European Journal of Orthopaedic Surgery & Traumatology (2019) 29:329–336
https://doi.org/10.1007/s00590-019-02362-1

GENERAL REVIEW • SPINE - BRACHIAL PLEXUS

Secondary procedures for restoration of upper limb function in late cases of neonatal brachial plexus palsy

Marios D. Vekris[1] · Dimitrios V. Papadopoulos[1] · Ioannis D. Gelalis[1] · Vasilios Kontogeorgakos[2] · Andreas G. Tsantes[1] · Ioannis Gkiatas[1] · Ioannis Kostas-Agnantis[1] · Dimitrios Kosmas[1]

Received: 6 December 2018 / Accepted: 2 January 2019 / Published online: 8 January 2019
© Springer-Verlag France SAS, part of Springer Nature 2019

Abstract
Neonatal brachial plexus palsy is a devastating complication after a difficult delivery. The incidence of this injury has not significantly decreased over the past decades, despite all the advances in perinatal care. Although primary repair of the nerves with microsurgical techniques is the common treatment strategy nowadays, there are late cases in which secondary procedures in tendons or bones are necessary. Moreover, secondary procedures may be needed to improve the results of primary repair. A careful preoperative assessment of all the residual defects and deformities in upper limbs of these patients is essential. The aim of these procedures is usually to restore the deficient shoulder abduction and external rotation, release of any elbow flexion contracture or to correct a weak elbow flexion. More distally a supination or pronation deformity is usually apparent, and available options include tendon transfers or radial osteotomy. The wrist of these patients may be ulnarly deviated or may has absent extension, so tendon transfers or free muscle transfers can also be used for correction of these deformities. In severe cases, wrist fusion is an alternative option. The clinical presentation of the hand is highly variable due to complex deformities including thumb adduction deformity, metacarpophalangeal joints drop, and weak finger flexion or extension depending on the level of the injury. Each of these deformities can be restored with a combination of soft tissue procedures like local or free muscle transfer and bony procedures like arthrodesis.

Keywords Brachial plexus paralysis · Neonatal · Obstetric · Secondary procedures · Late cases

Introduction

Neonatal brachial plexus palsy results from forceful lateral traction of the head during delivery that applies severe tension to neonatal brachial plexus. Despite the advances in perinatal care, its incidence which varies from 0.5 to 3 cases per 1000 live births has only slightly declined over the last years and it represents a major problem due to its catastrophic sequelae [1, 2]. However, in up to 90% of these cases spontaneous recovery will occur during the following months [3].

When surgical intervention is needed, primary repair by neurolysis, nerve grafting or nerve transfers yields the most successful results, and thus, early recognition and treatment of these devastating injuries is of paramount importance [4–7]. Even though nowadays the majority of these injuries are diagnosed and treated early, secondary procedures for restoration of major upper limb functions are required in several cases. Moreover, secondary procedures may be required to enhance the functional results of early repair [5]. The deformities that develop in the upper limbs of these patients are sequelae of soft tissue contractures and osteoarticular changes, which in turn result from muscle imbalance. During the initial stages when muscle imbalance has not resulted in fixed contractures yet, dynamic deformities may be treated conservatively with physical therapy and serial splinting, while fixed deformities need surgical intervention. When in case of dynamic deformities conservative treatment fails, soft tissue releases or tendon transfers are suitable options, whereas in fixed deformities due to either soft tissue contractures or osseous changes soft tissue releases and osteotomies are usually required.

✉ Marios D. Vekris
vekrismd@otenet.gr

[1] Department of Orthopedics, University Hospital of Ioannina, Stavros Niarchos Avenue, 45500 Ioannina, Greece

[2] 1st Orthopaedic Department of "Attikon" University Hospital, Athens, Greece

The pattern of presented deformities in each patient depends on the injured level of the brachial plexus and the affected muscles that are subsequently denervated. In upper plexus palsy, shoulder abduction and external rotation, as well as elbow flexion, may be affected due to functional loss of shoulder external rotators (supraspinatus, infraspinatus muscles), shoulder abductors (deltoid muscle, external rotators) and elbow flexors (biceps brachii, brachialis muscle). Additionally, pronation deformity may develop due to loss of supinators (i.e., biceps brachii muscle). When C7 nerve root is injured, elbow extension and wrist extension may also be compromised. In these cases, elbow flexion contracture may also develop. Last, in total plexus lesions all the described deformities may be present along with hand deformities including thumb adduction, metacarpophalangeal joints drop or interphalangeal joint flexion deformity [8].

This review aims to describe the most commonly performed secondary procedures for correction of residual functional defects of the shoulder, elbow, forearm, wrist and hand in patients with neonatal brachial plexus palsy (Table 1).

Procedures for shoulder deformities

Restoration of shoulder abduction

Abduction of the shoulder is of great significance since it enables the hand to reach the head and objects that are not close to the body. Howell et al. found that loss of at least one of the deltoid or the rotator cuff muscles results in 50% decrease of abduction power [9]. Several techniques for local tendon transfers have been described, with the majority of them replacing the deltoid function. It has been proven in many studies, though, that adequate abduction needs the presence of at least two rotator cuff muscles and part of the deltoid [10]. Local tendon transfers include trapezius transfer, pectoralis major transfer and latissimus dorsi transfer [10–12]. Saha et al. [10] reported good results in all of his patients when trapezius transfer was performed for shoulder abduction.

Our preferred technique for restoration of shoulder abduction includes transfer of the trapezius on the lateral

Table 1 Most common secondary procedures for restoration of upper limb function in late cases of perinatal brachial plexus palsy

Upper limb functions	Secondary procedures
Shoulder	
Abduction	Trapezius transfer
External rotation	Anterior soft tissue release, transfer of latissimus dorsi and teres major tendons
	Humerus rotational osteotomy (> 8 years)
Elbow	
Flexion	Local muscle transfers (latissimus dorsi, Steindler procedure, triceps)
	Free muscle transfers (gracilis, latissimus dorsi, rectus femoris)
Flexion contracture correction	Arthrodiastasis (Authors' preferred method)
	Open soft tissue release
Forearm	
Pronation	Biceps' tendon rerouting
	Internal rotation radial osteotomy (Authors' preferred method)
Supination	External rotation radial osteotomy
Wrist	
Ulnar deviation deformity correction	Extensor carpi ulnaris to extensor carpi radialis brevis
	Wrist fusion (Authors' preferred method)
Wrist extension	Pronator teres to extensor digitorum communis transfer (Authors' preferred method)
Flail wrist stabilization	Wrist fusion (Authors' preferred method)
Hand	
Thumb abduction	Transfer of extensor carpi ulnaris to abductor pollicis longus
Metacarpophalangeal joints extension	Wrist flexor to extensor digitorum communis transfer
Finger flexion	Wrist extensor to flexor digitorum profundus transfer
	Free muscle transfer
	Local transfer of the latissimus dorsi
Metacarpophalangeal joints flexion and interphalangeal joints extension	Distal advancement of the digital extensor mechanism
	Reconstruction of the lumbricals
	'Lasso' procedure (Authors' preferred method)

humerus, above and anterior to the insertion site of the middle deltoid. This transfer is recommended to be performed in older children though, so that a better degree of cooperation postoperatively is possible. Adequate shoulder abduction with an abduction range over 90 degrees can be achieved when a certain degree of the supraspinatus function is preserved. In cases of anterior serratus presence, the postoperative range of abduction is much better. In totally flail shoulders though, the main functional result of this transfer is stabilization of the shoulder, while the achieved abduction range of motion is much lower (about 30–40 degrees).

Dynamic restoration of external rotation

External rotation of the shoulder is essential because it contributes to greater arm elevation by preventing impingement of the humeral head on the coracoacromial arch and by stabilizing the humeral head on the glenoid cavity. The earliest procedures to restore external rotation included release of subscapularis and pectoralis major which are commonly contracted. However, in many cases these procedures resulted in anterior shoulder dislocation [13, 14]. Gilbert reported satisfactory results in his series of patients who underwent anterior shoulder release. He recommended performing this procedure before any muscle transfer and if possible before the age of 2 [15]. Conversely, Narakas did not support the successful results of soft tissue release, and he preferred muscle transfers to restore external rotation [16].

L' Episcopo described in 1934 anterior release and transfer of the teres major to the posterolateral side of humeral head in order to act as external rotator [17]. Later on, he added latissimus dorsi to teres major transfer. Many modifications of this technique have been described since then, with most of them focusing on the humeral site for reattachment of the transferred tendons [18–20]. Excellent results have been described by several authors using the L'Episcopo technique or modifications of this technique [19, 21, 22].

Our preferred procedure, called shoulder arthroplasty, involves release of the anterior capsule of the shoulder joint, along with subscapularis plus conjoint tendon lengthening and proximal transposition of the pectoralis major insertion. Additionally, in all patients with lack of external rotation, dynamic external rotation is achieved through latissimus dorsi and teres major tendon transfer. The tendons of these two muscles are rerouted around the shaft of the humerus and attached via bone anchors to the anterolateral surface of the humeral head. This procedure should be performed at the age of 4–8 years. In the long term, some of the children may lose a certain degree of external rotation range of motion when an intensive exercise program is not followed postoperatively. This could be explained by the fact that external rotation is not a frequent movement during daily activities, especially in patients who concurrently have deficient abduction (less than 90 degrees).

Rotational osteotomy of the humerus

In order to achieve successful results with all the previous soft tissue procedures for restoration of external rotation, the glenohumeral joint must be congruent. Otherwise tendon transfers and anterior release will not work. Incongruity results from internal rotation contractures which lead to osseous deformity and posterior transposition of the humeral head. Joint incongruity is confirmed by computed tomography scan measurements, when more than 20% of the humeral head's surface is posteriorly displaced relative to the posterior border of the glenoid [21]. Rotational osteotomy is an effective procedure in restoring glenohumeral congruity [23]. This procedure is preferred in older patients (i.e., above 8–10 years of age), as in these patients osseous deformities have already been developed, resulting in humeral head incongruity. Moreover, in patients with humeral head incongruity the adjacent local muscles that are commonly used for transfer may be atrophied and inadequate, and thus, humeral osteotomy is the only option.

The amount of rotation depends on the degree of fixed internal rotation contracture. Usually, around 45 degrees of rotation is needed, but in certain cases the required correction may be up to 90 degrees. Preoperative planning is essential in order to determine the exact amount of the rotation that is necessary, so as to avoid excessive correction and insufficient internal rotation. This is a serious complication of the procedure, as internal rotation is essential to several daily activities (i.e., inability to put the hand in the trousers pocket, inability of the hand to reach the mouth). The osteotomy is stabilized with the aid of plate and screws. Simultaneous correction of the limb length discrepancy can be performed, but in this case an external fixator is placed so that that the proximal and distal screws of the external fixator are placed in two planes according to the angle of rotation that is required. Then, distraction osteogenesis proceeds accordingly. This procedure has been performed in some patients who wanted correction of the length discrepancy, mainly for cosmetic purposes, in combination with the external rotation osteotomy.

Procedures for elbow deformities

The most common problems around the elbow joint include loss of flexion and conversely flexion contracture. Elbow flexion contractures result from chronic denervation of the triceps. The resulting muscle imbalance leads to biceps' forceful forward pull. Despite these biomechanics that lead

to elbow flexion contracture, there are some rare cases in which flexion contractures are combined with a weak biceps. This could be explained by irregularities in the normal anatomy of the bony structures at the elbow joint.

The elbow flexion weakness is treated either by local muscle transfers or, if no local donors are available, by free innervated muscle transfers. Commonly used muscles for free transfers include the gracilis (preferred especially in Asian patients since in Caucasians gracilis might be inadequate in bulk and strength), the latissimus dorsi which is a real workhorse in the field of free muscles and the rectus femoris, which has an excellent shape and bulk for biceps despite its short neurovascular pedicle. Regarding local donors, pectoralis major with or without pectoralis minor can be transferred as an island flap [24]. Surgeons must be aware that this muscle is not strong enough to substitute biceps in cases of total absence of elbow flexion, thus in cases like that this particular transfer is not ideal. Another local option is latissimus dorsi which can be used as pedicled muscle graft [25]. The transferred muscle is hooked proximally on the clavicle and distally on the radial tuberosity. Care should be taken to maintain the proper tension on the muscle so that at the end of the procedure the elbow must be held in a flexed position of more than 90 degrees. Last, the Steindler flexorplasty can be applied in upper plexus palsies in which the wrist and hand functions are spared. This procedure involves transfer of the origin of wrist and hand flexors from the medial epicondyle to the anterior humeral surface [26–28].

The treatment strategy for flexion contracture depends on the radiographic appearance and the osseous changes that may have been developed around the elbow joint. In cases of soft tissues contractures alone, the most popular method for correction of flexion contracture includes both Z-plasty of the skin at the antecubital fossa and Z-lengthening of the biceps tendon. Further release of the lacertus fibrosus, brachialis and anterior capsule is also necessary for an adequate elbow extension [29]. Despite anterior release, the muscle imbalance responsible for flexion contracture is still present. An interesting approach to restoration of this muscle imbalance is the one described by Chuang et al., who proposed transfer of biceps or brachialis to triceps in order to restore elbow extension [30].

Our preferred method for correction of flexion contracture in adult patients is arthrodiastasis of the elbow with application of an external fixator. This procedure yields successful results using gradual soft tissue distraction without opening the elbow joint. This method should be performed only in skeletally mature patients since there is no chance for recurrence, while in skeletally immature patients recurrence of the contracture might develop in the following years. After flexion contracture release, a certain degree of flexion power decrease must be anticipated, but it usually comes back after a few months.

Procedures for forearm deformity

One common deformity in patients with obstetrical brachial plexus palsy is forearm supination, which can be associated with ulnar wrist deviation and several hand defects. Forearm supination deformity progresses over time and ultimately results in severe contracture of the interosseous membrane as well as in dislocation of the distal radio-ulnar joint. In severe cases, anterior dislocation of the radial head may also occur.

This deformity results from a certain muscle imbalance in which supinator muscles (biceps and supinator) overact in the presence of weak or absent pronators. During the initial stages, supination deformity can be passively corrected, but after a period of about 2 years, contracture of the interosseous membrane develops and the deformity becomes rigid. Concomitant osseous deformities may become apparent. The lateral curve of radius can be accentuated, while the distal end of the ulna or the radial head may be dislocated anteriorly. It is recommended that supination deformity must be corrected before this deformity becomes rigid [31]. Surgical correction of supination deformity includes careful evaluation of the interosseous membrane. Surgeons must also consider the developed deformities around the adjacent joints and the functional status of the hand. A moderate flexion contracture of the elbow does not contraindicate forearm surgery. In the case of associated shoulder deformities, these must be corrected first, while surgeries for restoration of the hand function should follow correction of supination deformity and deformities around the wrist.

Zancolli proposed surgical correction of supination deformity by rerouting the biceps tendon around the radius to a pronation position, or by transferring the flexor carpi ulnaris to the brachioradialis tendon [31]. For a successful outcome, triceps must have an adequate power, while longitudinal division of the interosseous membrane is also necessary. Although Zancolli reported excellent results with this procedure, this was not evident in other studies, especially when contracture of the interosseous membrane had been developed [32, 33]. Pronation osteotomy of the radius is an alternative option that has been shown to provide promising functional improvement in these cases [34, 35]. The plate for stabilization of the osteotomy must be placed proximally so that the distal radius growth plate is spared.

In those cases that pronation deformity has been developed, external rotation osteotomy of the radius also restores the function of the upper limb and improves the positioning of the hand in space.

Procedures for wrist deformities

Frequently seen deformities around the wrist include ulnar wrist deviation (27% in Zancolli's series) and drop wrist [36]. Ulnar wrist deformity develops due to the unopposed activity of the extensor and flexor carpi ulnaris, while thumb extensors and extensor carpi radialis brevis and longus are deficient. Ulnar deviation of the wrist can be treated conservatively with a brace, or surgically by either soft tissue procedures (tendon transfers) or wrist arthrodesis (permanent or temporary depending on the status of the distal radius growth plate). Tendon transfers include transfer of the extensor carpi ulnaris or the flexor carpi ulnaris to the extensor carpi radialis brevis, or transfer of extensor carpi ulnaris to the abductor pollicis longus.

Regarding restoration of weak or absent wrist extension, pronator teres to extensor carpi radialis brevis transfer (such as that used for radial nerve palsy) is the optimal method of treatment when forearm flexors have adequate strength [37, 38]. Patients with concurrent drop wrist and ulnar deviation can be managed with a flexor carpi ulnaris to extensor carpi radialis brevis. By passing the tendon around the radius, rather than through the interosseous membrane, both the wrist extension and ulnar deviation of the wrist can be corrected (Fig. 1).

Procedures for hand deformities

Although the clinical presentation of the hand is highly variable, it usually includes (1) thumb adduction deformity, (2) metacarpophalangeal joints drop, (3) interphalangeal joints flexion deformity or iv) weak finger flexion. Thumb adduction deformity develops due to weak extensor pollicis longus or abductor pollicis longus, while metacarpophalangeal joints drop results from a weak extensor digitorum communis. Last, metacarpophalangeal joints hyperextension and interphalangeal joints flexion deformity result from intrinsic palsy (claw hand deformity).

Restoration of the thumb adduction deformity can be achieved through transfer of extensor carpi ulnaris to abductor pollicis longus, while deficient interphalangeal joints extension can be treated by distal advancement of the digital extensor mechanism, or by reconstruction of the lumbricals (achieved by flexor digitorum sublimis or extensor carpi radialis longus transfer). For restoration of metacarpophalangeal joints drop, flexor to extensor transfer is a reliable option when forearm flexors are strong enough. Otherwise, several different procedures can be used for restoration of this deformity like wrist extensor to extensor digitorum communis transfer, or plication of the extensor digitorum communis. In order for these tendon transfers to work, wrist fusion must be performed first so that fingers' movement due to tenodesis effect with wrist flexion or extension is eliminated [39].

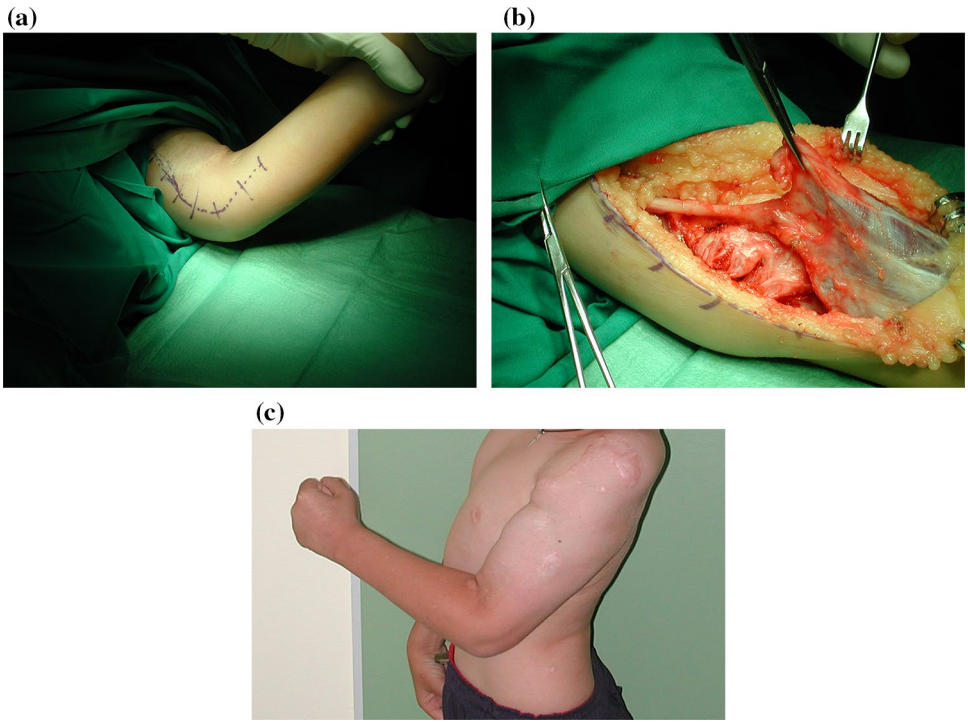

Fig. 1 Steindler flexorplasty in a 6-year-old patient with inadequate elbow flexion. **a** Preoperative planning, **b** intraoperative figure showing the elevation of forearm flexors before the reattachment to the distal humerus, **c** six months postoperatively: Note that the patient in order to achieve strong elbow flexion places his hand in a grasping position

There are two main options for correction of weak finger flexion, based on the status of the wrist extensors. When good wrist extensor function is present, transfer of these tendons to flexors in a manner similar to that performed for ulnar nerve palsy is an effective measure [40]. Otherwise, if strong wrist extensors are not available (which is usually the case), free muscle transfer for flexor digitorum profundus replacement is the optimal method. For neurotization of these grafts, available donor nerves include the intercostals nerves or the contralateral C7 nerve root (two-stage reconstruction). An alternative option in the case of weak wrist extensors is local transfer of the latissimus dorsi [41]. In the case of global paralysis of both finger flexors and extensors, the latissimus dorsi muscle can be transferred for digital flexion, while the gracilis muscle can be transferred as a free muscle graft for fingers extension.

In cases of claw hand deformity, our preferred method of repair is the 'Lasso' procedure that includes the following: harvest the one of the insertion bundles of one sublimis flexor tendon from long or ring finger, split it in four sections and pass each one of them around A1 and proximal A2 pulleys. This transfer improves claw hand and creates a stronger grip of the fingers.

Discussion

Neonatal brachial plexus palsy is the result of lateral traction of the brachial plexus during a difficult delivery. Although most of the infants fully recover within the first few months, some may develop permanent defects. The only chance for these infants to have a favorable prognosis is early microsurgical reconstruction [5, 42–44]. Moreover, in several cases spontaneous reinnervation invariably results in bony deformities and joint contractures due to muscle imbalance that develops after this random asymmetrical reinnervation that favors the flexors, pronators and adductors. This is usually the case in upper plexus injuries, with or without C7 root lesion [15, 45]. An injury like that results in deficient function of the shoulder abductors and external rotators. Either elbow may be contracted in a flexed position, or conversely deficient flexion may be present.

Stabilization of the shoulder joint, and restoration of shoulder abduction and external rotation are the goals of secondary procedures in shoulder [46]. The authors believe that trapezius transfer is a reliable method to restore shoulder abduction, which can reach to 90 degrees or more if supraspinatus and serratus anterior are functional.

In addition, the combination of anterior soft tissue release, and transfer of the latissimus dorsi and teres major tendons around the humeral head is an excellent procedure with good results in younger patients up to 6–8 years old. In older children, rotational osteotomy of the humerus is our preferred method for restoration of external rotation.

Usually, a certain degree of limb length discrepancy becomes apparent over the years, which is further accentuated by flexion contracture of the elbow. In adult patients, arthrodiastasis of the elbow joint with the aid of external distraction device is an excellent choice and it is our preferred method for correction of flexion contracture in this age group. Advantages of arthrodiastasis compared to open release are as follows: Arthrodiastasis is a minimal invasive procedure, and the correction with this method is gradual [47]. In a decreasing order of preference according to the authors, local muscle transfers for restoration of weak elbow flexion include latissimus dorsi transfer, the Steindler procedure and the triceps to biceps transfer, especially in cases of co-contraction. Otherwise, if no local donors are available, our preference is to perform free muscle transfers innervated by either three intercostals nerves or by a banked nerve graft from the contralateral C7 nerve root (two-stage procedure) [48].

More distally, the developing deformities around the hand and wrist are more complex, and the procedures for correction of each of these deformities need careful preoperative assessment of any available donors for tendon transfers. If there are no such donors, free muscle transfer is the only option [49].

To correct rotational deformities, we prefer the rotational osteotomies of the radius and for the flail wrist our method of choice is the wrist fusion (temporary or permanent depending on the skeletal maturity). Furthermore, not only wrist fusion is an excellent method to stabilize the wrist and correct its fixed deformities, but it may provide function of muscle–tendon units around the wrist that can be transferred to enhance finger flexion and/or extension. Authors' preferred method for wrist fusion is the fixation of the wrist with a self-compressing screw and an external fixator compared to the traditional method of plate and screws. The advantage of our technique is that the extensor compartment is minimally disturbed by the fusion and therefore is not subjected to adhesion formation that might be a problem in future tendon transfers [50].

In conclusion, secondary procedures aim to restore and/or improve the function by minimizing the residual defects of the paralyzed upper extremity in late cases of neonatal brachial plexus palsy. Careful preoperative planning is mandatory, and a multistaged approach should be applied, depending on the type of palsy and the age of the patient.

Compliance with ethical standards

Conflict of interest All authors declare that they have no conflict of interest.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed consent Informed consent was obtained from all individual participants included in the study.

References

1. Abid A (2016) Brachial plexus birth palsy: management during the first year of life. Orthop Traumatol Surg Res 102(1):S125–S132
2. Heise CO, Martins R, Siqueira M (2015) Neonatal brachial plexus palsy: a permanent challenge. Arr Neuropsiquiatr 73(9):803–808
3. Hale HB, Bae DS, Waters PM (2010) Current concepts in the management of brachial plexus birth palsy. J Hand Surg Am 35A(2):322–331
4. Coroneos CJ, Voineskos SH, Christakis MK, Thoma A, Bain JR, Brouwers MC (2017) Obstetrical brachial plexus injury (OBPI): Canada's national clinical practice guideline. BMJ Open 7(1):e014141
5. Vekris MD, Lykissas MG, Beris AE, Manoudis G, Vekris AD, Soucacos PN (2008) Management of obstetrical brachial plexus palsy with early plexus microreconstruction and late muscle transfers. Microsurgery 28(4):252–261
6. Gkiatas I, Papadopoulos D, Korompilias A, Vekris M, Beris A, Kostas-Agnantis I (2018) Traumatic upper plexus palsy: Is the exploration of brachial plexus necessary? Eur J Orthop Surg Traumatol. https://doi.org/10.1007/s00590-018-2345-1
7. Zyaei A, Saied A (2010) Functional outcome of ulnar nerve fascicle transfer for restoration of elbow flexion in upper brachial plexus injury. Eur J Orthop Surg Traumatol 20(4):293–297
8. Thatte MR, Babhulkar S, Hiremath A (2013) Brachial plexus injury in adults: diagnosis and surgical treatment strategies. Ann Indian Acad Neurol 16(1):26–33
9. Howell SM, Imobersteg AM, Seger DH, Marone PJ (1986) Clarification of the role of the supraspinatus muscle in shoulder function. J Bone Joint Surg [Am] 68:398–404
10. Saha AK (1967) Surgery of the paralyzed and flail shoulder. Acta Orthop Scand Suppl 97:5–90
11. Ozben H, Atalar AC, Bilsel K, Demirhan M (2011) Tranfer of latissums dorsi and teres major tendons without subscapularis release for treatment of obstetrical brachial plexus palsy sequela. J Shoulder Elbow Surg 20(8):1265–1274
12. Elhassan B, Bishop A, Shin A, Spinner R (2010) Shoulder tendon transfer options for adult patients with brachial plexus injury. J Hand Surg Am 35(7):1211–1219
13. Pearl ML (2009) Shoulder problems in children with brachial plexus birth palsy: evaluation and management. J Am Acad Orthop Surg 17(4):242–254
14. Andres-Cano P, Toledo MA, Farrington DM, Gil JJ (2015) Arthroscopic treatment for internal contracture of the shoulder secondary to brachial plexus birth palsy: report of a case series and review of the literature. Eur J Orthop Surg Traumatol 25(7):1121–1129
15. Gilbert A (1995) Long term evaluation of brachial plexus surgery in obstetrical palsy. Hand Clin 11(4):583–593
16. Narakas AO (1993) Muscle transpositions in the shoulder and upper arm for sequelae of brachial plexus palsy. Clin Neurol Neurosurg 95(suppl):S89–S91
17. L'Episcopo JB (1939) Restoration of muscle balance in the treatment of obstetrical paralysis. N Y State J Med 39:336–357
18. Al Qattan MM (2003) Latissimus dorsi transfer for external rotation weakness of the shoulder in obstetric brachial plexus palsy. J Hand Surg Br 28(5):487–490
19. Freund RK, Terzis JK, Jordan L, Taylor G (1986) Modified latissimus dorsi and terres major transfer for external rotation deficit of the shoulder. Orthopedics 9:505–506
20. Cohen G, Rampal V, Aubart-Cohen F, Seringe R, Wicart P (2010) Brachial plexus birth palsy shoulder deformity treatment using subscapularis release combined to tendons transfer. Orthop Traumatol Surg Res 96(4):334–339
21. Terzis JK, Vekris MD, Okajima S, Soucacos PN (2003) Shoulder deformities in obstetric brachial plexus paralysis: a computed tomography study. J Pediatr Orthop 23(2):254–260
22. Terzis JK, Kostopoulos E (2010) Our experience with secondary reconstruction of external rotation in obstetricalbrachial plexus palsy. Plast Reconstr Surg 126(3):951–963
23. Waters PM, Bae DS (2006) The effect of derotational humeral osteotomy on global shoulder function in brachial plexus birth palsy. J Bone Joint Surg Am 88(5):1035–1042
24. Cambon-Binder A, Walch A, Marcheix PS, Belkheyar Z (2018) Bipolar transfer of the pectoralis major muscle for restoration of elbow flexion in 29 cases. J Shoulder Elbow Surg 27(11):e330–e336
25. Azab AA, Alsabbahi MS (2017) Bipolar transfer of latissimus dorsi myocutaneous flap for restoration of elbow flexion in late traumatic brachial plexus injury: evaluation of 13 cases. Ann Plast Surg 78(2):198–201
26. Monreal R (2007) Steindler flexorplasty to restore elbow flexion in C5-C6-C7 brachial plexus palsy type. J Brachial Plex Peripher Nerve Inj 2:15
27. Chen WS (2000) Restoration of elbow flexion by modified Steindler flexorplasty. Int Orthop 24(1):43–46
28. Brunelli GA, Vigasio A, Brunelli GR (1995) Modified Steindler procedure for elbow flexion restoration. J Hand Surg [Am] 20:743–746
29. Price AE, Grossman JA (1995) A management approach for secondary shoulder and forearm deformities following obstetrical brachial plexus injury. Hand Clin 11(4):607–617
30. Chuang DC, Hattori Y, Ma And HS, Chen HC (2002) The reconstructive strategy for improving elbow function in late obstetric brachial plexus palsy. Plast Reconstr Surg 109(1):116–126
31. Zancolli EA, Zancolli ER (1988) Palliative surgical procedures in sequelae of obstetrical palsy. Hand Clin 4:643–669
32. Gilbert A, Tassin JL (1987) Obstetrical palsy: a clinical, pathologic and surgical review. In: Terzis JK (ed) Microreconstruction of Nerve Injuries. WB Saunders, Philadelphia, pp 529–553
33. Owings R, Wickstrom J, Perry J, Nickel V (1971) Biceps brachii rerouting in treatment of paralytic supination contracture of the forearm. J Bone Joint Surg [Am] 53:137–142
34. Gladstein AZ, Sachleben B, Ho ES, Anthony A, Clarke HM, Hopyan S (2017) Forearm pronation osteotomy for supination contracture secondary to obstetrical brachial plexus palsy: a retrospective cohort study. J Pediatr Orthop 37(6):e357–e363
35. Van Kooten EO, Ishaque MA, Winters HA, Ritt MJ, Van der Sluijs HA (2008) Pronating radius osteotomy for supination deformity in children with obstetric brachial plexus palsy. Tech Hand Up Extrem Surg 12(1):34–37
36. Zancolli E, Zancolli E (2000) Reconstructive surgery in brachial plexus sequelae. In: Gupta A, Kay SPJ, Scheker LR (eds) The growing hand: diagnosis and management of the upper extremity in children. Mosby, St. Louis, pp 805–823
37. Green DP (1993) Radial nerve palsy. In: Green D (ed) Operative Hand Surgery, 3rd edn. Churchill-Livingstone, New York, pp 1401–1417

38. Wheeler DR (1996) Reconstruction for radial nerve palsy. In: Peimer A (ed) Surgery of the Hand and Upper Extremity. McGraw-Hill, New York, pp 1363–1379
39. Chuang DCC (2001) Palliative surgery: forearm and hand deformities. In: Gilbert A (ed) Brachial Plexus Injuries. Martin Dunitz, Paris, pp 294–302
40. Terzis JK, Kokkalis ZT (2008) Outcomes of hand reconstruction in obstetric brachial plexus palsy. Plast Reconstr Surg 122(2):516–526
41. Gousheh J, Arab H, Gilbert A (2000) The extended latisimus dorsi muscle island flap for flexion or extension of the fingers. J Hand Surg [Br] 25:160–165
42. Murison J, Jehanno P, Fitoussi F (2017) Nerve transfer to biceps to restore elbow flexion and supination in children with obstetrical brachial plexus palsy. J Child Orthop 11(6):455–459
43. Waters PM (2005) Update on management of pediatric brachial plexus palsy. J Pediatr Orthop B 14(4):233–244
44. Xu J, Cheng X, Gu Y (2000) Different methods and results in the treatment of obstetrical brachial plexus palsy. J Reconstr Microsurg 16(6):417–420
45. Egloff DV, Raffoul W, Bonnard C, Stalder J (1995) Palliative surgical procedures to restore shoulder function in obstetric brachial palsy. Critical analysis of Narakas' series. Hand Clin 11:597–605
46. van der Lingen M, de Joode S, Schotanus M, Grimm B, van Nie F, Speth L, Samijo S (2018) Satisfied patients after shoulder arthrodesis for brachial plexus lesions even after 20 years of follow-up. Eur J Orthop Surg Traumatol 28(6):1089–1094
47. Vekris MD, Pafilas D, Lykissas MG, Soucacos PN, Beris AE (2010) Correction of elbow flexion contracture in late obstetric brachial plexus palsythrough arthrodiatasis of the elbow (Ioannina method). Tech Hand Up Extrem Surg 14(1):14–20
48. Vekris MD, Beris AE, Lykissas MG, Korompilias AV, Vekris AD, Soucacos PN (2008) Restoration of elbow function in severe brachial plexus paralysis via muscle transfers. Injury 39(Suppl 3):S15–S22
49. Soucacos PN, Vekris MD, Zoubos AB, Johnson EO (2006) Secondary reanimation procedures in late obstetrical brachial plexus palsypatients. Microsurgery 26(4):343–351
50. Vekris MD, Pakos EE, Soucacos PN, Gavriilidis I, Beris AE (2010) Wrist arthrodesis for brachial plexus palsy using an external fixator and a cannulated screw (Ioannina technique). J Orthop Surg (Hong Kong) 18(1):87–91