Morphometric analysis of the effect of scapula stabilization on obstetric brachial plexus paralysis patients

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Abstract

Background Scapular position and size deficiency is evident in obstetric brachial plexus paralysis (OBPP) patients due to the absence of balanced muscular forces acting on the scapula. Scapula stabilization (SS) procedures aim to restore a balanced musculature and anatomic position and to augment shoulder function and enhance developmental potential.

Methods Retrospective chart review of 106 patients with OBPP between March 1979 and March 2007 was performed. Forty-one female and 27 male were included in the study. In 38 patients, the paralysis was global, 13 had Erb's paralysis with C7 root involvement; in 18 patients, the lesion was limited to C5 and C6. X-rays were evaluated, and scapula dimensions were manually measured at several stages. Shoulder abduction (SA) and external rotation (SER) outcomes were also recorded.

Results Mean improvement was 85.68° in shoulder abduction and 36.74° in shoulder external rotation. SA and SER improvement was significantly better in those who underwent SS

procedures compared to those who did not (mean improvement was increased by 9.15° and 8.54°, respectively). Improvement was noted in all scapular dimensions, in all groups, postoperatively. However, the mean improvement in scapular height, big width, small width, and oblique axis discrepancies was 4.92, 14.04, 12.66, and 13.89 %, respectively, higher in patients who underwent SS procedures compared to those who did not.

Conclusion Dimensional discrepancies and functional outcomes are improved by SS procedures. Maximal results are attained in patients who have undergone both primary and secondary shoulder reconstruction before age 2.

Keywords Scapula stabilization · Scapular bone growth · Shoulder function · Secondary shoulder reconstruction · Obstetric brachial plexus paralysis

Introduction

In upper plexus lesions, the unopposed pull of the pectoralis major (PM), the teres major (TM), and latissimus dorsi (LD) muscles, results in the shoulder being held in an adducted and internal rotated position [16, 20]. Using range of motion exercises and abduction maneuvers, the scapula tends to adhere to the humerus and rotation is accomplished in a 1:1 scapulohumeral relationship. Despite attempts to stabilize scapula position on the thorax and prevent stretch of the partially paralyzed rhomboid muscles, the adhesion remains and the scapulohumeral rhythm is not restored [3]. Full range of motion can only be maintained if there is good recovery of the deltoid, supraspinatus, and infraspinatus muscles [13, 16, 20, 27, 34].

Scapular winging is associated with discomfort, cosmetic deformity, decreased shoulder strength, and range of motion [39] (Fig. 1) resulting from the inability of the periscapular

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muscles to stabilize the scapula against the rib cage during normal shoulder motion. Both the trapezius and serratus anterior (Serr) muscles are integral to proper functional shoulder movement since they primarily produce upward scapular rotation and elevation [31], and since the upper arm long bones are not subjected to the appropriate muscle forces, discrepancies in bone length as well as scapula size can result compared with the unaffected arm [31, 32].

Secondary shoulder procedures (SSP) date back to 1918 when Sever [25] described PM and subscapularis tenotomy for shoulder internal rotation deformity treatment in Erb palsy. L'Episcopo [19] restored active external rotation by TM and LD transfer to the posterolateral aspect of the humerus. Hoffer et al. [18] modified the L'Episcopo technique by anchoring the transferred tendons to the rotator cuff or the infraspinatus. Gilbert [15] believed that the muscular excursion of the LD and other transferred muscles were different and must be transferred individually. Chuang et al. [8] minimized the cross innervation influence by transferring the TM to the infraspinatus and reinserting both clavicular ends of the PM laterally. Chen et al. [7] advocated concomitant trapezius transfer to the humerus to improve weak deltoid function when shoulder abduction was less than 90°.

Codman [9] described the importance of the trapezius during scapulothoracic motion and introduced the term “scapulohumeral rhythm”. Velpeau [35] described isolated Serr palsy, and today it is recognized as the most common cause of scapular winging [14, 32].

Scapula stabilization (SS) by PM transfer is a well-documented procedure by several authors [10, 22, 23] with slight technical modifications, including the extension of the tendon by autografts, such as fascia lata or the semitendinosus tendon.

The present study investigates the effect of SS procedures on scapular growth in patients with obstetric brachial plexus paralysis (OBPP) and compares scapular growth discrepancy between patients who underwent and those who did not undergo SS.

Material and Methods

Retrospective chart review of 106 patients with OBPP between March 1979 and March 2007 was performed. In our center, SS procedures included the contralateral trapezius dynamic transfer with or without the rhomboid major muscle and anchoring these to the affected scapula. In severe, late cases, the contralateral LD muscle was transferred to achieve adequate dynamic SS. Surgical technique as well as postoperative care and rehabilitation were described in detail by the senior author (JKT) in previous reports [28–30, 32].

SSP without SS procedures included pedicle muscle transfers (pectoralis major, pectoralis minor extended with a slip of fascia lata, teres major), free muscle transfers (adductor longus with gracilis, gracilis, rectus femoris), joint contracture releases (shoulder arthroplasty with or without muscle transfers), rerouting of the LD muscle, and rotational osteotomies. Table 1 shows the types of SSP and SS procedures and the number of patients who underwent them.

Out of the 106 patients, only those who underwent both primary and secondary shoulder reconstruction procedures were included ($n=68$). The 38 patients that were not included were those who underwent primary shoulder reconstruction procedures alone. The reason why patients who underwent primary procedures alone were excluded is because they comprise a category of patients with a higher potential for recovery due to (a) the younger age at which they undergo the primary procedures, (b) the shorter denervation time, and (c) the better initial prognosis of their lesion. Patients who eventually undergo secondary procedures do so because of their long denervation times which do not allow primary procedures or the need to augment the functional outcome achieved of previously performed primary procedures.

Sixty-eight consecutive patients were included and divided into:

- Group A patients who underwent SS procedures. Subgroup A are patients who underwent primary and SSP.

Fig. 1 Long-term follow-up of untreated scapular instability. A 6-year-old boy born with left obstetric brachial plexus paralysis. The pregnancy was complicated by juvenile-onset diabetes of the mother and also by a

high birth weight (10 lbs 8 oz). There was also shoulder dystocia. **a** Scapular asymmetry and winging at 6 years of age and **b** scapula deformity (asymmetry, instability, and winging) at 12 years of age

Table 1 The types of secondary shoulder reconstruction and scapula stabilization procedures

Sub	Secondary shoulder	Scapula stabilization	Patients
A1	Arthr., rerouting LD+TM	Contra Trap	4
	Arthr., rerouting LD+TM	Contra Trap and Rh	1
	Arthr., rerouting LD+TM, PM trans, Pm trans+FL	Contra Trap and LD	1
	—	Contra LD	1
	Arthr., rerouting LD to infraspinatus	Contra Trap	1
	Arthr.	Contra Trap	1
	Arthr.	Contra LD	1
	Arthr., LD trans	Contra Trap	1
	Arthr., rerouting LD, PM trans	Contra Trap and Rh	1
	Arthr., rerouting LD+TM, PM trans	Contra Trap	1
	Arthr., rerouting LD+TM, PM trans	Contra Trap and Rh	1
	Rerouting LD, Trap trans	Contra Trap and Rh	1
A2	Arthr., rerouting LD+TM	Contra Trap	4
	Arthr., rerouting LD+TM, Trap trans+FL	Contra Trap	1
	Arthr., rerouting LD+TM, Trap trans+FL	Contra Trap and LD	1
	Arthr., rerouting LD+TM, PM trans	Contra Trap	1
	Arthr., rerouting LD+TM, Trap trans+FL, PM trans	Contra Trap	1
	Arthr., rerouting LD+TM	Contra Trap and Rh	1
	Arthr., rerouting LD+TM	Contra Trap and LD	2
	Arthr., rerouting LD+TM	Contra Trap and Rh and LD	1
	Arthr., rerouting LD+TM, Trap trans	Contra Trap	1
	Arthr., rerouting LD+TM, Tricep trans	Contra Trap and Rh	1
B1	Rerouting LD	Contra Trap	1
	Arthr., rerouting LD	—	3
	Arthr., rerouting LD+TM		9
	Arthr., rerouting LD+TM, free gracilis to PM		1
	Arthr., rerouting LD+TM, rerouting+FL		1
	Arthr., rerouting LD+TM, Trap trans+FL		1
	Arthr.		1
	Arthr., rerouting LD		1
	Arthr., rerouting LD+TM, PM trans		1
	Arthr., Trap trans+FL, LD trans		1
	Free Add. longus		1
	Free Add. longus and free gracilis		1
	Trap trans		1
	Trap trans, free Rectus Femoris		1
B2	Arthr., rerouting LD+TM		9

Table 1 (continued)

Sub	Secondary shoulder	Scapula stabilization	Patients
	Arthr., free Add. Longus, free gracilis, TM trans		1
	Arthr., rerouting LD+TM, Trap trans+FL		1
	Arthr., rerouting LD+TM, Trap trans, PM trans		1
	Trap trans+FL, PM trans, TM trans		1
	Rotational osteotomy		3
Total			68

Subgroup A1 consists of patients who underwent scapula stabilization along with primary and secondary shoulder reconstruction. Subgroup A2 consists of patients who underwent scapula stabilization and only secondary shoulder reconstruction. Subgroup B1 consists of patients who underwent primary and secondary shoulder reconstruction without scapula stabilization. Subgroup B2 consists of patients who underwent only secondary shoulder reconstruction without scapula stabilization

Secondary shoulder reconstruction procedures include:

- Pedicle muscle transfers—trapezius, pectoralis major, pectoralis minor, latissimus dorsi, teres major muscle transfers
- Free muscle transfers—adductor longus, gracilis and adductor longus with gracilis simultaneously as a double muscle free transfer
- Joint contracture releases—shoulder arthroplasty with or without muscle transfers
- Rerouting of latissimus dorsi and/or teres major
- Rotational osteotomies

Scapula stabilization procedures include:

- Contralateral trapezius and/or rhomboid and/or latissimus dorsi muscles transfers.

Detailed descriptions of the surgical techniques are available in previous papers: Terzis and Papakonstantinou [32], Terzis and Kokkalis [28], Terzis and Kokkalis [29]

Sub subgroups, *Arthr.* arthroplasty, *trans* transfer, *LD* latissimus dorsi muscle, *Trap* trapezius muscle, *TM* teres major muscle, *PM* pectoralis major muscle, *Pm* pectoralis minor muscle, *Tricep* triceps muscle, *FL* extension of the transfer muscle with a slip of fascia lata

Subgroup A2 are patients who underwent SSP alone.

Group B patients who did not undergo SS procedures and subgroup B1 and B2 included patients who had primary and secondary or only secondary procedures, respectively. The decision to perform primary shoulder reconstruction depended on the type of injury, the availability of motor donors, and denervation time.

Complete patient history; the detailed preoperative evaluation including physical, radiological, neurological, nerve conduction studies, and needle electromyography examination; and a follow-up period of 5 years or longer were prerequisites. Patients' demographics and OBPP etiology is shown in Table 2.

Computed tomography/myelography was carried out under general anesthesia for identification and localization of the lesion. The primarily investigated factor was the effect of SS procedures on the growth of the scapula. Therefore, four dimensions of both scapulae in each patient were manually measured in posteroanterior and lateral X-rays as shown in detail in Fig. 2. A standardized protocol was followed according to which patients begun the X-ray procedure being at the anatomical position, so as at the frontal plane, the distances between the medial ends of the clavicles from the midline were the same on each side. The distance of the patient from the X-ray tube was standard and always the same. Three posteroanterior views were obtained: (a) one with the shoulder in anterior flexion and the patient pushing against a solid surface, (b) one with the upper limbs fully adducted without

Fig. 2 Scapular bone and the dimensions being measured. H height (distance between the medial and the inferior angle), W big width (distance between the tip of the acromion and the medial end of the scapular spine), w small width (distance between the glenoid and medial edge of the spine), and O the distance between the tip of the acromion and the inferior angle. 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. As expected, these ratios were never equal to one because the affected scapula could not grow adequately enough as to match in size the unaffected one. The resulting discrepancy between dimensions of the affected and unaffected scapulae was therefore recorded

any rotation, and (c) one with the scapula in full protraction and the upper limbs in medial rotation.

The radiology system and settings as well as the film quality and development were identical. The measurements were obtained by two independent raters and were

Table 2 Patients' demographics and OBPP diagnosis

Total patients included	68 Patients
Female:	41 Patients
Male:	27 Patients
Mean age at presentation-denervation time	6.3±3.72 years old
Side	
Right	34 Patients
Left	33 Patients
Bilateral	1 Patients
Global paralysis	38 Plexuses
Erb's paralysis with C7 root involvement	13 Plexuses
Erb's paralysis without C7 root involvement	18 Plexuses
Scapula stabilization (group A, $n=26$)	
Subgroup A1 (primary and secondary reconstruction)	14 dt=2.02 years
Subgroup A2 (Secondary reconstruction only)	12 dt=6.3 years
Without scapula stabilization (group A, $n=42$)	
Subgroup B1 (primary and secondary reconstruction)	23 dt=1.98 years
Subgroup B2 (secondary reconstruction only)	19 dt=6.4 years
Gestation	
<37 Weeks	7 Patients
37–42 Weeks	56 Patients
>42 Weeks	5 Patients
Presentation	
Vertex	63 Patients
Breech	5 Patients
Birth weight	
<4,500 g	48 Patients
>4,500 g	20 Patients
Assistance	
Forceps	19 Patients
Suction	11 Patients

OBPP obstetric brachial plexus palsy, dt denervation time

Table 3 The 11 variables that have been included in the data analysis

Data analysis of the following variables
• Gender
• Side of brachial plexus paralysis
• Gestation
• Birth weight
• Apgar score
• Denervation time
• Intraoperative diagnosis
• Degrees of improvement in shoulder abduction
• Degrees of improvement in shoulder external rotation
• Primary procedures
• Number of secondary shoulder reconstruction procedures

Table 4 The mean preoperative and postoperative functional results and the improvement in the various types of injury

Type of injury	Pre SA	Post SA	Imp	<i>p</i> Value	Pre SER	Post SER	Imp	<i>p</i> Value
Global	38	99	61	<0.001*	2	51	49	<0.001*
Erb's	42	153	111		5	76	71	
Erb's with C7	51	137	86		3	67	64	

Patients diagnosed with global paralysis, Erb's palsy, and Erb's palsy with C7 root involvement and the respective improvement in shoulder abduction and external rotation. Mean values are in degrees

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

* $p < 0.05$, statistically significant results

subsequently converted into ratios. Interpretation of the X-rays and comparisons was performed using these ratios in order to minimize any unaccounted errors due to differences in distances between the radiology units. Interpretations were made on an individual basis without any direct comparison of dimensions between different patients.

The ratio of each dimension on the paralyzed side to that of the scapula on the nonparalyzed side was calculated (Fig. 2). The initial preoperative measurement was obtained at the first office visit. A second preoperative measurement was performed in patients who underwent second-stage reconstructive procedures. The third measurement was performed at the last follow-up visit. Postoperative functional improvement in shoulder abduction (SA) and external rotation (SER) was also considered to evaluate the effect of SS procedures. Data analysis included 11 variables (Table 3).

Types of Paralysis and Strategies for Reconstruction

In global palsy, the usual findings are rupture of the upper roots with avulsion of the lower plexus which makes the C5 root the best motor donor choice due to its distance from the zone of injury. Consequently, neonates have a greater potential for hand reinnervation because the distances from the roots to the target muscles of the hand are much smaller than in the adults. The first step is usually to neurotize the two lower avulsed roots (C8 and T1) from the C5 root and to use the C6 root for reconstruction of the lateral and posterior cords. If C7

is available, which is rare, C7 motor fibers can be used to neurotize C8 and T1 roots directly by end-to-end repair, due to proximity (faster reinnervation of the hand musculature). The restoration of shoulder stability is through elbow flexion (reinnervation of the supraspinatus, deltoid, and biceps). So after the reanimation of the hand, reinnervation of the lateral and posterior cords is pursued preferably from intraplexus remaining donors (C6). In cases of longer denervation time, when muscle substitution is required, during the first-stage reconstruction, nerve grafts are “banked” at the elbow level so they can be used later in a second-stage reconstruction for the innervation of transferred free muscles for hand reanimation. Restoration of hand sensation is achieved using supraclavicular sensory nerves and ipsilateral sensory intercostals.

In Erb's and Erb's+C7 paralysis, shoulder stability is restored by the reconstruction of supraspinatus and deltoid muscles through reinnervation of the axillary nerve by elements of the proximal upper plexus or direct neurotization of the suprascapular nerve from the ipsilateral distal accessory nerve. Elbow flexion is restored by the neurotization of biceps through the musculocutaneous nerve which is reinnervated by C6 (if not avulsed) or the anterior division of C7 transfer to the lateral cord directly by end-to-end repair or the contralateral C7 via saphenous or sural cross-chest nerve grafts or the ipsilateral intercostal nerves. Triceps function is restored by the reinnervation of the posterior cord from the intraplexus donors or from the ipsilateral intercostals (unless used to neurotize musculocutaneous).

Fig. 3 The positive correlation of shoulder abduction and shoulder external rotation improvement. Note that the linear correlation between shoulder external rotation and shoulder abduction improvement, showing parallel recovery of both functions

Table 5 Preoperative and postoperative ratios of scapular dimensions in the four patient groups of the population

Dimension ratios	A1 (%)	A2 (%)	B1 (%)	B2 (%)
pre-op height (H_{pre})	93.01	89.89	94.06	91.94
post-op height (H_{post})	96.15	92.57	94.57	93.22
pre-op big width (W_{pre})	89.68	83.31	92.82	88.71
post-op big width (W_{post})	98.25	91.51	93.97	93.03
pre-op small width (w_{pre})	80.86	82.91	92.04	85.75
post-op small width (w_{post})	92.03	85.63	93.05	87.20
pre-op oblique axis (O_{pre})	86.76	91.16	96.02	89.41
post-op oblique axis (O_{post})	97.21	94.82	96.29	89.58

Subgroup A1 consists of patients who underwent scapula stabilization along with primary and secondary shoulder reconstruction. Subgroup A2 consists of patients who underwent scapula stabilization and only secondary shoulder reconstruction. Subgroup B1 consists of patients who underwent primary and secondary shoulder reconstruction without scapula stabilization. Subgroup B2 consists of patients who underwent only secondary shoulder reconstruction without scapula stabilization. Percentages comprise the mean ratio of each scapular dimension (height, big width, small width, and oblique axis) between the affected and the unaffected side (e.g., pre-op big width 89.68 % means that the preoperative big width of the scapula of the paralyzed side comprises the 89.68 % of the preoperative big width of the scapula of the normal side. All values are mean ratios). Dimensions are shown in Fig. 1

Secondary procedures are reserved for late cases when the muscle targets have been degenerated and there is the need for muscle substitution or when the outcomes of the primary

procedures need to be augmented. They aim at hand reanimation and the restoration of elbow flexion/extension and shoulder functional reconstruction. Scapula stabilization procedures comprise a special category of secondary shoulder reconstruction procedures which aim in the restoration of the functional and anatomic integrity of the scapula and the scapulothoracic joint. They include tendon transfers, pedicled muscle transfers, free muscle transfers, joint fusions and a variety of osteotomies, and scapula-stabilization procedures.

Statistical Analysis

An assistant professor (ND) in biostatistics at Old Dominion University statistically analyzed the results. The SAS system (Cary, NC, USA) was used in all data analysis. The statistical significance of the effect of each factor (Table 3) on dimensional discrepancies was assessed using linear regression analysis. Data transformation was considered when there was the need to stabilize variance. Statistical significance was considered at $p < 0.05$

Results

Considerable agreement between the rating of the two investigators was found as shown by the high intraclass correlation coefficient (ICC=0.87). Side of the paralysis, birth weight,

Fig. 4 Preoperative and postoperative scapula **a** height, **b** small width, **c** big width, and **d** oblique axis ratios in the patient groups. Subgroup A1 consists of patients who underwent scapula stabilization along with primary and secondary shoulder reconstruction. Subgroup A2 consists of patients who underwent scapula stabilization and only secondary shoulder reconstruction. Subgroup B1 consists of patients who underwent

primary and secondary shoulder reconstruction without scapula stabilization. Subgroup B2 consists of patients who underwent only secondary shoulder reconstruction without scapula stabilization. Percentages comprise the mean ratio of each scapular dimension (height, big width, small width, and oblique axis) between the affected and the unaffected side

Table 6 Examples of consecutive patients who underwent scapula stabilization procedures in the last 10-years of our experience (1997-2007)

P	AT	Sex	Side	Diag.	C5	C6	C7	C8	T1	Primary motor donor (target)	Secondary	SS	Improvement					SER (degrees)
													H (%)	W (%)	O (%)	SA (degrees)		
1	0.3	M	R	Global	R	R	R/A	T	A	C5 (SS,LC,T1) C6 (PC)	Arthroplasty PM trans for abduction Rerouting LD+TM	contra Rh and Trap	4.12	10.1	12.5	11.7	90	60
2	0.6	M	R	Erb's+C7	R	R	A	T	T	C5 (PC) C6 (Lpec)	Arthroplasty Rerouting LD+TM	contra Trap	3.7	9.7	11.3	11.1	80	40
3	1.7	F	R	Global	R	R	A	R/A	A	C5 (PC) C6 (T1) T4 (Thd) T5 (Tri) T6-T9 (Med) cC7 (to MAC) C5 (C8, T1) C6 (SS,PC,LC) T5 (Lthor) T6 (Thd) T7 (Tri) T8-T10 (Mc) cC7(med, rad) T6-T8 banked	Arthroplasty PM trans for abduction Rerouting LD+TM Forearm pron. ost. 90°	contra Rh and Trap	2.9	9.9	12.1	9.9	75	35
4	0.8	F	L	Global	R	R/A	R/A	A	A		Arthroplasty ips. LD trans for ant. flexion rot.ost. 40° for SER. L grac. to EDC (XI) Tendonolysis (EDC, EPL)	contra Trap	3.3	10.2	11.8	11.4	95	35
5	2.5	F	R	Global	R	A	A	A	R		Arthroplasty Rerouting LD+TM FCU trans to EDC and EPL FDS III trans to EDC L grac. to EDC (T7,T8) Tendonolysis (EDC, EPL)	contra Rh and Trap contra LD	2.88	8.8	10.1	9.3	45	30
6	5	F	R	Erb's	Traumatic/umbilical cord compression	R	R/A	A	R/A	A	n/a	contra Trap	3.1	9.6	11.2	10.9	60	35
7	5.5	F	R	Global	R	R/A	A	R/A	A	C6 (SS,Ax,Mc) Neyrolsis C8 T1 T4 (Thd) T6 (to MAC for future) T7 (to MBC for future) T8, T10 (Tri)	Rerouting LD Rans. Trap Rerouting LD Z leghening of biceps brachialis to triceps Free LD for flexion (XI) FDS III trans for key pinch ECRL+plantaris for intr.III-V digits	contra Rh and Trap	2.2	8.3	9.8	8.2	35	20

These are consecutive cases and do not represent the entire population.

P patients, AT age at presentation, Diag. diagnosis, M/F male/female, R rupture, A avulsion, T traction, SA shoulder abduction, SER shoulder external rotation, SS suprascapular nerve, PC posterior cord, LC lateral cord, Thd thoracodorsal nerve, Lpec lateral pectoral nerve, Lhor long thoracic nerve, Mc musculocutaneous nerve, Med median nerve, Rad radial nerve, MAC medial antebrachial cutaneous nerve, C5-C8 fifth to eighth cervical roots, T1 thoracic root, T2-T10 second to tenth intercostal nerves, trans transfer, LD latissimus dorsi muscle, ips. LD ipsilateral LD, Trap trapezius muscle, TM teres major muscle, PM pectoralis major muscle, Tri triceps muscle, L grac. left gracilis free muscle transfer, FDS flexor digitorum superficialis, ECRL extensor carpi radialis longus, FCU flexor carpi ulnaris, EDC extensor digitorum communis, EPL extensor pollicis longus, rot.ost. rotational osteotomy, pron. ost. pronation osteotomy

Fig. 5 A 6-month-old male patient at presentation with right obstetric brachial plexus paralysis (Erb's palsy with C7 root involvement) due to craniopelvic disproportion and shoulder dystocia which required the use of forceps for distraction. First-stage reconstruction included exploration of the right brachial plexus during which C5 and C6 roots were ruptured, C7 root were avulsed, and C8-T1 roots had traction injury. Additionally, following harvesting of bilateral sural nerves, microneurolysis of all cords and roots, microneural coaptation of the C5 root was performed to the posterior cord, C6 root to the lateral cord and to the lateral pectoral nerve. Second-stage reconstruction, 33 months later, included scapula stabilization procedure with contralateral trapezius transfer, shoulder arthroplasty, and rerouting of the ipsilateral teres major and latissimus dorsi for external rotation. **a** Preoperative posterolateral X-rays of the patient showing the initial developmental discrepancy of the scapular bones between the normal (*left*) and the paralyzed sides (*right*). **b** Postscapula stabilization procedure lateral scapula X-rays of the patient, 7 years after the operation. The discrepancy is considerably decreased showing that the affected scapula maintained its developmental potential

gestation period, and Apgar scores did not have a statistically significant effect on scapula growth and functional results. There was no statistically significant correlation between the postoperative ratios of scapular dimensions and the intraoperative diagnosis. Conversely, the type of injury was significantly correlated with the functional results following SSP (Table 4).

Linear regression analysis of each dimensional discrepancy based on all the other variables showed that the most statistically significant factor was the age of presentation. The younger the patient was, the higher the postoperative functional improvement. Data transformation was considered when there was the need to stabilize variance.

The improvement in SA and SER showed a significant negative correlation with the denervation time (-0.39 ,

$p < 0.03$; -0.34 , $p < 0.05$). Conversely, there was no significant correlation between denervation time and scapular growth. It was also shown that in both age groups, SA and SER improvement was significantly better in those who underwent SS compared to those who did not (a mean of 9.15° more of SA and a mean of 8.54° more in SER). SA and SER were positively correlated (0.44 , $p < 0.05$; Fig. 3).

The postoperative decrease of discrepancy in each dimension was significantly correlated with that of the other dimensions. The strongest correlation was between the small and the big width of the scapula (0.53). This finding shows that the scapula retained an analogous growth rate in all the measured dimensions, indicating symmetrical bone growth. The effect of SS procedures in the measured scapular dimensions is shown in Table 5 and in Fig. 4 in the form of mean scapular dimensions ratios between the paralyzed and nonparalyzed sides. Statistical significance is demonstrated in group A where the effect of SS increases the difference between the preoperative and postoperative ratio in all dimensions when compared to group B (in all cases $p < 0.047$). This indicates that the procedure aids scapular growth in all directions, and the affected scapula catches up more effectively in size with the unaffected scapula.

The postoperative ratios in all dimensions (except for small width which is the second highest, 92 %) are higher in group A1. This is an indication that the best results of the procedure (ranging from 92 to 98.25 %) are noted in patients who underwent both primary and SSP.

In 26 patients who underwent SS procedures, the postoperative decrease of dimensional discrepancy was measurable after the sixth postoperative month in both age groups. After that time, the effect of the procedure was maintained resulting in parallel growth of the scapula. However, the affected side never reaches fully the optimal size of the unaffected scapula, despite its documented developmental attainment.

Gender had a statistically significant effect in H , with females obtaining better results from the procedure than males (means, 97.26 and 94.98 %, respectively; $p < 0.05$). Gender was not statistically significant regarding the other dimensions in all groups.

The number of primary procedures was not statistically significant in subgroup A1, but it was significant in subgroup B1 regarding the functional results (SA, SER) with a correlation factor of 0.28 ($p < 0.05$).

The number of primary procedures was also positively correlated to W_{post} with a factor of 0.33 ($p < 0.04$) and with means of 98.25 % for subgroup A1 and 93.97 % for subgroup B1. There was no statistically significant effect on the other dimensions.

The number of SSP was not statistically significant for any of the dimensions. However, it was positively correlated to the functional result in a statistically significant way (0.63 for SA, $p < 0.034$; 0.52 for SER, $p < 0.028$). Finally,

Fig. 6 A patient presenting with right Erb's palsy (C5 and C6 roots rupture) at the age of 3 years and 9 months. He underwent scapula stabilization by transferring the left trapezius to the right scapula as well as secondary shoulder procedures (rerouting latissimus dorsi to restore external rotation and transfer of the clavicular head of the pectoralis major to deltoid for abduction). **a** Pre-first-stage reconstruction photo of the patient. The scapula size discrepancy between affected (*right*) and normal

(*left*) side is notable. **b** Above-shoulders-view emphasizes the winging of the right scapula. **c** Functional and developmental outcome is noted in the postoperative photos. Scapular size on the affected side has considerably improved and nearly matched the developmental level of the unaffected one. Arrow points to the trapezius transfer. **d** Above-shoulder-view indicates the correction of winging, with near-symmetrical presentation of bilateral scapulae

patients whose first surgery was performed before age 2 had better functional results compared to those that were operated after the age of 2 (mean improvement in SA of 88° in patients younger than 2 versus 76.8° in patients older than 2 years old and mean improvement in SER of 41° in patients younger than 2 versus 31° in patients older than 2 years old).

Examples of consecutive patients who underwent scapula stabilization procedures in the last 10 years of our experience (1997–2007) are shown in Table 6.

Discussion

There is paucity of data regarding postoperative scapular dimensions evaluation. This study investigates the dynamic SS by evaluating scapula growth in multiple axes and functional outcomes.

Birch [3], after reviewing the results of LD transfer for SA and SER restoration in 22 patients, suggested that in order to obtain optimum functional results, there must be normal skeletal development of the shoulder without any fixed deformities.

Gilbert [14], who studied 44 patients who had undergone LD transfer, supported the previous suggestion and additionally recommended the concomitant transfer of the trapezius in cases of weak or absent shoulder abduction.

Chen et al. [7], in 18 cases of weak SA and SER, showed that the concomitant transfer of LD, TM, and trapezius yielded better results. Al-Qattan [1] stated that scapular winging leads to no significant functional impairment. However, Terzis and Papakonstantinou [32] reported that the lack of substantial force applied to the scapula by the affected stabilizer muscles lead to extensive decrease in the range of motion of the glenohumeral and scapulothoracic joints and to decreased rate of bone growth. By introducing the SS procedure of the contralateral trapezius transfer in their series of 26 patients with a mean follow up of 21 months, Terzis and Papakonstantinou [32] showed that the procedure led to significant improvement in SA and SER as well as to a significant decrease in size discrepancy between the affected and unaffected scapulae.

Scapulothoracic fusion may achieve SS but at the expense of scapulothoracic motion and with the complication of pseudarthrosis as high as in 50 % of the cases [17]. The major disadvantage is that scapular growth is hampered, and the resulting shoulder deformity is gradually increasing [4]. Sternal portion of PM transfer to Serr was described by Tubby [33], but proved unsuccessful due to scapula winging recurrence. The elongation of the pectoralis tendon with fascia lata graft was described by Durman [11], but complications such as stretching or tearing of the fascia lata graft were observed in more than 20 % of the cases.

Fig. 7 Male patient with left Erb's palsy with sparing of the hand. Although some improvement was noted during the first year of his life, there was a residual internal rotation of the left shoulder with inability to elevate the shoulder beyond 90° from the resting position. When he was 4 years old, he underwent a modified Zancolli procedure to correct internal rotation of the shoulder. Scapula stabilization procedure was not included in the treatment. **a** Preoperative posteroanterior X-rays of the patient's right (normal) and left (affected side) scapular bones. The initial discrepancy of the scapular dimension between the scapular bones of the normal and the affected side is shown. **b** Postoperative posteroanterior X-rays of the patient's scapular bones, 2 years after the operation. The increased discrepancy in scapular dimensions is noted. Although secondary shoulder reconstruction remarkably improved shoulder elevation and abduction, the discrepancy in the size of the scapular bones was notably increased, even in the relatively small period of 2 years postoperatively

Fig. 8 Vector analysis after scapula-stabilization procedures. The muscle transfer is shown and the force it exerts on the scapular bone is analyzed on the vertical and horizontal axis in each case: **a** trapezius muscle transfer, **b** rhomboid muscle transfer, **c** latissimus dorsi muscle transfer. Note the direction and the magnitude of the forces applied on both axes due to the function of the transferred muscle. This results in intermittent shear stresses which promote and define the direction of expected scapula growth

Fig. 9 Detailed vector analysis on each dimension axis. The direction of each one of the four measured dimensions is defined and the muscular force is analyzed in each one of them. Each component is noted and has its distinct effect on the axis that is applied. The magnitude of each component of the muscular force and the direction of its stress effect is therefore demonstrated. V the muscular force exerted on the scapula, Wv the component of V on big width axis, wv the component of V on small width axis, Hv the component of V on the height axis, Ov the component of V on the oblique axis. The different magnitude of the components on each axis is noted and compared.

El-Gammal et al. [12] demonstrated that subscapularis release and transfer of the TM to infraspinatus with or without pedicle transfer of the clavicular head of PM to deltoid is best performed before age 2 to attain the maximum benefit in movement and prevent secondary bone changes. Improvement in SA averaged 64° and SER by 50° . In our study, there is statistically significant improvement in the cohort that was operated before age 2 regarding functional and developmental measurements compared to those that were operated beyond the age of 2. Figures 5 and 6 show exemplary cases of a patient younger than 2 years old at presentation that underwent primary brachial plexus reconstruction and subsequently SS procedure and of a patient older than 2 years old who did not undergo primary brachial plexus reconstruction but had only the SS procedure, respectively.

Tauber et al. [26] used in their clinical study the technique initially described by Povacz and Resch [24] in their anatomic study, which consists of the transposition of the split PM with a wedge of humeral bone. The osseous wedge is secured with trans-osseous fixation to the lateral margin of the inferior scapular angle, without the use of graft extension. Limitations in this study were the lack of a control group and that only the functional and MRI results in adult patients with traumatic or iatrogenic long thoracic nerve palsy were investigated.

In Warner's [36] study of eight patients undergoing PM transfer, none of the patients could actively flex their shoulders above 120°. The average amount of forward flexion was 97° (80–120°). When the scapula was manually stabilized against the chest wall, shoulder discomfort relief was obtained, and the patients were able to flex their shoulder above 150° [36].

The main considerations regarding PM transfer with or without free autologous graft extension is that, in OBPP patients, PM is frequently involved in the initial injury as well as the subsequent disfigurement of the anterior chest, anterior axillary fold, and breast asymmetry.

In conservatively treated cases, only infants who recover antigravity biceps strength within the first 4 to 6 weeks of life will have no shoulder girdle asymmetry on long-term evaluation [37]. However, early microsurgical reconstruction of plexus lesions improves shoulder function and reduces the need for palliative surgery. In our center, early treatment is generally indicated earlier than 3 months for infants with global palsy and at 3 months in Erb's type lesions.

Improvement in scapula growth rate was consistently better in patients who had SS procedures (Fig. 7). It was found that all dimension discrepancies between the affected and unaffected scapula were considerably decreased after SS procedure. The biggest improvement was noted in the scapular big width. The dynamic restoration of SS entails the attachment of active normal muscle units to its medial border and inferior angle. In this way, dynamically coordinated traction forces acting on the scapula correct scapular anatomic position, inferiorly and towards the midline, and comprise a considerable stimulus for bone growth. Vector analysis of the muscle force exerted on the scapula demonstrates the direction of expected growth (Fig. 8). Vector analysis on each dimension axis is shown in Fig. 9.

The explanation of the findings is that in vivo, high compressive-dilatational forces suppress endochondral ossification. Conversely intermittent shear stresses, like the one by the transferred muscles in SS, promote it [2]. In the absence of mechanical stresses, progression of skeletal morphogenesis is inhibited [2]. In patients with OBPP, healthy mechanical stresses critical to early skeletal development are missing [5, 6, 7, 21, 38].

Conclusions

- Maximal results were attained when early intervention is performed, prior to 2 years of age.
- SS procedures considerably augmented the effect of SSP in both age groups.
- Growth discrepancy between the affected and unaffected scapula was lessened due to the restoration of the muscular stabilizers which provide the stimulus for bone growth.
- The horizontally oriented vectors were most benefited by the muscular transfer.
- Improved scapula stability results in greater range of motion and functional outcome.

Conflict of Interest Julia K. Terzis declares that she has no conflict of interest and that she has not received any kind of financial support/funds from any source.

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Statement of Human and Animal Rights 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).

Statement of Informed Consent Informed consent was obtained from all patients for being included in the study. Additional informed consent was obtained from all patients for whom identifying information is included in this article.

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