	6	17	Ulnar fascicle to biceps motor branch	4+
4	11/female	Sledding	Complete	C5,7	8	82	ICN to MCN	4
5	15/male	Automobile	C5–7	C6	6	9	Ulnar fascicle to biceps motor branch	4
6	14/female	Sledding	Complete	C5–7	2	28	SAN to biceps motor branch	4
7	16/male	Ped vs vehicle	C5–7	C7	6	35	Double fascicular transfer	4+
8	16/male	Ped vs vehicle	C5–6	C5–6	4	44	Ulnar fascicle to biceps motor branch	4+
9	6/female	Automobile	Complete	C5–8	4	10	ICN to biceps motor branch	0
10	17/female	Automobile	C5–6	None	10	25	Double fascicular transfer	3+
11	13/male	ATV	C5–7	C6–7	5	24	Double fascicular transfer	4+
12	10/male	Motorcycle	C5–7	C6–7	6	21	Ulnar fascicle to biceps motor branch	3

ATV, all-terrain vehicle accident; Double fascicular transfer, ulnar fascicle to biceps motor branch transfer and median fascicle to brachialis motor branch transfer; Ped, pedestrian.

finger flexion, wrist flexion and finger extension, and finally, intrinsic hand function. The approach relies on maximizing function while prioritizing movements that have the least distance required for nerve regeneration to target muscles. Because of a paucity of nerve donors, the majority of patients have reconstructive efforts targeted only at restoration of elbow flexion and shoulder abduction. For children between 4 and 12 years old, treatment is controversial in regards to prioritization of restoring hand function or shoulder abduction and elbow flexion. We have focused on restoring shoulder abduction and elbow flexion for these patients. Our approach relies on the use of a combination of nerve grafts or nerve transfers, where available. Because of continued growth during childhood, we try to avoid secondary reconstructive procedures such as FFMT and arthrodeses, which may interfere with skeletal growth and also result in contractures of the FFMT due to differential growth between the muscle and the limb. This approach is based on our experience with 2 children who developed elbow flexion contractures after FFMT.

Limitations of our study include those resulting from a retrospective chart analysis with some patients lost to follow-up and some missing data. In addition, the small sample size of patients undergoing nerve grafts or nerve transfers for restoration of shoulder and elbow function limited the accuracy of statistical analysis with the possibility of a statistical difference between nerve grafts and transfers that might be detected with a larger sample size. The small sample size also did not allow us to determine the effect of patient age and time to surgery on outcome. Another limitation is the less than 1 year follow-up of some patients. Patients with 9 months of postoperative follow-up were included owing to the rarity of patients with traumatic pediatric BPI. In our practice, many patients are from out of state and unable to return for follow-up. The difference in proportion of patients achieving MRC grade 4 and above and MRC grade 3 and above shoulder abduction between patients who had nerve grafts alone and those with nerve transfers alone or in combination with grafts was not statistically significant, although statistical analysis was been hampered by a small sample size. In addition, the wide variety of nerve grafts and transfers performed made the cohort very heterogeneous. Owing to the rarity of BPIs in children, however, these were unavoidable issues. Regardless of these limitations, this study represents a relatively large series of pediatric BPIs as compared with previously reported series.[4]

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