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ORIGINAL PAPER

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Microsurgical repair and secondary surgery in obstetrical brachial plexus palsy

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Abstract We present a personal experience with 750 children suffering from obstetrical brachial plexus palsy. The related surgery is described, including early microsurgical nerve reconstruction and secondary procedures including tendon and muscle transfers. The clinical examination, indications and timing for surgery, technical details of primary and secondary operations and the possible outcome are discussed. Both clinical and research work need an interdisciplinary team approach, and diagnostic, therapeutic and prognostic improvement is based on the refinements of microsurgical skills and the continuous exchange of information between specialized centers.

Keywords Obstetrical brachial plexus palsy · Microsurgery · Tendon · Muscle transfers

Introduction

We describe our personal journey into the complex field of reconstructive surgery for children suffering from obstetrical brachial plexus palsy (OBPP). Our 9-year experience is presented. Surgical procedures have been established and improved to perform nerve repair, joint contracture release, as well as tendon and muscle transfers. The decision-making strategy and results are described.

This is a cooperative effort shared with our anesthesiologists, pediatricians, orthopaedists, neuropathologists, research engineers, physiotherapists and last but not least all the parents in Germany and Belgium, who continuously stimulate our daily work through their questions, hints, support and gratefulness.

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Nerve repair: indications, timing and technique

Indications for primary plexus reconstruction

These are established on clinical criteria; we do not perform nerve conduction measurements or electromyography preoperatively. Although MRI is becoming more reliable in adult plexus patients, we only advise the use of this imaging technique in the case of severe upper lesions (especially when associated with a breech delivery) when upper root avulsions are suspected. In these children, it is better to have a strong preoperative indicator, to discuss the issue with the parents and to directly plan an extraplexic neurotization procedure.

Table 1 shows the principles for deciding upon a primary plexus exploration and microsurgical reconstruction [1]:

- The upper (C5 and C6 involved) or extended upper (plus C7) plexus lesion with poor proximal recovery within the first 6–9 months: according to Gilbert [2], the biceps should start developing activity around 3 months and be functional and powerful at 6 months. Increasingly the shoulder is investigated, since these muscles should support the whole upper limb throughout life and must accept the increasing weight of the growing upper limb: so a definitely weak shoulder abduction and/or flexion (under 60° for active movement against gravity) will also be a strong indication for nerve reconstruction.
- Severe lesion of the suprascapular nerve, either in a recovering or severe upper or total lesion, should be addressed either at a planned plexus exploration or as an isolated procedure (through a limited dorsal approach) within the first 18 months of life. We have no experience with this extraplexic neurotization performed at a later age as advocated by some authors such as Boome (personal communication), but we believe that this could be done in cases who present at a later age (3–8 years).

Table 1 Indications for primary surgery

Total palsy with insufficient proximal recovery (weak shoulder abduction and flexion, weak or no biceps), especially when a flail hand is present, Horner +, phrenic nerve palsy, breech delivery: operation at 4 months
Upper palsy with insufficient shoulder and/or biceps recovery: operation between 6 and 9 months
C7-centered lesion (flexed forearm and medially rotated shoulder): operation at 6 months
Permanent palsy of shoulder lateral rotators, otherwise good recovery: extraplexic neurotization of the suprascapular nerve by the distal branch of the accessory nerve: operation between 6 and 18 months

- The total lesion with poor recovery should be appreciated within the first 3 months of life and be explored at 4 months at the latest. The presence of a Horner sign (severe trauma or avulsion of Th1 with serious hand palsy), a flail and insensate hand and diaphragmatic palsy are additional factors to hasten the decision. Even if some deltoid or pectoral muscle recovery is seen, hand function must be the priority (sensation and motion), otherwise the child will never integrate this extremity within his cortical representation and thus never use this limb like the unaffected side.
- The rare C7-centered lesion (Fig. 1) with flexed elbow and medially-rotated arm, paralysed triceps but sometimes good shoulder abductors, brings the otherwise normal hand into a very disabling position (Fig. 2), preventing good re-education. These cases also need early reconstruction of the suprascapular nerve and the posterior division of the upper and middle trunk; an anterior shoulder release must sometimes be associated because a severe shoulder contracture may develop very early.

Surgical technique

Anesthesia in children under 1 year

The child should be free of upper airway infection. A routine blood sample is taken either before admission or when starting anesthesia [3]. Careful monitoring of body temperature and fluid balance is mandatory. The anesthesia is treated as a prolonged sleep, with analgesics being administered on demand when painful operative steps (skin incision, preparation of roots, osteotomy and sural nerve harvesting) are foreseen.

In very small children with extended nerve lesions or multiple avulsions (with a need for multiple extraplexic neurotizations), the reconstruction is performed at a second operation several weeks later.

Exposure

The horizontal supraclavicular approaches. The child is positioned supine, the head turned to the opposite site of the plexus lesion. Draping includes both legs.

We always begin exploring the plexus through a horizontal supraclavicular skin incision of about 4 cm (Fig. 3A). Platysma is divided and the soft tissue (fat and lymph nodes) over the anterior scalenus muscle is reflected laterally. The dissection is extended far enough proximally (root C4) and distally (under the clavicle) according to the extent of the lesion; the phrenic nerve is identified and carefully neurolysed.

In rare cases, an extended oblique distal skin incision is necessary. Osteotomy of the clavicle is performed only when the fibrosis extends onto the trunk and divisions.

The brachial plexus is progressively exposed under the anterior scalenus muscle and the roots are individualized by rubber loops (Fig. 3B).

Fig. 1 C7-centered OBPP lesion, clinical aspect

Fig. 2 C7-centered OBPP lesion, hand position in an older child

Neurolysis

Careful microsurgical neurolysis using loop magnification or a microscope is performed according to Millesi's description and classification [4]. Neurolysis is performed proximally onto the neuroforamen and distally into unaffected nerve bundles. The lesional zone (fibrosis with or without neuroma) is limited in between. Intraoperative stimulation is then performed proximal and distal to the lesions to ascertain conductive bundles and the different motor targets.

We agree with Clarke [5] that a neuroma should be excised. Out of 130 cases, we only have one case of upper trunk neurolysis with a superb reinnervation after the release of a constricting fibrotic cuff (Fig. 4).

After the neuroma has been resected and root avulsions have been identified, the remaining roots are carefully dissected onto the foramen. Transverse sections are performed until fascicles with smooth and retractable epineurium appear. The last slice of the resection is taken for neuropathologic examination and the proximal side is marked by ink.

This neuropathologic examination takes about 1 h. Meanwhile, a drawing of the lesion is performed (Fig. 3C) and discussed with the parents, while the assistant harvests the sural nerves.

Donor nerves

One or two sural nerves are harvested through short oblique skin incisions. Longer collateral branches are also harvested. The skin is closed using only inverted dermal sutures and Steri-Strips are applied on the skin, thus scarring is limited.

Microsurgical reconstruction

The neuropathologist stains the root and distal trunk samples with hematoxylin eosin (HE) and analyses the

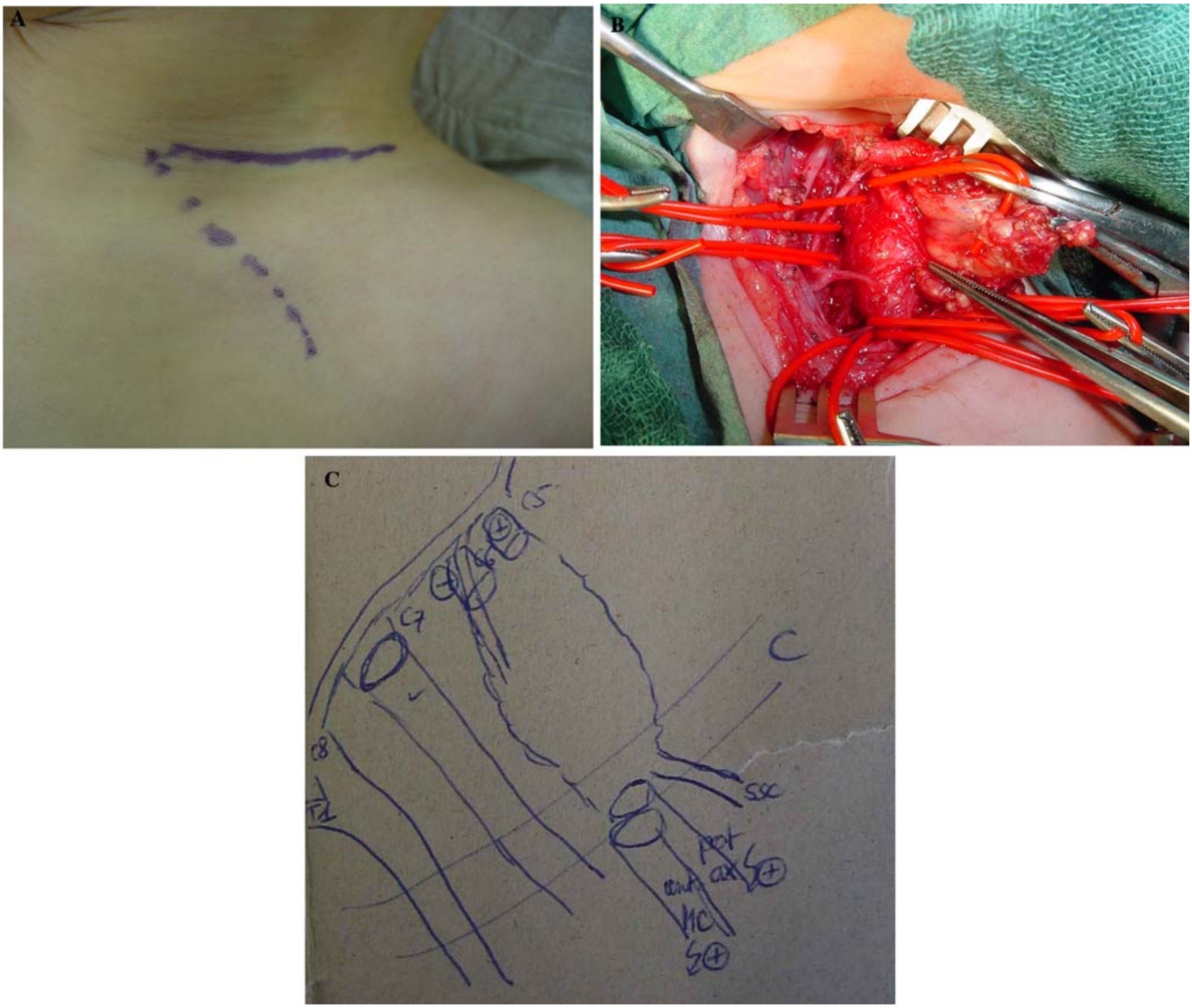

Fig. 3 Primary OBPP plexus exploration. **A** Supraclavicular approach. **B** Nerves on loops. **C** Drawing

extent of intraneural fibrosis, perineural thickening, the organization of fascicles and the presence of minifascicles and neuromatous reinnervation. Ganglion cells may also be identified (Table 2, Fig. 5).

If the root quality is not satisfactory, an additional cut is done; otherwise the root(s) are ready for transplantation.

We take on trust studies about intraneural topography (Fig. 6) and organize the sural nerves in fascicular groups of sufficient length to adapt them without tension, before suturing or gluing them under magnification. Very precise coaptation is mandatory. End-to-end suture after short neuroma resection seems to be feasible in selected cases (also to reduce the reconstruction to only one coaptation site), but tension might preclude a good recovery.

Targeting functional priorities is very important [1–3, 6].

In a total lesion the priorities are: the hand, the biceps, the shoulder abduction and lateral rotation, the triceps (Table 3).

In an upper lesion, the biceps should be neurotized individually and a lot of grafts should be transferred onto the nerves for the shoulder and pectoralis muscle, as this is the only way to restore power in the shoulder girdle. This is essential in order to maximize arm function throughout lifetime.

In cases with multiple avulsions, extraplexic neurotizers are selected. We use the distal branch of the XIth nerve (for suprascapular or musculocutaneous nerve), intercostal nerves (for musculocutaneous or thoracicus longus nerve), ulnar motor branches (Oberlin) or end-to-side coaptation (distal C8 on C7 or Th1).

After the repair, the clavicle is sutured using a non-absorbable filament, and muscle and the soft tissue layers are closed. Intracutaneous suture produces an

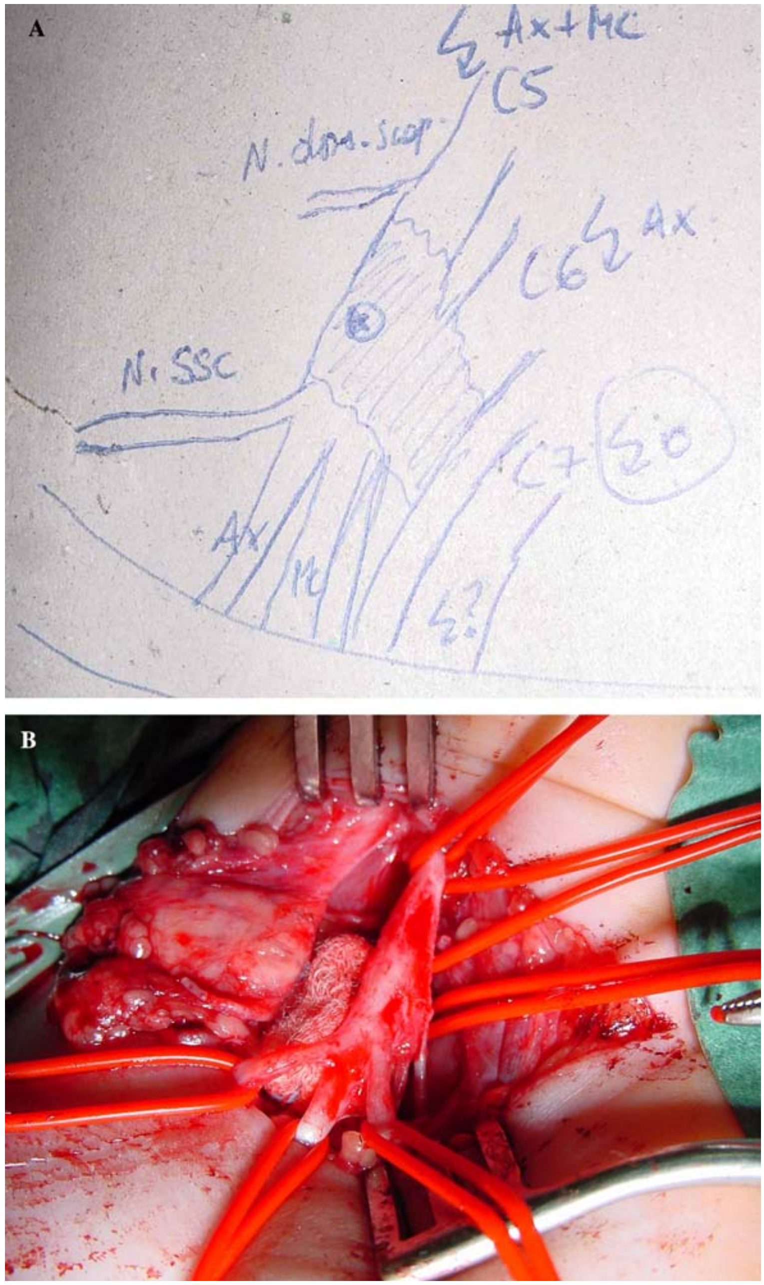

Fig. 4 Successful neurolysis of upper trunk

aesthetic scar—also evidence that plexus revision does not necessarily lead to major disfigurement.

The child is immobilized in a handmade, well-padded head and neck plaster for a minimum of 17 days.

Secondary surgery: indications, timing and technique

Correction of medial rotation contracture of the shoulder (2, 9)

In this section, we cover the frequent and severe lesion of the suprascapular nerve, very often involved in upper and total plexus lesions (Fig. 7). This first important motor branch, exiting the upper trunk, innervates the supraspinatus and infraspinatus muscles [7, 8]. This second muscle is the only powerful lateral rotator of the shoulder. Thus muscular imbalance favouring a medial rotational position of the humeral head is frequent, and capsular contractures and growth disturbances of the gleno-humeral joint may develop [8]. In the growing child, the initial nerve lesion (without sufficient recovery) is responsible for a complex musculo–articular problem: the humeral head is turned medially, and ossification is delayed. The glenoid develops more posteriorly, there is a compensatory overgrowth of the coracoid process with a tightened coraco–humeral ligament and an anterior shoulder contracture. The whole upper limb motion pattern is shifted into a medially rotated shoulder, thus limiting shoulder abduction, biceps activity and forearm

Table 2 Neuropathology

Roots: fibrosis, internal or external neuromatous reinnervation, ganglion cells
Distal targets: fascicle quality and organization, fibrosis

supination. A complex glenohumeral dysplasia may develop over the years.

There are in addition rare cases where a severe anterior shoulder contracture is already present in the first months of life necessitating early surgical release: we believe that in these children a direct contusional trauma to the shoulder may have happened during delivery.

From this pathophysiologic sequence, the treatment strategy becomes clear (Table 4):

- The glenohumeral joint should maintain free passive ROM in lateral rotation, either by physiotherapy (stretching exercises), or by surgical release [8].
- A severe nerve lesion of the suprascapular nerve should be repaired by intraplexic or extraplexic neurotization, either within a plexus reconstruction (by the anterior supraclavicular approach) or by a dorsal transmuscular approach.
- Permanent weak or absent lateral rotation is due to muscular hypotrophy and should be treated over time by additional muscle mass, either by a simple tendon rerouting or a real musculo-tendinous transfer [9–12].
- Restoration of a movement vector requires replacement by another muscle pulling in the same direction: the classic Hoffer transfer [9] restores lateral rotation of the shoulder in abduction, while the active movement with an adducted arm may only be improved when a rerouting of the pectoralis muscle is performed.
- The different procedures are detailed below.

Contracture release

Muscular weakness induces motion restriction responsible for capsular shrinkage and some tendomuscular shortening—these are the soft-tissue contractures we see in OBPP children at various joint levels. Releasing these structures is only successful if the responsible muscle palsy is also corrected.

The shoulder joint

Various segments of the complex capsular tissue of the gleno-humeral joint may be involved. The best description of the clinical situation and the treatment modalities of these contractures has been given by Birch [8].

The *anterior contracture* is a consequence of the medial rotation position of the shoulder, and involves the

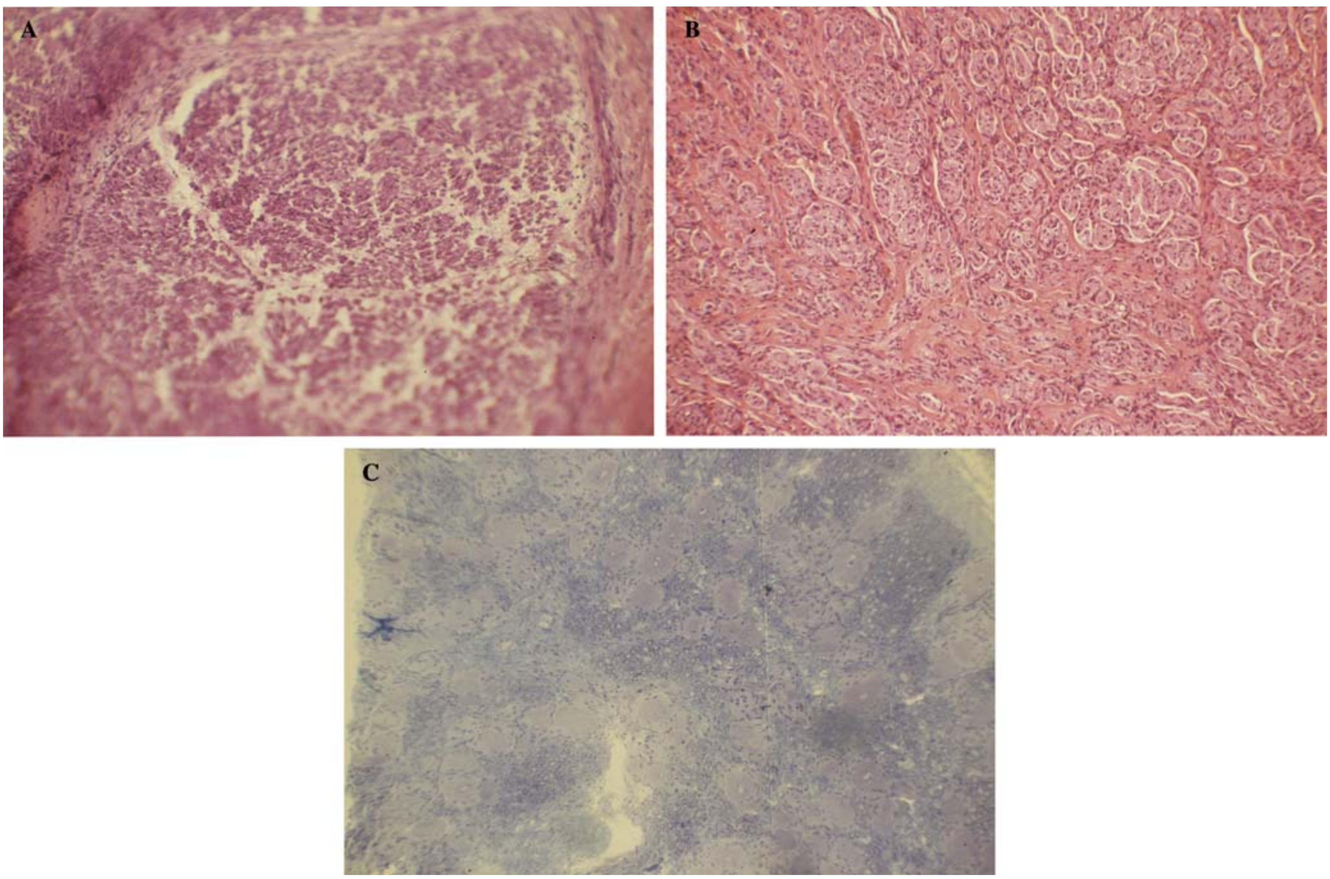

Fig. 5 Neuropathology: normal, fibrosis and avulsion

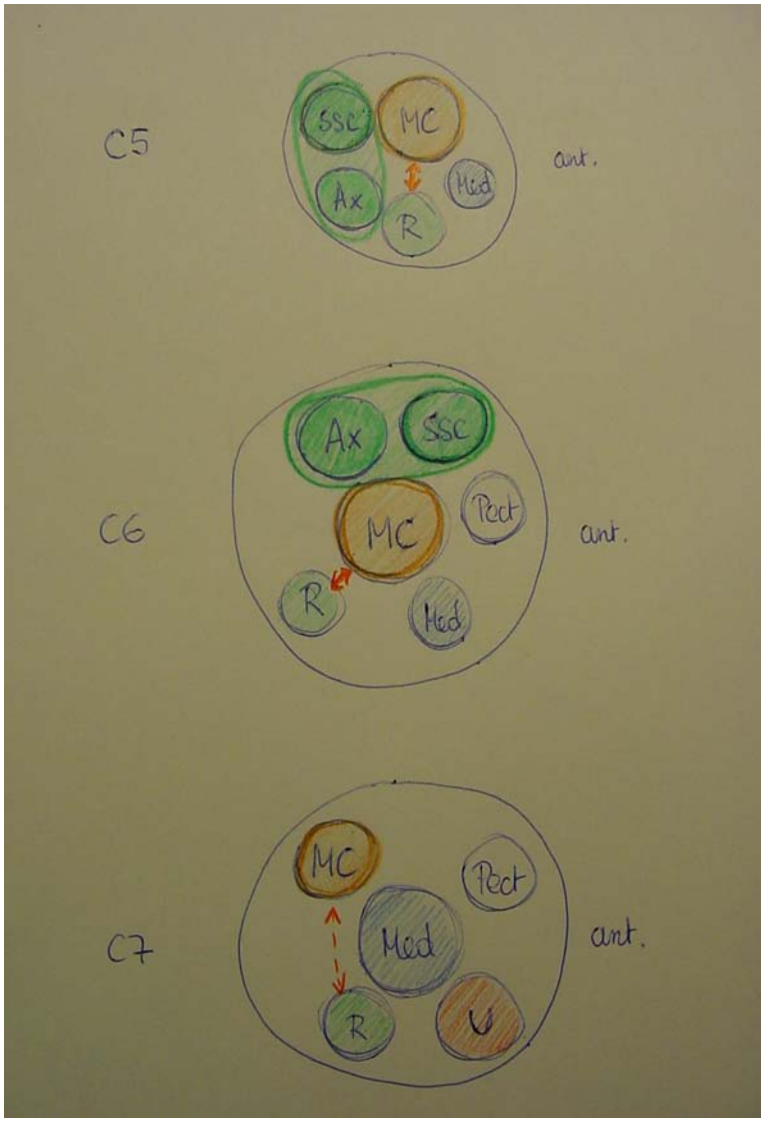

Fig. 6 Intraneural topography: C5, C6 and C7

anterior capsular structures, the coraco–humeral ligament, the subscapular tendon and the coracoid process. The anterior release thus proceeds through an anterior deltopectoral approach sparing the cephalic vein, identifying the coracoid, sectioning the conjoined tendon and freeing the coracoid process subperiosteally. Frequently, a rather hypertrophied, lateralized and curved coracoid impinges on the laterally-rotating humeral

Table 3 Intraoperative microsurgical strategy

Upper palsy
1. Specific targeting for musculocutaneous motor fascicle
2. Redundant transplantation for the shoulder
3. Separate grafts for triceps muscle
Total palsy
1. Hand and biceps
2. Shoulder
3. Triceps and pectoralis
Extraplexic donors: distal XI (on SSC), ulnar fascicles (MC) and intercostals (MC, long thoracic nerve)
Only one root (of good quality): root to hand, IC to MC, evtl. contralateral C7 for shoulder and XI on SSC
Two roots: root 1 to hand, root 2 to MC and axillar nerve and XI on SSC
Three roots: “anatomic” intraplexic reconstruction: root 1 to hand, good and large (motor) root (C6) to upper trunk (SSC, MC, ax) and root 3 to middle trunk

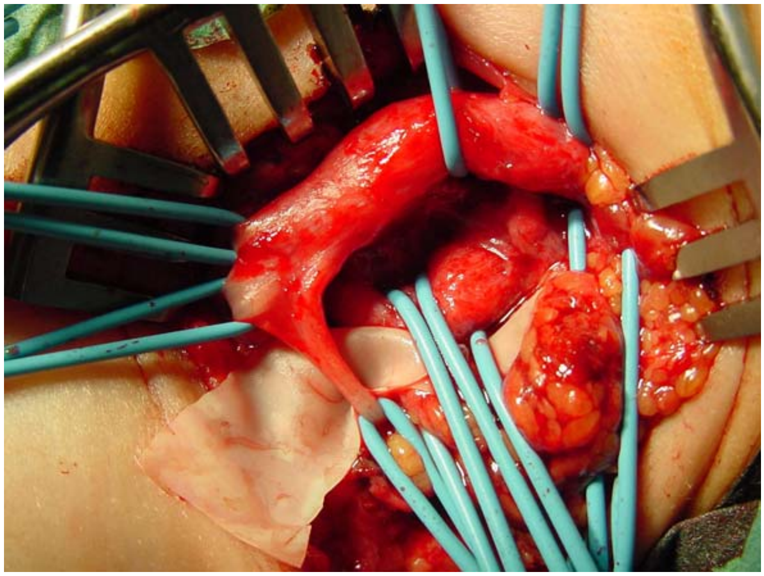

Fig. 7 Suprascapular nerve

Table 4 Surgical strategy in medial rotation contracture of the shoulder

pLR under 20° despite good physiotherapy: early anterior release
pLR 40–80°, aLR under 50°: LD rerouting under 4 years, real Hoffer muscle transfer if child over 6 years
Always consider need for extraplexic neurotization of suprascapular nerve
Humeral osteotomy only in old children (>10 years) with proven severe gleno-humeral dysplasia

head, and then it is resected. The coraco–humeral ligament is cut, the contribution of the underlying subscapular tendon is checked (remaining elastic resistance to passive lateral rotation) and this tendon is eventually lengthened by a step-cut incision and suture. At this moment, the joint should become congruent, and passive lateral rotation of almost 80° may be reached. The degree of glenohumeral dysplasia may be tested. Only in severe incongruence in children older than 10 years is a derotational osteotomy of the humerus performed in the same operation. When there is evidence for permanent muscle weakness, a tendon transfer is performed simultaneously.

The *inferior contracture* is tested with passive abduction of the arm: the inferior angle of the scapula may be pulled outwards by thickened fibrotic bands on the latissimus dorsi edge. This is a functional (premature tilting of the scapula in abduction) and aesthetic problem. Unfortunately, the inferior release with excision of this thickened muscle aponeurosis gives poor clinical results.

The *posterior contracture* affects the posterior scapulohumeral angle and may result in a pseudarthodesis motion pattern. The surgical strategy is debated, and may include sectioning of the coraco-humeral ligament and humeral osteotomies. Capsulotomy alone without correction of the underlying imbalance vectors will result in contracture recurrence (Fig. 8).

Elbow flexion contracture

Imbalance between and triceps and the preference of elbow-flexion training may lead to an elbow-extension deficit of 30–50°. The underlying imbalance may rarely be corrected, so the results of anterior elbow release alone or even dynamic splinting devices are disappointing in the long term.

Contracted membrana interossea

In the forearm supination contracture, the Grilli–Zancolli procedure includes transposition or rerouting of the distal insertion of the tendon, thus transforming the supinating vector into a pronating one. On inspection and while intraoperatively testing the passive pro-/supination, it appears that the interosseous membrane is contracted due to the immobile supination position. The sectioning of the proximal half improves passive ROM very well.

Tendon and muscle transfers

Key motor functions may be reinforced by muscular enhancement.

Shoulder abduction may be improved by transfer of the cranial trapezius muscle, sometimes reinforced by the levator scapulae. Lateral rotation is improved by converting the teres major and latissimus dorsi into lateral rotators [9, 10].

The may be strengthened by a latissimus dorsi transfer ($n=3$) or— in the rare situation of severe co-contractions—by a triceps- to- transfer ($n=3$).

We have no experience with other muscle transfers (pectoralis or gracilis) nor with Steindler flexorplasty.

We also focus on active wrist extension and prefer a FCU to ECR (L and B) transfer.

Fig. 8 Posterior shoulder contracture

Table 5 Scoring systems

Value	Abduction	Lateral rotation	Hand on head	Hand on back	Hand on mouth
Mallet (modified after Gilbert et al. [2])					
I	Total palsy				
II	< 30°	0°	Impossible	Impossible	Trumpet sign +
III	30–90°	< 20°	Difficult	Level S1	Slight trumpet
IV	> 90°	> 20°	Easy	Level T12	Needs < 40° abd.
V	Normal				
Gilbert (personal communication on the Inernational Meeting on Obstetric Palsy in Heerlen/NL, 1996)					
0	Total palsy				
I	45°	No active LR			
II	< 90°	No active LR			
III	= 90°	Weak active LR			
IV	< 120°	Moderate active LR			
V	> 120°	Normal active LR			

The trumpet sign + means that a hand to mouth movement can only be executed using the brachioradialis (and eventually parts of the muscle) while abducting the shoulder

Indications

Preoperative discussion is mandatory with parents, physiotherapists and all children above preschool age. We strongly advise correction of severe medial rotation contracture of the shoulder if the passive lateral rotation remains under 20° after 3 months of intensive physiotherapy. We focus on the complex impairment of the motion pattern, but also consider the overall effect on the growth disturbance of the gleno-humeral joint. For these reasons, we strongly suggest the parents to accept this surgery [7].

Table 6 Timing in secondary surgery

Shoulder contracture release: from 6 months to 2 years
Tendon transfers (wrist and LD rerouting): 2–4 years
Motor enhancement by muscular transfer (Hoffer, trapezius tf and triceps-to- tf): 6–10 years
Free-functioning ggracilis tf: 5 years minimum

Muscle or tendon transfers should be determined individually and not decided on a "feasibility" basis: the surgeon meets the parents, who are prepared to accept any option which promises their child significant or total recovery, and which offers a technically-possible operation, without truly considering each child as a special case with his own functional requirements. We strongly believe that the goal of a significant gain of function should be part of the decision. This is then a criterion for obtaining compliance for the initial weeks of immobilization and the necessary physiotherapy and sport exercises later prescribed.

We thus advocate a trapezius transfer only if the average gain of 50° active abduction will really improve the status of the child: either there is (nearly) nothing, and then even 30–40° of active abduction against gravity will reduce the torso compensation movements and allow some independent ROM, or we start with less than 60° and could expect an active range of 90°.

Table 7 Outcome after nerve repair

Depends on OBPP type (upper better than total), number and histologic quality of available roots, quality and redundance of transplants, precise targeting on good distal nerves
Depends on cortical integration training (Vojta)
Depends on rootwise separation of antagonists (biceps and triceps); weak reinnervation of shoulder medial rotators and triceps favors good shoulder LR and biceps activity
Grouping of the results and scoring is very difficult due to individual lesion type

When discussing lateral rotation, we focus on hand movements towards the top of the head and neck. We are however aware that Mallet's scheme (Table 5) and some of the positional endpoints may be reached without active lateral rotation of the humerus. Children are very skillful at developing compensatory movements and will use a combination of abduction and shoulder flexion, then or brachioradialis activity, to reach the same end-point.

Timing

After simple tendon transfers, patients do not require sophisticated re-education. Such transfers may be performed at any age, even quite early for functional reasons (activation of wrist extension and LD rerouting between 2 and 5 years) (Table 6).

Muscle transfers in combination with progressive training require good compliance by the patient and should be performed after 6 years of age (trapezius transfer and free gracilis).

Outcome

Assessment Although we have seen and operated on a lot of children in the previous 9 years, several major problems remain. In the actual setting, the children operated upon are reviewed by the surgeon, and there is always a risk of "positive thinking"; independent observers would guarantee objective assessment.

However, this rare opportunity to follow all these patients also provided precious hints about successes and pitfalls. These experiences have been integrated into our actual surgical strategy.

There are to date no reliable and precise scoring systems for results after primary surgery.

So far, we have evaluated our nerve reconstruction cases by clinical measures of ROM and muscle power grading (British MRC) every 6 to 9 months.

Scoring systems For shoulder problems in particular we use the Mallet and Gilbert scoring systems (Table 5).

Mallet's scheme does not always reflect separate motor functions. Trick movements executed without using the muscles referred to in such scoring examination may still reach the same endpoint.

The score value obtained from these schemes will only be a mean value reflecting a mixture of different situations. We have seen a number of older children with perfect shoulder abduction and flexion, and with severely-restricted lateral rotation: the mean score was bad, but the clinical situation was not comparable with an otherwise average result in abduction, flexion and poor active lateral rotation of the shoulder.

Gilbert's score does not reflect active medial rotation of the shoulder.

Primary microsurgery After some 130 primary plexus reconstructions, we have collected some empirical data, which we will comment on here [1] (Table 7). We actually study the correlation between the histologic root quality and the functional outcome.

Our actual guidelines and clinical results are:

– Functional recovery in relation to cortical integration is much better in upper than in total lesions: a child who is not aware of his hand will use the limb muscles in a delayed, occasional and rather "on demand" manner.
– The biceps muscle recovers well if the musculocutaneous nerve is targeted individually from a good motor root and if the triceps is rather weak.
– The shoulder needs redundant transplantation to achieve powerful flexion and abduction.
– Neuroma in continuity is dangerous when left in place [5], especially for the lower trunk: severe functional impairment and neglect is a frequent result if the neuroma is left in place.
– The growth cone progression (reinnervation) rate observed (1–2 mm per day) should apply only to nerve reconstruction, it may take approximately 2–3 months more to strengthen a muscle against gravity.

Table 8 Outcome after secondary surgery ($n = 171$)

Shoulder Trapezius tf		
Under 10 years	$n = 14$	+ 50° abduction
Over 10 years	$n = 6$	+ 30° abduction
Anterior release	$n = 65$	+ 50° passive lateral rotation
Lat.dorsi rerouting	$n = 36$	+ 60° active lateral rotation
Hoffer tf	$n = 7$	+ 50° active lateral rotation + 20° abduction
Humeral osteotomy	$n = 2$	
Elbow		
Lat. dorsi tf (neurovascular)	$n = 3$	
Triceps-to-biceps tf	$n = 3$	
Zancolli rerouting	$n = 13$	
Wrist		
Tendon FCU on ECR	$n = 22$	20° active wrist extension

Table 9 Future goals

Extraplexic neurotization of specific target nerves
Suprascapular nerve by the distal branch of the accessory nerve
Musculocutaneous nerve by motor fascicles of ulnar or median nerve
Radial nerve by subscapular nerve (C7-centered lesion)
Thoracodorsal nerve by two motor intercostal nerves
End to side neuroraphy: distal C8 onto middle or lower trunk in case of C8 avulsion

– When there are more than two root avulsions, the global result is poor, because the adjacent roots are rather severely affected.

Secondary surgery We include Table 8, which gives an overview of possible results (ROM against gravity) in 171 operated cases.

Future goals

Some techniques or tools have specifically attracted our surgical interest, as applied to the treatment of these children (Table 9).

Specific extraplexic neurotization The suprascapular nerve is frequently supplied by an extraplexic neurotization; the distal branch of the accessory nerve is a good and reliable motor donor. Intercostal nerves may be separated into motor and sensate branches even in children, but their reinnervation power for the musculocutaneous nerve is not constant, because of diameter discrepancy. Alternatives in the case of upper lesions are motor fascicles derived from the ulnar (Oberlin) or median nerve.

In our series, only one contralateral partial C7 transfer was needed in a young boy with four root avulsions.

In C5 and C6 avulsions, good recovery may be the result of pure extraplexic reconstruction (XI on SSC, U fascicles on MC and branches of medial pectoral nerve on axillar nerve).

End-to-side neurorraphy We tried this technique in selected cases where avulsion of C7 or C8 without sufficient donor roots made an adjacent end-to-side connection reasonable. We made only an epineural window and connected motor areas in the root onto motor fascicles identified by intraoperative stimulation. The results have not been evaluated up to now.

Neuropathology as a tool for precise targeting We have performed neuropathological examination of nerve specimens regularly since 1997 and are presently performing a correlation study. Using this approach, we have refined a lot of our proximal and distal target dissection techniques. Under magnification, we cut back the root until fascicular structure appears and fibrotic tissue is absent; the epineural sheath at this level should be smoothly retractable. With time, and after these improvements in microsurgical neurolysis, we have achieved a good correlation between our "macroscopic view" of the slice and the neuropathologist's appreciation of nerve root quality. Since we want to know if this approach really gives "better" reinnervation results, we asked colleagues to independently study this aspect on the last 65 revision cases.

Conclusion

Reconstructive surgery for OBPP children is challenging and yet rewarding. Each plexus lesion is individual and also needs precise reconstruction. It is rewarding to keep secondary procedures in mind even while exploring the plexus; one should be aware at all times of the particular plasticity of the motor cortex in children, their compensation mechanisms, their changing compliance—and finally the need for a good interaction with physiotherapists in order to assure that our surgical work results in rewarding functional skills.

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