Morphometric analysis of the association of primary shoulder reconstruction procedures with scapular growth in obstetric brachial plexus paralysis patients

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Abstract

Background Obstetric brachial plexus paralysis (OBPP) has been associated with shoulder deformities, scapular growth, and shoulder function impairment. The absence of balanced muscular forces acting on the scapula has been considered responsible for scapula dysplasia and impaired growth as compared with the normal side. Scapula growth impairment may also lead to shoulder and upper extremity dysfunction. This study aims at showing the association of primary nerve reconstruction with the restoration of scapular bone growth potential.

Methods This is a retrospective review of 73 patients with OBPP who underwent primary shoulder reconstruction. Patients were categorized for assessment and analysis into group A, global paralysis; group B, Erb's palsy; and group C, Erb's

palsy with C7 root involvement. Scapular posteroanterior and lateral X-rays were obtained in which four scapula dimensions were manually measured. The growth discrepancy depending on the applied treatment was investigated.

Results The highest improvement was noted in scapular height in the Erb's palsy group who underwent simultaneous neurotization of the suprascapular and axillary nerves. The oblique axis was more improved in the Erb's palsy group while both big and small widths were more improved in the Erb's palsy with C7 root involvement group in patients who underwent concomitant neurotization of the suprascapular and the axillary nerves. Functional improvement correlated positively with growth improvement in all groups and scapular dimensions.

Conclusion Scapula growth and shoulder function improvement were higher in patients with Erb's palsy. Simultaneous axillary and suprascapular nerve neurotization provided the best outcome in both functional and growth restoration.

Keywords Scapula · Bone growth · Obstetric brachial plexus paralysis · Primary plexus reconstruction · Shoulder

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Introduction

Most of the patients presenting with obstetric brachial plexus paralysis (OBPP) experience gradual spontaneous recovery. About 10 % of cases with C5–C6 lesion, 35 % with C5–C7 lesion, 50 % with C5–T1, and nearly all cases with C5–T1 with positive Horner sign most commonly report dysfunction of shoulder abduction (SA) and external rotation (SER) [5]. Sjöberg et al. [32] studied the prognosis of children with OBPP among 25,000 newborns in a 10-year period and emphasized prevention regarding obstetric and pediatric management.

Early in the twentieth century, osseous deformities in patients with OBPP were frequently observed in plain X-rays and reported but little or no evidence was provided regarding

the etiology of these deformities. According to Ebaug et al. [7], the upper and lower portions of the trapezius and the serratus anterior muscles are important for scapulothoracic motion. In patients with OBPP, the anatomical integrity and function of these muscles are impaired due to the developmental irregularities of the scapula. Therefore, it was observed that the aforementioned long-standing muscle imbalance leads to glenohumeral deformity which further deteriorates the residual weakness and functional limitation of the shoulder. Nevertheless, they did not analyze specific anatomic irregularities of the scapula and they did not investigate the effect of treatment on the latter. Pearl and Edgerton [25] investigated the pathological changes that occur in the glenohumeral joint during growth in 25 patients with OBPP, but their findings were not associated with the anatomic characteristics of the scapula and the scapulothoracic joint. Waters et al. [41] described glenohumeral and other skeletal deformities, such as glenoid hypoplasia, posterior subluxation and flattening of the humeral head, and hooking of the coracoid, in 42 children with OBPP evaluated with computerized tomography or magnetic resonance imaging. Although they noted improvement in both function and growth of the glenohumeral joint and scapula, they did not provide an evaluation of a potential association between improvement and specific treatment.

In their study including 58 children with unilateral OBPP, van Gelein Vitringa et al. [40] showed that the affected scapula was significantly smaller compared to that of the normal side. This reduction of growth was more noted on the dorsal surface of the affected scapula than on its ventral surface, and it was significantly associated with the subluxation of the humeral head due to the brachial plexus lesion. However, their study included the measurement of only the horizontal distance between the medial side of the scapula and the subchondral glenoid.

Russo et al. [28] reported the significance of scapulothoracic and glenohumeral contribution to shoulder and upper extremity motion and the degree that this contribution is decreased in children with OBPP. This decrease was significantly associated with the scapulothoracic displacement due to abnormal scapular morphology and dysplasia. However, these results were not clearly associated with specific scapular deformities or treatment histories.

Terzis et al. [39] also reported the radiologic characteristics of shoulder deformities in OBPP such as the elevated and hypoplastic scapula, the shallow and flattened glenoid fossa, the inferiorly directed coracoid process, and the abnormally tapered acromion. However, the analysis of scapular growth and the association of the improved developmental and functional potential of the shoulder with the treatment were not included.

It is therefore evident that the absence of appropriate muscle force on the bones in OBPP patients leads to bone growth and size deficiency compared to the unaffected side. Apparently, there is a paucity of literature on scapula growth

impairment in particular which comprises both a functional and cosmetic deformity that needs to be addressed due to the role of the scapula in shoulder function [5, 32].

The aim of this study is to report the association of primary shoulder reconstruction procedures with scapular growth in OBPP patients.

Methods and Material

This is a retrospective review of 73 patients with OBPP who underwent primary shoulder reconstruction procedures between March 1979 and March 2007. Detailed patient history and a follow-up time of 2 years or longer were prerequisites for patient inclusion. Table 1 shows patients' demographics and OBPP diagnosis.

Primary shoulder reconstruction procedures ($n=125$) included neurolysis and axillary (Ax) and/or suprascapular nerve (Ss) neurotization using extraplexus and intraplexus motor donors. The term neurotization refers to primary nerve repair using interposition nerve grafts, most often harvested sural and saphenous nerves. The proximal end of the interposition nerve graft is coapted to the motor donor and the distal end to the nerve being neurotized, in an end-to-end fashion. Nerve regeneration is enabled along the nerve grafts. In intraplexus neurotization, donor options include the undamaged roots or available branches or fascicles of functioning donors. In global root avulsions where intraplexus donors are

Table 1 Patients' demographics and OBPP diagnosis

Total patients included	73
Female	37 patients
Male	36 patients
Mean denervation time	0.39±0.58 year old
Global paralysis in	48 patients
Erb's paralysis	10 patients
Erb's paralysis with C7 root involvement in	15 patients
Mean follow-up time	5.85±2.54 years
Gestation (weeks)	
<37	8
37–42	64
>42	1
Forceps	15
Suction	9
Birth weight (g)	
<4,500	54
>4,500	19
Right	34
Left	37
Bilateral	2

OBPP Obstetric brachial plexus paralysis

few, reconstruction is carried out by a combination of the few intraplexus donors available and available extraplexus donors. Table 2 shows the times of Ax and Ss neurotization and the motor donors that were used. Postoperative functional improvement in SA and SER and 10 additional variables (Table 3) were included in data analysis. Patients were categorized into three groups: group A, patients with global paralysis; group B, Erb's palsy; and group C, Erb's palsy with C7 root involvement.

Detailed physical examination; myelography and cervical spine CT scans under general anesthesia; inspiratory and expiratory films; clavicle, shoulder, arm, and chest radiographs (for phrenic nerve paralysis detection); nerve conduction studies; and needle electromyography were performed during preoperative evaluation. Clinical evaluation in infants also included muscle contraction determination by palpating the muscles and check for possible color and trophic changes of the upper extremity. Shoulder function evaluation included SA and SER measurements in degrees. Sensation was tested in the different dermatomes. The association of primary shoulder reconstruction procedures with scapula growth was the primary factor of investigation in this study.

Table 2 Primary axillary and suprascapular nerve reconstruction

Motor donor	Ax	Motor donor	SS	Roots	Neurolysis
Acc	2	Acc	25	C5,C6,C7, C8,T1	4
C5	9	Acc, C5	1	C5,C6	2
C6	4	Acc, Phr	1	C6, T1	2
T1	1	C3 and C5	1		
T5	1	C5	21		
T6 and T7	2	C5 and C6	1		
T6, T7, and T8	1	C6	6		
cC7	1	C7	1		
cC7 and T10	1				
cC7 and PC from C5	1				
PC from C5	16				
PC from C6	11				
PC from C5 and C6	4				
PC from C7	4				
PC from C6 and C7	1				
PC from cC7	1				
Total	60	Total	57	Total	8

The times of neurotization of the axillary (Ax) and the suprascapular nerve (SS) and the motor donors that were used are shown. The axillary nerve was neurotized directly by specific roots or indirectly by reconstructing the posterior cord.

C5, C6, C7, T1, T5, T6, T7, T8, T10, motor donors from the third, fifth, sixth, and seventh cervical and first, fifth, sixth, seventh, eighth, and tenth thoracic roots, respectively; cC7, contralateral (to the side of the brachial plexus lesion) seventh cervical root; PC, posterior cord of the brachial plexus; Acc, accessory nerve; Phr, phrenic nerve

Table 3 The variables that have been included in the data analysis

Independent variables	Dependent variables
Gender	Scapular height ratio improvement ^a
Side of brachial plexus paralysis	Scapular big width ratio improvement ^b
Gestation	Scapular small width ratio improvement ^c
Birth weight	Scapular oblique axis ratio improvement ^d
Apgar score	
Denervation time	
Intraoperative diagnosis	
Degrees of improvement in shoulder abduction	
Degrees of improvement in shoulder external rotation	
Primary procedures	
^a Post-op scapular height paralyzed side / Pre-op scapular height paralyzed side Post-op scapular height normal side / Pre-op scapular height normal side	
^b Post-op scapular big width paralyzed side / Pre-op scapular big width paralyzed side Post-op scapular big width normal side / Pre-op scapular big width normal side	
^c Post-op scapular small width paralyzed side / Pre-op scapular small width paralyzed side Post-op scapular small width normal side / Pre-op scapular small width normal side	
^d Post-op scapular oblique axis paralyzed side / Pre-op scapular oblique axis paralyzed side Post-op scapular oblique axis normal side / Pre-op scapular oblique axis normal side	

Scapular X-rays were obtained according to a standardized protocol which included the following criteria:

- Each patient had the standard anatomical position so as the medial ends of the clavicles were equidistant from the midline and the distance from the X-ray unit was always the same. The distance (150 cm) could be read from the scale on the rotating arm of the unit.
- The same standard three posterior–anterior views were included, one with anterior flexion of the shoulder with the patient pushing against a steady surface without any medial or lateral rotation, one with the upper limbs in full adduction without any medial or lateral rotation, and one with the scapula fully protracted and the upper limb medially rotated.
- The same standard X-ray system, settings, housing and parts, film quality, and development were used.
- The ratio of each dimension on the paralyzed side to that of the scapula on the nonparalyzed side was calculated. Thus, X-ray interpretation and scapula dimensions comparisons were all converted into ratios (Fig. 1) so as to eliminate any errors due to differences in distances between the X-ray system and the patient or among the X-ray views despite the aforementioned standardized protocol.

All procedures followed were in accordance with the ethical standards of the responsible committee on human experimentation (institutional and national) and with the Helsinki Declaration of 1975, as revised in 2000 and 2008 (5).

Fig. 1 The scapular dimensions that were measured. Height (H), the distance between the medial and the inferior scapular angle; big width (W), the distance between the tip of the acromion and the medial end of the scapular spine; small width (w), the distance between the glenoid and medial edge of the spine; oblique axis (O), the distance between the tip of the acromion and the inferior angle of the scapula. The corresponding ratios that were calculated based on the aforementioned dimensions were the preoperative and postoperative scapular height (H_{pre} and H_{post}), big width (W_{pre} and W_{post}), small width (w_{pre} and w_{post}), and oblique axis (O_{pre} and O_{post}) ratios between the paralyzed and the normal side

Data Collection Tool and Methodology

A data collection instrument was designed to promote accuracy of data transcription, to limit the likelihood of missing data items, and to enable efficient and accurate data entry into the computerized database which was used for the analysis. The validity of the format of the instrument has been established in similar previous studies conducted in our center and in the same population and is shown in Table 4. The specific reliability of the instrument was evaluated before its implementation using (a) intrarater reliability which was determined when an experienced abstractor (DK) used the abstraction forms twice to collect data from the same records, and the two sets of results were then compared, and (b) interrater reliability which involved the comparison of the results from the two independent investigators of equal skill who performed the evaluation each using the same data collection form. Cohen's kappa was used for nominal variables (all-or-nothing agreement between raters and ratings, e.g., gender, side of paralysis) and intraclass correlation coefficient (ICCs) average (of measurements from two raters) for ratio variables (magnitude of the disagreement between raters and ratings, with larger-magnitude disagreements resulting in lower ICCs than smaller-magnitude disagreements, e.g., degrees of improvement, preoperative and postoperative scapular dimensions ratios). Eventually, Cohen's kappa was 0.88 indicating a very high degree of agreement between raters and ratings and the average measure intraclass correlation was 0.91 with a lower value of 0.8089 and an upper value of 0.94 at 95.00 % confidence interval.

Table 4 Morphometric analysis of the association of primary shoulder reconstruction procedures in obstetrical brachial plexus paralysis patients. Data collection form

Field	Entry (standardized data/information filled in by the investigators)
Gender	The gender of the patient, male or female
Side of brachial plexus paralysis	Right or left or bilateral
Gestation	Number of weeks of gestation (38–42 weeks)
Birth weight	The weight of the newborn in grams (2,500–4,000 g)
Apgar score	The established five-criteria evaluation of the newborn baby (0–10)
Denervation time	The time between birth and first-stage reconstruction, when innervation is restored
Intraoperative diagnosis	The exact diagnosis made during the operation, when nerve root lesions are identified following meticulous intraoperative investigation
Age of presentation	The age of the patient in the first office visit
Last postoperative age	The age of the patient in the last follow-up visit
Hpre and Hpost	Preoperative and postoperative scapular height ratio between paralyzed and normal side
Wpre and Wpost	Preoperative and postoperative scapular big width ratio between paralyzed and normal side
wpre and wpost	Preoperative and postoperative scapular small width between paralyzed and normal side
Opre and Opost	Preoperative and postoperative scapular oblique axis ratio between paralyzed and normal side
Degrees of improvement in shoulder abduction	The postoperatively gained angle of rotation during shoulder abduction in degrees
Degrees of improvement in shoulder external rotation	The postoperatively gained angle of rotation during shoulder external rotation in degrees
Primary procedures	The specific primary reconstruction procedures the patient has undergone

Scapula Measurements Comparison

Comparisons of scapular measurements when estimating growth improvement concerned each patient separately, and no actual measurements were compared among different patients. In this way, the comparison of scapular dimensions concerns the same person, with the same developmental potential, at the same age who has undergone a specific procedure. In each patient, scapular dimensions of both the affected and unaffected side were measured manually using a metric ruler by two independent investigators. The ratio of each dimension on the paralyzed side to that (the corresponding/same one) on the nonparalyzed side was calculated. Consequently, in each patient, the normal scapula played the role of the “control” because it was the scapula with the expected normal growth potential with which the (postoperatively achieved) growth of the scapula on the affected side was compared. The initial scapular hypoplasia on the affected side and the fact that its growth rate cannot be adequately restored as to match in size the unaffected one are the main reasons why the aforementioned ratios were always less than 1 [28, 29, 39, 41]. These ratios are therefore indicative of how effectively the scapula on the paralyzed side is “catching up” with the optimum growth of the scapula on the normal side. Since normal scapulae exhibit proportionally symmetrical growth rates and almost equal final sizes [19, 27], it could be assumed that the scapular growth rate on the unaffected side is equal to the highest possible one on the affected contralateral side in the same person.

Thirty-six patients underwent only primary shoulder reconstruction procedures. Secondary procedures needed to be performed in 37 patients. However, these patients were included in this study only up to the age prior to their secondary procedures. No postoperative measurements following secondary shoulder reconstruction procedures were considered.

Fig. 2 Graph of the improvement (%) in all scapular dimensions in the patient groups, as shown in Table 6. *Group A* patients diagnosed with global paralysis, *Group B* patients with Erb's palsy, *Group C* patients with Erb's palsy with C7 root involvement. *N* neurolysis, *A* axillary nerve neurotization, *S* suprascapular nerve neurotization, *AS* axillary and suprascapular nerve neurotization, *H*, *W*, *w*, and *O* the improvement in scapular height, big width, small width, and oblique axis ratios between the paralyzed and the normal side, respectively

Time of X-Rays Comparison

For the patients who underwent secondary procedures ($n=37$), X-rays and preoperative measurements and ratios were obtained at the first office visit (mean age 0.38 ± 0.13 years

Fig. 3 Example of early brachial plexus reconstruction in Erb's palsy with C7 root involvement (group C). **a** Female patient presenting at 3 months of age with right C5 rupture, C6 avulsion, and C7 rupture. C5 and C7 roots were used as motor donors to reconstruct the posterior and lateral cord with interposition nerve grafts. The suprascapular nerve was neurotized by phrenic and spinal accessory nerves. Preoperative chest X-ray shows the patient holding both arms up. The discrepancy in scapula size between the affected (height=3.4 cm) and normal (height=4.9 cm) side is noted. **b** Postoperative X-rays at 4 years depicting the decreased developmental discrepancy of scapula. (Affected side height=7.1 cm, normal side height=7.2 cm). **c** Posterior view of the patient at 4 years since primary brachial plexus surgery. Note nearly symmetrical size of the right and left scapulae

of age) and postoperative measurements at the last follow-up visit prior to secondary procedures (mean age 10.26 ± 1.14 years of age).

In patients who underwent primary shoulder reconstruction procedures alone ($n=36$), the first preoperative X-rays, measurements, and ratios were obtained at the first office visit. The mean age was 0.41 ± 0.15 years. Postoperative measurements and ratios were obtained at around 10 years of age in order to comprise comparable age-related values with patients who underwent secondary procedures. The mean postoperative age was 10.11 ± 0.45 years of age.

Statistical Analysis

The SAS system (Cary, NC) was used in data analysis. Statistical significance was considered at $p < 0.05$. Linear regression analysis of each scapula dimension based on all the other variables was performed in order to determine the factor with the most statistically significant association with it. The

rationale for using regression analysis include the need to identify and explore the relationships among several variables, to use a simple and credible method of organizing observational data, and if possible, to identify valid predictor variables so as to be able to make predictions such as the expected scapular growth improvement following a specific procedure.

Data (logarithmic) transformation was considered when there was the need to stabilize variance, to improve the interpretability and uniformity of the results. Logarithmic transformation and normality check were performed using normal Q–Q plots for each one of the following independent variables: gestation, birth weight, Apgar score, denervation time, and degrees of improvement in shoulder abduction and shoulder external rotation with each one of the independent variables (improvement in scapular height, big width, small width, and oblique axis). The resulting plots were approximately linear suggesting that it is plausible that the data come from a nearly normal distribution. The paired t test was used between the

Fig. 4 **a** Example of early brachial plexus reconstruction in global palsy (group A). A boy presented at 2 months of age with right Erb's+C7 palsy (C5, C6, C7 roots avulsion and C8, T1 roots traction). Primary reconstruction included microneurolysis of C8, T1 roots, suprascapular nerve neurotization by distal spinal accessory, neurotization of the musculocutaneous nerve by intraplexus transfer from the lower trunk, transfer of the medial antebrachial cutaneous to the ipsilateral median nerve by direct repair, and intercostal neurotization of the axillary nerve. Preoperative chest X-ray in which the right (affected) side with height=4.2 cm and left (normal) height=4.5 cm scapular bones are shown. The initial discrepancy of the scapular dimension between the scapular bones of the normal and the affected side is noted. **b** Scapula X-rays 5 years following primary brachial plexus reconstruction. The discrepancy is considerably decreased upon reinnervation of the scapular muscles showing that the affected scapula recovered its developmental potential (height of the affected=5.4 cm, height of the normal=5.4 cm)

Fig. 5 **a** Example of late brachial plexus reconstruction at 12 months. A female patient presenting at 1 year of age with left global OBPP. She underwent microneurolysis of the upper trunk, suprascapular nerve, and lower trunk. Intraplexus neurotization from C6 root to the musculocutaneous and from C7 to the middle trunk and posterior cord using interposition nerve grafts. Preoperative X-rays show scapular dimensions discrepancy between the left and right side (normal height (R)=4.8 cm, affected height (L)=4.3 cm). **b** Postoperative X-rays showing normal height (R)=10.02 cm and affected height (L)=9.9 cm. The decreased dimensional discrepancy is notable

Table 5 The mean preoperative and postoperative shoulder abduction and external rotation and the improvement in all groups

Group	Pre SA	Post SA	Imp	<i>p</i> value	Pre SER	Post SER	Imp	<i>p</i> value
A	36.92	109.90	72.98	0.031*	0.48	45.19	44.71	0.04*
B	39.16	138.33	99.16	0.17	5	65	60	0.30
C	50.29	145	94.70	0.045*	2.05	60.58	58.52	0.05*

Mean values are in degrees

Group A patients diagnosed with global paralysis, *Group B* patients with Erb's palsy, *Group C* patients with Erb's palsy with C7 root involvement; *SA* shoulder abduction; *SER* shoulder external rotation; *Pre SA* preoperative shoulder abduction; *Post SA* postoperative shoulder abduction; *Pre SER* preoperative shoulder external rotation; *Post SER* postoperative shoulder external rotation; *IMP* improvement

**p*<0.05, statistically significant results

pre- and postoperative degrees of shoulder abduction and external rotation, respectively, in each group of different diagnosis. The observed power for the regression study with a *p* value of 0.05, a sample size of 73 patients, and 10 independent variables as shown in Table 3 is 0.90.

Results

Scapular Growth Improvement

The highest improvement was noted in scapular height (*H*) in the Erb's palsy group who underwent simultaneous neurotization of the Ss and the Ax. The oblique axis (*O*) was more improved in the Erb's palsy group while both big (*W*)

and small (*w*) widths were more improved in the Erb's palsy with C7 root involvement group in patients who underwent concomitant neurotization of the Ss and the Ax. The graph in Fig. 2 shows the improvement (%) in all scapular dimensions in the patient groups.

The postoperative decrease of discrepancy in each dimension was significantly correlated with that of the other dimensions. The strongest correlation was between the *w* and *W* of the scapula (0.58), showing that the scapula retained an analogous growth rate in all the measured dimensions, which is a strong indication of symmetrical bone growth. However, the affected side never reaches fully the size of the contralateral unaffected scapula, despite its documented developmental attainment. There was no significant correlation between denervation time and scapular growth in all groups.

Table 6 The preoperative and postoperative scapular dimensions ratios and the improvement in all groups, on account of the type of primary procedure that was performed

Group	Primary procedures	Height preop	Height postop	Imp	Big width preop	Big width postop	Imp	Small width preop	Small width postop	Imp	Oblique axis preop	Oblique axis postop	Imp
A	Neurolysis	88.1	93.2	5.1	86	90.5	4.5	88.6	90.7	2.1	92.4	94.1	1.7
	Axillary n.	88.6	94.6	6	89	93.1	4.1	86.8	88.4	1.6	93.3	96.7	3.4
	Suprascapular n.	86.1	91.9	5.8	84.8	92.4	7.6	83.1	84.7	1.6	90.1	94.6	4.5
	Axillary+suprascapular n.	86.6	95	8.4	89.8	98.3	8.5	83	86	3	88.6	93.6	5
B	Neurolysis	91	98	7	89.9	96.8	6.9	94.3	98	3.7	92.7	97	4.3
	Axillary n.	92	97	5	89.8	97.6	7.8	94.1	95.8	1.7	84.6	90.4	5.8
	Suprascapular n.	89	94.8	5.8	87.8	96.2	8.4	95	96.2	1.2	90.1	95.1	5
	Axillary+suprascapular n.	83.9	97.9	14	90.5	99.6	9.1	90.7	97.9	7.2	87.3	99.2	11.9
C	Neurolysis	85	96	11	88.9	95	6.1	92.5	96	3.5	93.8	98.9	5.1
	Axillary n.	89.6	94.4	4.8	87.5	95.8	8.3	91.3	94.1	2.8	88.7	94	5.3
	Suprascapular n.	89.5	93.8	4.3	86.8	96.1	9.3	86.7	95.8	9.1	89.7	95.2	5.5
	Axillary+suprascapular n.	83.5	97.2	13.7	88.1	97.9	9.8	89.2	98.8	9.6	93.6	99.3	5.7

Patient group A, global paralysis; group B, Erb's palsy; group C, Erb's palsy with C7 root involvement. Primary procedures that were performed: Neurolysis, Axillary n. (Axillary nerve neurotization), Suprascapular n. (Suprascapular nerve neurotization), Axillary+Suprascapular n. (Axillary and suprascapular nerve neurotization). Height preop and Height postop, the pre- and postoperative scapular height ratios between the paralyzed and the normal side; Big width preop and Big width postop, the pre- and postoperative scapular big width ratios between the paralyzed and the normal side; Small width preop and Small width postop, the pre- and postoperative scapular small width ratios between the paralyzed and the normal side; Oblique axis preop and Oblique postop, the pre- and postoperative scapular oblique axis ratios between the paralyzed and the normal side; Imp, the improvement in the aforementioned ratios. All numbers are percentages

Functional Improvement

Functional improvement correlated positively with growth improvement in all groups and scapular dimensions. Exemplary cases are presented in Figs. 3, 4, and 5. The improvement in SA and SER showed a significant negative correlation with the denervation time (-0.4 , $p<0.03$, and -0.38 , $p<0.05$). Primary shoulder reconstructive procedures resulted in a mean improvement of 88.9° in SA and of 54.41° in SER ($p<0.02$). The mean preoperative and postoperative SA and SER in degrees and the improvement in each group are shown in Table 5.

Preoperative and postoperative ratios of each dimension and mean improvement on account of the primary shoulder reconstructive procedures that were performed are shown in Table 6. Functional results and the rationale for primary reconstruction are shown in Table 7.

Other Variables

Birth weight, gestation period, the side of the paralysis, and Apgar scores did not have a statistically significant

association with scapula growth nor with functional results of all the procedures and in all groups. Gender had a statistically significant association with H and among patients with global paralysis, females obtaining better results from primary shoulder reconstruction procedures than males (means 96.5 and 94.6 %, respectively, $p<0.05$). Gender was not statistically significant regarding the other dimensions in all groups.

Discussion

This study showed that scapular height and big width had the highest improvement (mean values 7.57 and 7.53 %, respectively) and small width had the lowest (mean improvement 3.92 %). It was also shown that scapula growth and shoulder function improvement were higher in patients with Erb's palsy. Patients with global palsy had the lowest improvement in both scapula growth and shoulder function. Simultaneous Ax and Ss neurotization provided the best outcome in both functional and growth restoration which is consistent with

Table 7 The mean preoperative and postoperative shoulder abduction and external rotation and the improvement in all groups

Anatomical diagnosis, N =number of patients	Rationale for primary reconstruction	Shoulder abduction mean improvement (p value)	Shoulder external rotation mean improvement (p value)	Quality of life
Global paralysis (C5–T1), $N=48$	Usually: rupture of the upper roots with avulsion of the lower plexus. 1. Neurotize the two lower avulsed roots (C8 and T1) from the C5 root and use the C6 root for reconstruction of the lateral and posterior cords 2. If C7 available (rare): C7 motor fibers to neurotize C8 and T1 roots directly by end-to-end repair, due to proximity (faster reinnervation of the hand musculature) 3. Restore shoulder stability, elbow flexion (reinnervation of the supraspinatus, deltoid, and biceps) 4. Restore hand sensation (supraclavicular sensory nerves and ipsilateral sensory intercostals)	72.98° (0.031*)	44.71° (0.04*)	Average–good
Erb's palsy (C5, C6), $N=10$	1. Restore shoulder stability (reconstruction of the supraspinatus and deltoid muscles through reinnervation of the axillary nerve through elements of the proximal upper plexus or direct neurotization of the suprascapular nerve from the ipsilateral distal accessory nerve)	99.16° (0.17)	60° (0.30)	Good–Excellent
(C5–C7) $N=15$	2. Restore elbow flexion (biceps reconstruction through musculocutaneous nerve reinnervation through: -C6 (if not avulsed) or -Anterior division of C7 transfer to the lateral cord directly by end-to-end repair or -Contralateral C7 via saphenous or sural cross-chest nerve grafts or -Ipsilateral intercostal nerves 3. Triceps reinnervation with reinnervation of the posterior cord from intraplexus donors or from the ipsilateral intercostals (unless used to neurotize musculocutaneous)	94.70° (0.045*)	58.52° (0.05*)	Good

Quality of life report is based on the clinical examination of each child and on the impression of the physician who performed the evaluation. The range included poor, fair, average, good, and excellent

*statistically significant ($p<0.05$)

several previous studies [2, 3, 24]. Early surgical intervention was attempted (earlier than 3 months) in global paralysis and yielded the best functional results.

Scapular stabilizing synergists comprise a group of muscles which act together producing opposing actions that result in the dynamic stability of the scapula (Fig. 6) [18, 19, 27, 31, 42]. Our reconstructive strategy depended on the denervation time, the type of plexus lesion, and the availability of motor donors. In early cases (mean denervation time=0.39 year old), the entire plexus reconstruction was undertaken using multiple interposition nerve grafts (mean length=3.2±1.1 cm) to reinnervate peripheral targets. In later cases (mean denervation time=0.9 year old), Ax and/or Ss neurotization was performed using interposition nerve grafts (mean length=7.7±2.1 cm) or

via direct coaptation with intercostal nerves (T5–T8) which were used as motor donors when intraplexus donors were not available (Table 2).

Consequently, reinnervation of the rhomboids (C4, C5), serratus anterior (C5–7), trapezius (CNXI: accessory nerve), levator scapulae (C3–5), and pectoralis minor (C8, T1) is achieved. Therefore, the balance of forces which is responsible for scapular dynamic stability around a horizontal axis perpendicular to its plane (upward, downward rotation) and around a horizontal axis in its plane (posterior, anterior tilt) is restored [21, 33]. Additionally, optimal muscle activation of the shoulder joint muscles is achieved due to functional scapular retraction and external rotation. This position is a prerequisite for a normal scapula–humeral rhythm maximizing the activation of all scapular muscles and making the scapula a stable base for the origin of all the rotator cuff muscles [21].

Additionally, with the aforementioned procedures, reinnervation of the rotator cuff muscles (supraspinatus, infraspinatus, subscapularis, and teres minor from C5, C6), teres major (segmental levels C5, C6), latissimus dorsi (LD) (C6–C8), deltoid (C5, C6), and coracobrachialis (C5–C7) muscles was also addressed. Supraspinatus fibers create a horizontal pull which counteracts the vertical pull of the deltoid muscle and stabilize the scapular position when the arm is raised in flexion and abduction [18, 21]. The diagonal arrangement of subscapularis fibers produces a diagonal line of pull which stabilizes the scapula during internal rotation of the arm. Similarly, the infraspinatus muscle produces a diagonal stabilizing pull during shoulder external rotation [18, 21, 42]. The teres minor externally rotates the shoulder and creates a concavity compression mechanism which pulls the humeral head into the glenoid fossa. The secondary stabilizer LD adducts, internally rotates, and extends the shoulder joint while it indirectly depresses the lateral angle of the scapula and retracts it downwards, also facilitating scapular anterior tilt along with the teres major. Similarly, the pectoralis major (C5–T1), responsible for adduction, horizontal flexion, and internal rotation at the glenohumeral joint, as a whole indirectly depresses and protracts the scapula. Additionally, the coracobrachialis facilitates scapular posterior tilt along with the anterior and medial deltoid [18, 21, 33, 42].

Secondary shoulder deformities in children with OBPP have been described in 1913 by Fairbank [8] and subsequently by several other authors [2, 7, 23, 25, 32, 41, 45]. However, there is no detailed knowledge of the factors that are responsible for the development of secondary shoulder deformities in infants with OBPP since most of the available studies have been based on children over 1 year of age [3, 25, 41].

Clarke et al. [7] reported the return of useful function in infants with Erb's palsy treated with neurolysis but not in the total palsy cases. There was no comparative analysis of their results with those of conservative treatment and nerve repair. Subsequently, Capek et al. [4] reported the early outcome of

Fig. 6 Scapular muscles and their effect on scapular dynamic stability. **a** Upward rotation-posterior tilt; UT upper trapezius, LT lower trapezius, SA serratus anterior. **b** Downward rotation-anterior tilt; LS levator scapulae, RM rhomboid major, Rm rhomboid minor, Pm pectoralis minor. **c** Deltoid-supraspinatus interaction during arm raising; Ssp supraspinatus, DT deltoid. **d** Stabilization during shoulder external rotation—scapular anterior or posterior tilt; Isp infraspinatus, Tm teres minor, TM teres major (scapular anterior tilt), CB coracobrachialis (scapular posterior tilt). **e** Ssc subscapularis (stabilization during shoulder internal rotation), LD latissimus dorsi (retraction, anterior tilt, angle depression), TC triceps-long head (shoulder stabilization). The serratus anterior and upper and lower trapezius muscles are the primary stabilizing synergists which produce upward scapular rotation and posterior tilt, whereas the rhomboids, levator scapulae, and pectoralis minor muscles are responsible for downward scapular rotation and anterior tilt. The serratus anterior protracts the scapula while the rhomboids and midtrapezius muscles retract it

neuroma-in-continuity resection and the superior results of interposition nerve grafting to neurolysis. Xu et al. [44] compared the effects of conservative treatment, neurolysis, and nerve transfer and grafting in 31 patients with OBPP. They found no statistically significant difference between neurolysis and conservative treatment. Gilbert et al. [9–13] published their successful outcomes of neuroma resection and brachial plexus surgery.

Gu et al. [17] reported better results with phrenic nerve transfers, and Gruber et al. [16] first reported a case of live-donor nerve transplantation in an 8-month-old infant with global OBPP without, however, clinically significant functional improvement. Amr et al. [1] investigated the effect of end-to-side neurotization of partially regenerated recipient nerves in improving motor power in late OBPP cases. Chen et al. [6] determined the advantages of contralateral C7 nerve root transfer in their series of 12 infants and children. Terzis and Kokkalis [35] published their outcomes in OBPP treatment concluding that reconstruction of the axillary nerve (Ax) should always be performed to maximize the final outcome of shoulder function. The best results were seen in cases operated on earlier than 3 months, where the posterior cord was reconstructed from intraplexus donors. Reconstruction of the Ax directly from the intercostal nerves was a reliable option in late cases. Scapula size increases proportionally with age more in width than in length, and the infrascapular height increases faster than suprascapular height [14, 24]. Postnatal growth is initially linear followed by an acceleration at shortly over 13 years of age which leads to the gradual decrease in growth rate near the age of 17 and finally to the completion of growth around 20 years of age [14, 28]. The inferior angle, the medial border of the scapula, and the acromion fuse around 23 and 20 years of age, respectively [15, 43].

The likelihood and the timing of early surgical intervention remain an area of controversy. According to Tassin [34], spontaneous recovery of shoulder function using the Mallet scale was observed in babies with deltoid and biceps contractions by 3 months of age. Recovery was less than average (Mallet grade III) when contractions had started after the third month of age. Shenaq et al. [30] agree with the previous observation and suggest that the ideal time for early surgical intervention in such patients is the fourth month of age. Gilbert [13] has incorporated the aforementioned time limit of 3 months of age in his suggested indications for surgery. Clarke et al. [7] also consider patients without improvement at 3 months of age to be candidates for early reconstruction. Conversely, Zancolli [45] delayed the decision for early intervention until 6–8 months and Laurent et al. [22] reported adequate arm functional return with attempted repair as late as 24 months. In our center [38], in a previous series of 80 infants who had undergone surgery for obstetrical brachial plexus injuries, those with denervation time more than 3 months needed secondary procedures such as muscle transfers, rotational osteotomies, or wrist fusions.

Additionally, in global paralysis cases with denervation time less than 3 months, adequate hand function was also possible to restore [35–38].

In OBPP patients, the lack of the normal forces applied to the scapula by the weakened muscles leads to a decreased rate of bone growth [20, 26]. Growth impairment has been reported to concern primarily the total width and the height of the scapula in addition to several inconsistently observed types of deformities such as the anterior rotation of the scapular spine which is responsible for a narrower scapuloclavicular space and the downward rotational deformity of the spine [39]. In our study, it has been shown that primary plexus reconstruction restores regional muscle function and biomechanics, which recovers the growth potential of the scapula. The positive correlation between functional and growth improvement supports the fact that muscular function plays a significant role in scapular growth and that impairment of the former affects negatively the latter.

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