Chapter 14

Summary and Discussion
Key Findings

1) The severity of the nerve lesion increases with birthweight.
2) The natural history has not been appropriately investigated.
3) Spontaneous recovery is not as optimistic as generally assumed.
4) Needle EMG at three months is overly optimistic.
5) Already at one month of age the spontaneous outcome can be reliably estimated with a combination of neurological examination and needle EMG of the biceps.
6) Intra-operative EMG does not improve decision-making.
7) After surgery, recovery of external rotation is only modest when expressed in degrees, but is satisfactory in terms of functional analysis.
8) There is no difference in recovery of external rotation after nerve transfer or nerve grafting.
9) Recovery of hand function is feasible after nerve reconstruction.
10) Recovery of biceps function after nerve transfer is good.
11) End-to-side nerve repair is not a reliable technique.
Summary and Discussion

In this thesis, several topics were studied specifically related to the nerve surgical treatment of Obstetric Brachial Plexus Lesions (OBPL). The ultimate aim of this thesis was to provide a framework for optimization of treatment by analyzing the strengths and weaknesses of the currently applied diagnostic and nerve surgical interventions. This thesis is in part based on a critical analysis of the literature, and in part on prospective and retrospective cohorts. The patient data that were analyzed were collected from the infants with OBPL who were treated in the LUMC. At present, over 1000 infants have been examined at the out-patient clinic almost 500 of whom have been operated. The majority was seen over the period of the last 15 years. Currently, this patient series is one of the largest in the world.

The large LUMC patient series provides the unique opportunity to analyze a relatively rare patient group and by so doing, improve the care for these patients who may suffer throughout their entire life from the nerve lesion that occurred during the first minutes of life.

After admission to the out-patient clinic, the first question that has to be answered is: how severe is the OBPL lesion, and is nerve surgery indicated? This question seems simple and easy to answer. On the contrary, there is at present no equivocal treatment which is widely accepted. More specifically, there is no consensus on how to analyze the severity of the lesion and what the optimal nerve surgical strategies are.

The general outline of this thesis follows the course of the process that the infants with OBPL and their carers experience. What is known about OBPL? (Part 1) What factors might have contributed to the lesion and what can be expected of spontaneous recovery? (Part 2) How severe is the lesion and how can it be assessed? (Part 3) What can we expect from a nerve surgical intervention? (Part 4)

It would be unwise to suggest that answers to all these questions have been provided in this thesis. Many aspects still need to be resolved. In the following discussion, a summary per chapter is provided, relevant aspects are discussed and directives for future research are suggested.

Part 1: Introduction

OBPL is a closed traction injury of a complex peripheral nerve network. Initially, mild and severe lesions present with the same clinical features. Only in time does it become clear whether there will be spontaneous recovery. This can be explained by the axonal degeneration that occurs distal to the lesion site. Restoration of function can only take place when regenerating axons can cross the lesion site and eventually reach the end organ.

Severe lesions without spontaneous recovery have been nerve surgically treated in the early 20th century. Interest faded because of the limited results of those interventions. The improvement of anaesthesia techniques, introduction of the operation microscope and development of fine suture material and equipment led to a renewal of interest around 1980. Currently, it is unlikely that nerve surgical techniques can be
further improved and nerve surgery has become a skill that requires specialized training.

The indication for nerve surgery is decided by different surgeons on the basis of different criteria. None of the discussed studies, however, has a sufficiently strong scientific basis to validate each separate criterion or surgical treatment itself.

**Part 2: Origin of OBPL and natural history**

It is widely, but not equivocally, accepted that OBPL results from traction during delivery. Especially in the obstetric literature, it is stated by some authors that traction forces can act on the brachial plexus during the intrauterine phase. The consequence of this presumption is that it acquits the obstetrician from responsiveness and liability for the nerve lesion.

In Chapter 4, we studied the relation between birthweight and severity of the nerve lesion in a cohort of 206 nerve surgically-treated infants. A strong dose-effect relationship was established between lesion severity and birthweight. Although such a dose-effect relationship seems intuitive, it had not previously been reported in the literature.

A better understanding of the mechanisms that contribute to the traction lesion may lead to greater prevention of obstetric nerve lesions. The most efficacious way of preventing the occurrence of OBPL, is to refrain from vaginal delivery in high risk cases, instead performing a Caesarean section which carries a very low risk of an OBPL. The difficulty is that identification of cases with high risk for shoulder dystocia is extremely difficult. An important predictor for occurrence of an OBPL is birthweight, which is difficult to assess accurately before birth.

Even if macrosomia were reliably predicted antepartum, not all cases of OBPL could be prevented. Had the suggested cutoff point for considering a caesarean section in current obstetric guidelines (5000 g for non-diabetics, 4500 g for diabetics) been applied to our cohort, only 17% of the traction lesions would have been prevented. If the cutoff point is lowered (4500 g for non-diabetics and 4250 g for diabetics), the number of prevented lesions would inevitably increase, but only to 44% in the current patient series. The majority of the OBPLs in our series would not have been prevented, despite a giant increase in the number of caesarean sections.

The main problem is that many macrosomic infants are born following a vaginal delivery without the occurrence of severe shoulder dystocia or with injury-free shoulder dystocia. It was calculated that between 1000 and 10,000 caesarean sections would have to be performed to prevent 1 permanent OBPL. Performing a preventive caesarean section in all macrosomia cases, would lead to increase of caesarean section-related morbidity of the newborn (for instance pulmonary complications), quite apart from complications for the mother. This would result in equivalent perinatal morbidity and mortality. One author referred to this problem as a “Faustian Bargain.”

In other words, preventive caesarean section would not seem to be the correct method for reducing the incidence of OBPL.
The difficulty is that OBPL is a rare lesion (1-3 per 1000 births). Ninety percent of permanent OBPL is associated with shoulder dystocia which in itself is rare (2% of deliveries). This may imply that obstetricians and midwives do not have elaborate experience with management of shoulder dystocia in order to be able to prevent birth nerve lesions. In one historic paper, 30 OBPLs following breech delivery performed by a single midwife were reported, which suggests insufficient technical skill in this particular case. It is inappropriate, however, to conclude that the obstetrician is to blame for the occurrence of all lesions. Two recent developments seem to imply that prevention of OBPL in a proportion of patients may be within reach.

The first development is the decrease the number of infants in breech presentation being delivered vaginally. After a randomized study – the Term Breech Trial – it became clear that the risks for the infant (specifically including brachial plexus lesions) after vaginal delivery exceed those after planned caesarean section. Since then obstetricians have applied more caesarean sections, thus the incidence of breech delivery-related OBPL will decrease. The proportion of OBPLs resulting from breech delivery is, however, small: in our own series around 10% of surgically treated OBPL. The majority of OBPLs result from shoulder dystocia associated vaginal birth with cephalic presentation.

A second preventive measure is to improve the management of shoulder dystocia. Such management may consist of the application of basic actions during the delivery (such as McRoberts’ manoeuvre and suprapubic pressure) or advanced management (internal rotational manoeuvres and delivery of the posterior arm). After extensive training of maternity staff, management of shoulder dystocia in a simulator was shown to improve. Additionally, following this training, the incidence of brachial plexus injury after shoulder dystocia decreased from 7.4% to 2.3% (compared with a pre-training cohort). Such a decrease in incidence of OBPL after shoulder dystocia training was confirmed by a second paper, but not supported by a third. In a similar way, it was shown that introduction of a shoulder dystocia protocol reduced the incidence of brachial plexus in shoulder dystocia-associated deliveries from 10.1% to 2.6%.

An alternative approach to investigating obstetric risk factors was a prospective analysis of a large cohort (40,000) of births. It was found that forceful downward traction had been applied in all cases of permanent brachial plexus palsy. The authors advise that forceful downward traction of the head should be avoided; instead, measures should be taken to relieve the impacted shoulder to prevent OBPL.

The data on factors predisposing for severe lesions may be obtained from large prospective cohort-studies, or alternatively from in-depth analysis of the obstetric antecedents of OBPL patients. Our own study may contribute to the understanding of pathogenesis. Cautious interpretation is, however, warranted given the nature of our analysis, as it is a retrospective analysis of the birth characteristics based on the recall of the parents.
In Chapter 5, a systematic review of the natural history was performed. Four criteria were defined to assess the methodological quality of the available studies: study-design, population, duration of followup, and assessment of end-stage. None of the papers fulfilled more than two inclusion criteria. The first conclusion was that the quality of the 76 included papers was insufficient to provide a proper representation of the spontaneous recovery of OBPL.

Such a poor score could raise the question: were our selected inclusion criteria too ambitious? The criteria were, however, defined by solid arguments and we did not wish to change them after the analysis as this would violate the scientific nature of the prospective study protocol.

In retrospect, the chosen followup criterion of minimally 3 years may have been too strict. As the speed of neurological recovery diminishes with age, one can probably judge with certain reliability at the age of 18 to 24 months whether a complete recovery will occur. Such a post-hoc change of the analysis would, however, not alter the results of our systematic review.

The second conclusion from our systematic review was that from the papers that fulfilled two criteria, the percentage of patients who did not recover completely was between 20% and 30%. This is in contrast to the popular belief in text-books and reviews that 90% of infants show complete spontaneous recovery. The spontaneous recovery may be more pessimistic than generally assumed.

After our systematic review appeared, three quality papers covering the natural history were published; these will be discussed here in more detail.

In the first study, Mollberg and Lagerkvist performed a prospective study of births in a specified region of western Sweden. An incidence of 2.9 / 1000 births was found. Of 118 OBPL children, 98 were followed until 18 months of age. Eighteen of the 98 had residual deficits. Of these, three were nerve surgically treated. Strong characteristics of this study were the prospective nature, the followup of 18 months and the systematic end-stage assessment. Additional findings were 1) that recovery of the biceps at three months of age eventually leads to full recovery, and 2) that severe lesions have a smaller tendency for recovery than upper plexus lesions. These findings are, of course, not new, but as they result from a prospective cohort study, the scientific value of these assumptions is strengthened.

In the second study, the UK paediatric surveillance was used. Paediatricians were asked to report a specific diagnosis on a monthly basis for the period of one year. The reported cases were checked to confirm diagnosis. In this way, 323 cases of OBPL were identified nationwide. After six months, neurological recovery was assessed in 276 cases. By then, half of the infants were reported to show full recovery (n=143), 127 a partial recovery, and 6 no recovery at all. Those infants in whom the initial lesion was severe had the least tendency to recover.

The main strong characteristic of this study was the Nationwide approach. The reported incidence (0.42 per 1000 births) does, however, seem low compared with the study by Mollberg (2.9 per 1000 births). This discrepancy suggests an inclusion bias.
Summary and Discussion

In the UK study, signifying that not all cases of OBPL were registered. The reason for this bias might be that the registration was initiated by paediatricians. It could be that children evaluated by a paediatric physiotherapist or paediatric neurologist were not included. Additionally, the followup protocol was not sufficiently specific, and the followup period was limited to 6 months.

In the third study, DiTaranto et al. report on spontaneous recovery in 91 infants born in a region where nerve surgery was not available as a treatment option. The outlook for infants with a total lesion proved grim; all 16 infants with a total lesion had a completely useless limb after two years of followup. Sixteen of the 79 patients (20%) with a C5-C6(-C7) lesion failed to show substantial recovery at 3 to 6 months, and in this group persistent deformity and functional loss was noted at final followup.

In conclusion, a significant number of papers have been published that address the natural history of OBPL. Unfortunately, the outcome of conservatively treated patients is not clearly depicted in the current literature. The results of surgical treatment, therefore, cannot be related to conservative outcome. The absence of a baseline outcome makes it difficult to assess the value of nerve surgical treatment.

The only solution to the problem would be that additional large cohorts are prospectively studied with sufficiently long followup and proper assessment of the end-stage.

Part 3: Electrophysiological support for prognosis and diagnosis

The capability of EMG to assess the severity and prognosis of OBPL is frequently debated. In comparison with EMG for traumatic brachial plexus lesions in adults, EMG for OBPL is often “too optimistic”. In Chapter 6, a number of limitations of electromyography (EMG) examination in infants with OBPL at a young age and their explanation are discussed. Especially the presence of “inactive” motor unit potentials (MUPs) in needle EMG, defined as action potentials without clinical activity of the muscle, leads to too optimistic an assessment of the nerve lesion. The major factors that account for the discrepancy between an overly optimistic EMG and poor functional recovery are a) a limited number of axons that grow through a neuroma-in-continuity, b) misrouting due to aberrant outgrowth through a neuroma-in-continuity, and c) an aberrant formation of motor programmes in the central nervous system. Additional factors are small muscle fibre size in infants and persistent fetal innervation patterns.

A prospective cohort study was reported in Chapter 7. The goal was to develop an early prediction model in order to facilitate referral and thus timely management of severe OBPL. We found that at one month, needle-EMG of the biceps muscle increases the predictive capacity of a clinical algorithm to identify a severe nerve lesion (neurotmesis or root avulsion) at an early stage. The predictive value of needle EMG disappeared at the age of three months. The pathophysiology of the specific birth lesion plays an
important part in understanding the EMG. Absence of MUPs in the biceps muscle at the age of one month is indicative of severe axonal injury to both the C5 and C6 trajectories to the musculocutaneous muscle.

Considering the traction lesion mechanism which results in OBPL, it might seem logical to predict the outcome of a nerve lesion by assessing the severity of the nerve lesion one spinal nerve level further in a caudal direction. After all, lateral traction to the head with fixed shoulders causes a progression of damage, starting at C5 and involving subsequent roots as traction increases. In view of this cascade of damage, weakness of elbow flexion (mainly innervated by C6) at three months of age does not only indicate C6 involvement, but makes C5 involvement almost inevitable. Likewise, clinical weakness and denervation of the triceps muscle (C7 damage) points to damage to C5 and C6 roots. Somewhat surprisingly, absent elbow flexion at three months was predicted with 100% specificity based on needle EMG of the triceps muscle at one month. The sensitivity is, however, too low to be of use in clinical practice.

Our findings lead to an algorithm (Chapter 7, page 114) which allows identification at as early as one month of age of those infants who will fail to recover biceps function at three months of age. The algorithm consists of three steps. The first step is clinical examination of active elbow extension; if active extension is absent, one should be pessimistic about prognosis, and the infant should be referred to a specialized clinic. If extension against gravity is present, active elbow flexion is investigated. If elbow flexion against gravity is present, prognosis is good. If extension is present, but flexion is not, a needle-EMG of the biceps should be performed. If the EMG does not show action potentials, again the prognosis is pessimistic, and the child should be referred.

All in all, we now have data that provide the primary carer of infants with OBPL with a simple algorithm based on clinical examination and needle EMG of a single muscle, that allows prediction of lesion severity at an early age. This helps to provide parents with information on prognosis, and additionally facilitates timely referral to a specialized centre.

These data were independently validated at the Department of Neurosurgery at the University of Michigan, Ann Arbor.

The predictive value of intra-operative nerve conduction studies was analyzed in Chapter 8. We measured conduction across the neuroma-in-continuity in 95 infants using nerve action potentials (NAPs) and compound motor action potentials (CMAPs). At a group level, the measurements correlate with the severity of the nerve lesion. A valid cutoff point for discriminating severe from mild lesions in the individual patient could not be found.

A weakness of this study was that the severity of the nerve lesion was assessed by the surgeon. On the basis of the peroperative aspect, CT myelographic findings and direct nerve stimulation, the surgeon makes the decision to resect or not resect the lesion. Unfortunately, there is no gold standard for expressing the severity of the nerve lesion. The decision to cut or not to cut is partially based on experience of the surgeon
and assertiveness or reluctance to resect the lesion-in-continuity, but also on the qualitative muscle response on direct stimulation, which is in fact a very basic form of testing of axonal continuity across the lesion. Our conclusions could theoretically be the result of circular reasoning. This is, however, unlikely because neuropathological examination of all resected segments convincingly showed neuroma formation.

Chapter 9 discusses the ideal study design for assessing the predictive values of EMG, NAP en CMAP. In short, a group of patients with a certain neurological deficit should be tested pre-operatively by EMG. Subsequently the brachial plexus should be explored and NAP and CMAP values recorded. Then the wound should be closed without reconstruction of the nerve lesion. The spontaneous recovery of upper limb function in these infants should be followed until the end-stage of recovery, preferably until adulthood. Neurological recovery which may have taken place should then be correlated to the electrophysiological measurements, in order to assess the prognostic value. In addition to the prognostic value of electrophysiological measurements, the prognostic value of clinical examination at a certain age can then be determined. It is unlikely, however, that such a study will be performed.

Part 4: Results of nerve surgery

Surgical nerve reconstruction should only be performed when the outcome of nerve reconstruction is superior to the natural history. As will be discussed in more detail later, a randomized controlled trial has not yet been performed, and is probably unlikely to be performed.

A critical appraisal of one’s own outcome of treatment is indispensable for a number of reasons. First, to evaluate the value of certain surgical techniques or strategies. Second, to set a standard for comparing surgical results to the natural history or to results of others. Third, to inform parents and carers of infants with OBPL realistically. In Chapters 10 to 13, the results of nerve reconstructive surgery were analyzed.

In order to compare our results to those of others, we performed a PubMed search aimed at identifying all series on surgical results in OBPL. (Table 1, page 233)

External rotation

Our review of the papers that study the natural history versus surgical reconstruction (Chapter 3) showed that recovery of external rotation is relatively poor compared with recovery of abduction or elbow flexion. Because the results of elbow flexion recovery are good (more than 90% to 95% good results), it would be difficult to identify factors that determine biceps recovery after nerve reconstruction. The outcome of external rotation is more varied, and so analysis of contributing factors is more likely to have a discriminating capacity.
On the one hand, our surgical results on external rotation (Chapter 10) were disappointing, as only 20% of patients were able to perform true glenohumeral external rotation of more than 20 degrees. On the other hand, in a functional evaluation, these children did very well.

The main research question was whether accessory nerve (XIN) to suprascapular nerve (SSN) transfer (n=21) is superior to nerve grafting from C5 to suprascapular nerve (n=65). The outcome in both groups was similar. Additionally, we found that age at surgery or extent of the lesion had no effect on outcome. A weakness of our study was that the patient characteristics of the two treatment groups proved to be different. In the nerve transfer group the lesion was more extensive than in the nerve grafting group. This is logical, because in more severe lesions with multiple avulsions, proximal nerve stumps are used to restore other functions, and the XIN-SSN transfer is the only option for reviving external rotation.

The only way to overcome this selection bias would be randomization between these two surgical techniques in patients where both techniques are anatomically possible. Such a randomized approach would, however, result in partial denervation of the trapezius muscle in half of the patients allotted to XIN-SSN transfer which may prove disadvantageous. Because of the comparable results in both groups, a randomized trial to compare these two techniques does not seem justified.

In addition, the equivalence of both surgical options has recently been confirmed by Clarke et al. in a larger group of infants (n=177). An interesting strategy to restore external rotation was proposed in two recent papers. In a subcategory of infants with OBPL, spontaneous recovery of elbow flexion occurred, but recovery of shoulder external rotation did not. An accessory to suprascapular nerve transfer was performed while the superior trunk (and other parts of the brachial plexus) was left intact. As a rule, the patients who were surgically treated with isolated XIN-SSN transfer were older than patients in our series: the mean age of surgery was 22 months.

The results of this strategy were reported as promising. The paper by Van Ouderkerk showed that 4 months after surgery 39 (72%) of 44 patients demonstrated an improvement in active external rotation of at least 20 degrees, and that 29 of 30 infants who were followed for two years had external rotation beyond the sagittal plane with the arm in adduction. The results of Schaakxs et al. showed a mean external rotation with the arm in adduction of 30 degrees (n=30).

Certain items concerning this late nerve repair strategy remain to be addressed: 1) the reported remarkable short postoperative interval in which external rotation recovered, 2) the influence of the neurological evaluation method, and 3) possible bias due to splinting or concurrent subscapular release surgery. Further study is required in order to determine whether late XIN-SSN transfer is indeed a valuable technique. It is of particular interest whether this technique is reliable and superior to latissimus dorsi / teres major tendon transfer.
**Hand function**

We analyzed our surgical strategy to reanimate hand function and outcome in 33 patients with a flail arm, the most severe form of OBPL (Chapter 11). Results after three years of followup were investigated in 16 infants. Of these 16 patients, 13 had complete discontinuity of the C7, C8, and T1 spinal nerves. Analysis showed that 69% of these 13 gained a functional assisting hand (defined as Raimondi grade 3 or more). Importantly, the recovery of hand function could be attributed solely to the nerve reconstruction.

The conclusion is that restoration of hand function through nerve reconstruction is feasible in infants with OBPL. These results prove to be substantially superior to those attained in adults with a pan plexopathy. In adults with a severe brachial plexus lesion, the primary goal of nerve surgery is, therefore, different, i.e. restoration of elbow flexion.

Supported by our results we feel that all effort should be made to restore hand function. In infants it is the primary goal of surgery. Our strategy to maximize nerve outflow to the hand is not shared by a few authors, who seem reluctant to cut and reconstruct nerve elements contributing to hand function.22,23

Our study was the first that proved beyond any doubt that functional hand reanimation can be achieved, solely on the basis of nerve reconstruction. Prior to our publication, one study by Haerle and Gilbert reported that useful restoration of hand function can be achieved.24 However, they combined results of nerve surgery and of secondary procedures on muscles and / or tendons. From Gilbert’s study it is not possible to assess the contribution of nerve surgery to the end result. In addition, the condition of complete discontinuity of C7-C8-T1 was not applied in this series. Following our report (Chapter 11), a number of papers addressing the nerve surgical results of hand function restoration were published.22,25-28 (see Table 1, page 233) The surgical strategy applied by the majority of surgeons appears to be similar to ours. They came to the same conclusion, which is that restoration of hand function is feasible and should, if indicated, be given priority over and above other functions.

**Elbow flexion**

We investigated the result of biceps recovery following grafting or transfer in our consecutive series of 416 patients (418 brachial plexus reconstructions) treated between 1990 to 2009 (manuscript in preparation). Biceps recovery of Medical Research Council (MRC) grade 3 or better was achieved in 95.5% of patients.

In Chapter 12 we focussed specifically on nerve transfers for biceps recovery. Nerve transfers are employed in the case that nerve grafting is not a viable option due to the severity of the lesion, specifically the presence of root avulsion.

The results of the two most frequently employed techniques were analyzed: intercostal nerve (ICN) transfer or medial pectoral nerve (MPN) transfer to the musculocutaneous nerve (MCN). We found biceps power MRC 3 or more in 88% of patients. The medial pectoral nerve transfer proved slightly better than the intercostal nerve transfer.
transfer (92% versus 82% reached biceps MRC >= 3) although this was not statistically significant. The indication for the ICN-MCN transfer, however, differs from the indication for a MPN-MCN transfer. A pre-requisite for the application of a MPN-MCN transfer is that preferably spinal nerves C7-T1 are intact, but at least C8-T1 are intact. In the ICN-MCN transfer group, 11 of 17 patients had a global lesion. The only treatment option, therefore, was an extra-plexal-intra-plexal nerve transfer. The difference in results may reflect the fact that in the ICN-MCN transfer group, the more severe lesion types were present; otherwise it might indicate that the pectoral nerve shows intrinsically better potential as donor. Our results compare well to those of others regarding these nerve repairs.29-31

Whether a normal function of C7 is mandatory to obtaining a successful result following nerve transfer of the pectoral nerves is a matter for discussion. The “medial” pectoral nerve does not usually consist of a single nerve, but appears as a plexiform structure of nerve branches, which arise in part from the anterior division of the medial trunk and from the anterior division of the inferior trunk.32 When the spinal nerve C7 is involved in the traction lesion, loss of the C7 axons results in lower axon content of the pectoral nerves. Intraoperative nerve stimulation is, therefore, an indispensable step towards assessing the function of the MPNs. Only when forceful contractions of the pectoral muscle can be elicited on direct stimulation, can the nerve be used for transfer. If contractions are weak, an alternative donor nerve should be favoured.

An alternative transfer technique for biceps muscle reinnervation, which has gained popularity in adult brachial plexus repair is the transfer of an isolated fascicle of the ulnar and/or median nerve to the biceps muscle branch and / or brachialis muscle branch of the musculocutaneous nerve. Although some authors also advocate this transfer for infants33,34, we do not as it carries the potential risk of reducing the growth of the hand due to partial denervation of the median and / or ulnar nerve. Since our current results are satisfactory without this potential risk, we see no reason to alter our strategy.

End-to-side

In Chapter 13 the results of end-to-side transfers in OBPL surgery are presented. The surgeries were performed in the Institut de la Main by Prof. Alain Gilbert, one of the leading pioneers of modern OBPL treatment. End-to-side is an old technique which gained new clinical interest following publication of good results in basic research. The technique involves creating an epineurial window in a healthy nerve. Subsequently, the distal stump of an injured nerve is coapted to this site. It has been claimed that the attached denervated recipient nerve stimulates collateral sprouting of the axons of the intact donor nerve. Sprouts of the intact donor nerve may then grow into the recipient nerve, leading to functional recovery of the recipient nerve without negatively effecting the function of the donor nerve.

Professor Gilbert performed 20 end-to-side repairs in 12 infants. Evaluation of functional recovery of the target muscle was performed after at least 2 years of follow up. Five repairs failed (25%); seven times (35%) good function (MRC >= 3) of the target
muscle occurred, in addition to eight partial recoveries (40%). In the majority of patients, however, the observed recovery could not be exclusively attributed to the end-to-side repair. The reinnervation may have been based on axonal outgrowth through grafted or neurolyzed adjacent nerves. In only two of the twelve patients did it seem likely that recovery was solely based on the end-to-side repair.

A critical evaluation of the current literature on end-to-side transfer is also presented in Chapter 13. This review concludes that true collateral sprouting without axonal damage in the donor nerve is unlikely to occur. It is more likely that the sprouting of axons documented in the experimental studies was caused by intentional or unintentional damage of the donor nerve fascicles.

Both from the literature analysis and the clinical results we conclude that end-to-side nerve repair should not be used in infants with an OBPL.

**Evaluation of outcome**

In order to compare our own results of surgical procedures or surgical strategies to those of others, we performed a PubMed search (Table 1, page 238). A proper comparison could not, however, be performed as the most striking finding was that almost all authors used a different scoring system to evaluate their outcome. Thus, the outcome from different centres could not be pooled and analyzed.

In adults, the MRC-grading of volitional force is often used to express results. This score is, however, dependent on children’s cooperation as it depends on grading muscle force against resistance. An additional drawback is that total failures (M0), near-total failures (M1) and normal function (M5) are rare. Hence, the MRC grading will mostly be M2, M3 or M4. Such a 3-way outcome measure is a small basis for statistical analysis to detect factors that might influence results.

The same limitation accounts for the Mallet-score. It was originally designed as a single score of 1 to 5 to rate shoulder function, but its five different components could be employed for specific research questions. A total failure (Mallet 1) is very unusual, as is normal function (Mallet 5) after nerve repair. This implies that outcomes are usually Mallet 2, 3, and 4, which has limited discriminating capacity. The Mallet score was simplified as the Gilbert shoulder score (ranging from 1 to 6), which includes only two components: abduction and external rotation. This score has not been used often since its introduction.

An alternative approach is to express the results as range of motion instead of force with the advantage that the execution of a motion is easier to assess in children than muscle force (as in the MRC gradation). This method has its own drawbacks. External rotation, for instance, can be assessed in degrees of motion with the arm in adduction or with the arm in abduction. The two methods will produce a different outcome. Because such subtle but important details of the applied evaluation are frequently not reported in papers, it is not possible to compare or pool results from different centres. Another drawback is that the range of active motion also depends on the passive range of motion of the joint. Frequently, the presence of contractures is not reported.
An evaluation system for grading muscle function based on joint motion is the Active Movement Scale (AMS), which expresses motion on a seven-point scale.\textsuperscript{38} Such an approach has the advantage that a 7-point system statistically discriminates better than the 3-way MRC or Mallet gradation. The AMS has been validated by its originators.\textsuperscript{39} The difficulty is that in various papers, joint movements were summated to form a combined limb score, or that means were calculated for motion scores. Such sum scores and means make it difficult to visualize the related clinical picture. This, however, can result from personal lack of experience with the AMS system. Fortunately, the creators overcome this problem themselves by dichotomizing between useful and not-useful function in key papers.\textsuperscript{26}

As a positive exception, the Raimondi Hand Score is used by most authors to evaluate functional outcome of hand function.\textsuperscript{40}

Apart from neurological examination, functional scores were proposed for evaluation of OBPL. The Assisting Hand Assessment (AHA) was designed for children with a unilateral impairment to evaluate how a child makes use of his/her affected hand in bimanual activity performance.\textsuperscript{41} Its use has been validated, but the drawback in the AHA is that scoring is time consuming, as the investigation comprises evaluation of video recordings of various tasks. Thus, it is not applicable in the routine outpatient clinic setting. Such video recording, however, allows for blinding of the investigator for the applied treatment strategy, and also allows scoring by an independent reviewer. Thus it could be a powerful research tool, but there is currently no general consensus or support.

An alternative is the Paediatric Outcomes Data Collection Instrument, which is a patient / parent derived outcome scale based on a 114-item questionnaire, designed to assess global function, as well as upper-extremity function, mobility, physical / sports activity, comfort / pain, and happiness.\textsuperscript{42} Such a patient based outcome measure evaluates the function of the limb in daily life, and not only neurological function during a visit to the clinic. It has been shown to correlate with neurological performance.\textsuperscript{42}

A more recent development is the International Classification of Functioning, Disability and Health (ICF) model, a model that was developed by the World Health Organization. The aim is to provide a universally accepted description of functioning in various health conditions. Currently, ICF Core Sets have been, or are being developed for more than 20 health conditions, including neurological traumas and musculoskeletal diseases like traumatic brain injuries, spinal cord injuries, osteoarthritis and low back pain. The development of an ICF score set for OBPL is currently in progress.

**Justification of nerve surgery for OBPL**

Irrespective of the surgical technique or strategy, the main scientific weakness of OBPL surgery is that quality evidence to support surgical intervention is lacking (Chapter 3). There are some comparative studies that show that surgical reconstruction produces better results than conservative therapy\textsuperscript{43} and is better than neurolysis\textsuperscript{26}. The number of patients in these series is, however, small, and inclusion and selec-
tion bias amplify the difficulties in interpreting results. A randomized trial comparing spontaneous recovery versus nerve surgery has not been performed although some authors do advocate it.44,45

The key approach of modern evidence-based medicine is that depending on the quality of the applied methodology, the level of evidence is determined, which subsequently leads to a specified grade of recommendation. The highest level of evidence (1A) is provided by a systematic review of randomized trials.46 Especially in surgical disciplines, however, difficulties in randomized controlled trials were outlined: equipoise (both patients and surgeons), bias (selection and observer), blinding, learning curve, effectiveness versus efficacy and standardization of technique.47

In the absence of level 1A evidence, a systematic review of homogeneous cohort studies (resulting in level 2A evidence) forms an acceptable alternative.46 The current OBPL literature consists mostly of case series and poor quality cohort and poor quality case control studies (level 4 evidence).

Although OBPL nerve repair has not been investigated in a randomized fashion compared with natural recovery, two important arguments support there being a place for surgical therapy in selected cases. The first justification of nerve surgery is formed by the poor outcome of spontaneous recovery in a certain percentage of patients; the second is the unique nature of the nerve lesion in each individual OBPL infant that justifies surgical exploration as a diagnostic step. These two arguments may interfere with the condition of equipoise which is mandatory for conducting a multicentre randomized trial to compare the spontaneous outcome with surgical results.

**Poor outcome after spontaneous recovery**

A number of observations have documented poor outcome after spontaneous recovery.

1) Around 30% of infants with OBPL do not show complete spontaneous recovery (Chapter 5); this has a permanent impact on daily life.

2) For infants with a total lesion, without any functional recovery at one to two months (frequently accompanied by Horner’s syndrome), the prospect is poor. Both in historical papers (see Chapter 2), as in a more recent paper, it is concluded that spontaneous recovery of useful hand function does not occur.

3) Autopsies and surgical exploration revealed totally ruptured nerves and nerves avulsed from the spinal cord. Such findings of complete discontinuity of the peripheral nerve exclude any spontaneous recovery.

4) After neurolysis, which is in fact an exploration of the nerve without a structural repair, some recovery may take place. This is, in fact, spontaneous recovery and this recovery cannot be attributed to the surgical intervention. A useful function, however, was not achieved especially in children with a total lesion.26

In severe lesions, with avulsions and ruptures, the neurological prognosis without treatment is very poor. This justifies intervention to improve prognosis. Nerve recon-
struction was shown to lead to neurological recovery even for hand function.\textsuperscript{24-26,49} For most physicians caring for infants with OBPL, a severe lesion with a diminished hand function without speedy recovery is a strong indication for surgical intervention. It is common for such severe lesions to consist of root avulsions at one or more levels. This subgroup of patients only contains, however, about 15\% of patients.

The most difficult group for assessing indication for surgery, are those patients who present with a C5-C6 or C5-C6-partial C7 lesion. Decision-making in this patient group was poetically called “the gray zone”.\textsuperscript{50} The anatomical substrate of these OB-PLs is usually a neuroma-in-continuity of the superior trunk. In such lesions, the fibrotic lesion site serves as a bridge for impaired, disorganized axonal outgrowth. Depending on the anatomical integrity of the different parts of the nerve elements involved, varying grades of recovery may take place. This may lead to axonal continuity in some way between de proximal and distal stump, which was demonstrated by electrical conduction studies (Chapter 8)\textsuperscript{51,52} and by histological investigation\textsuperscript{53} of the neuroma. However, the extent to which this partial axonal continuity leads to clinical recovery at the end-stage is not known. A gold standard for documenting spontaneous recovery of such lesions for use as comparison with surgical results is not available, and probably cannot be established (Chapter 9).\textsuperscript{54}

An alternative to nerve surgical treatment of OBPL is to await the degree of natural neurological recovery, and treat residual deficits with muscle / tendon transfers, rotation osteotomy or joint fusion. For many decades, before the revival of nerve reconstruction, this was the treatment approach of choice (Chapter 2). This strategy has two limitations. First, a functioning muscle must be available for transfer. If the initial nerve lesion consists of a flail arm, no functioning muscle is available to restore hand function. Thus, only upper trunk lesions are suitable for this approach. Second, secondary surgery can be employed as an additional procedure should neurological recovery be incomplete after nerve reconstruction. Performing nerve reconstruction after a failed muscle transfer is not possible.

Moreover, it does not seem logical to leave a nerve lesion which is repairable in place, to wait for recovery that is not likely to occur, and to perform an orthopaedic salvage procedure at a later stage. Furthermore, during the time spent waiting for spontaneous recovery, reversible or irreversible changes in the end organ will occur, for instance dysplasia of the shoulder joint, or impaired development of cerebral motor control over the affected limb.\textsuperscript{55,56}

\textbf{The unique nature of each nerve lesion}

The main difficulty with OBPL is that the specific extent and severity of the nerve lesion – as it is a closed traction injury – cannot be determined without invasive techniques. At the present time, non-invasive electrophysiological or radiological ancillary investigations are inadequate to diagnose lesion severity in each affected nerve. Three observations illustrate the fact that each OBPL lesion has unique features, and
Summary and Discussion

that the indication for surgical exploration is difficult to dichotomize. They also support surgical exploration being considered as an additional diagnostic step in the assessment of the nerve lesion. Of course, such a surgical exploration should be reserved for those infants in whom there is a high probability of encountering a severe lesion which necessitates nerve reconstruction. In only a minority of the LUMC patient cohort, did nerve reconstruction appear not to be indicated, and the procedure was limited to neurolysis.

1) Root avulsions are not uncommon
In closed traction lesions such as OBPL, the clinical picture is identical for post-ganglionic lesions (i.e., neuroma-in-continuity) and pre-ganglionic lesions (i.e., root avulsion). In the case of root avulsion, it is evident that longer conservative management will not likely result in functional recovery. Root avulsions are not uncommon: for infants selected for surgery with the least extensive injury (neurological deficit of C5 and C6 only), we found root avulsions on CT myelography in 11 of 26 infants. This high incidence of root avulsions justifies ancillary investigation or surgical exploration in infants without spontaneous recovery after 3 to 4 months.

2) Spinal nerves C5 and C6 may not show equally severe damage
A common surgical finding in C5-C6 lesions is a neuroma-in-continuity of the upper trunk, where spinal nerves C5 and C6 are equally damaged. In some cases, however, the lesion only consisted of a neuroma of the C5 contribution to the upper trunk while the C6 contribution was largely intact, or vice versa. In such cases, only the affected spinal nerve was repaired, leaving the other nerve intact.

In other cases, both C5 and C6 seemed to be equally involved on the proximal side of the lesion, but direct stimulation of the distal target nerves (suprascapular nerve, anterior and posterior divisions) resulted in different muscle responses. Occasionally shoulder movements could be produced, but biceps contraction could not. This indicates that axonal continuity to infraspinatus and deltoid muscle had recovered spontaneously, but biceps re-innervation had failed. In such cases a selective nerve transfer was performed to re-innervate biceps muscle, leaving the pathways to shoulder function intact (Chapter 12). In a comparable way, we have performed early isolated transfer to the suprascapular nerve, when spontaneous re-innervation of the biceps had taken place.

3) Trick movements can mimic spontaneous recovery
Exact assessment of muscle function in babies is difficult, because movements or muscle contractions cannot be performed on command. The clinical absence of biceps function is often used as an indicator for surgery because it signals absence of recovery of the spinal nerve C6. Occasionally, however, babies can flex the elbow without activating the biceps muscle. The movement is then executed mainly by the wrist extensors; this is referred to as Steindler-effect. As the extensor carpi radialis muscle spans both the elbow joint and the wrist joint, it produces movement in both joints.
The main difference in the two movements is the absence of supination. Such a compensatory movement can result in the impression of C6 recovery, while the movement is executed by C7 or C8 innervated muscles.

In a number of cases, surgery was performed despite the presence of elbow flexion judged on the basis of the Steindler-effect. During surgery the C5 and C6 neuromatous tissue was resected, and the gap reconstructed with nerve grafts. Two months after surgery, the infants were neurologically investigated. The preoperative compensatory elbow flexion based on Steindler effect was unchanged postoperatively. The short time-span between surgery and evaluation precludes that the movements result from reinnervation based on the nerve reconstruction. This observation confirms that the pre-operative elbow flexion was indeed a “trick” movement, and that the neuroma-in-continuity did not contribute to neurological function.

The unique nature of each OBPL lesion supports the decision for exploratory surgery as an extra diagnostic step in selected cases. They also illustrate that the unique features of each nerve lesion and the described tailor-made surgical solutions make it difficult to randomize patients, and to compare results from different institutions.

**Equipoise**

In order to perform randomization, the ethics of clinical research require equipoise, a state of genuine uncertainty on the part of the clinical investigator regarding the comparative therapeutic merits of each arm in the trial. 59

The absence of presence of uncertainty on the part of all participants may interfere with the enrolment of patients in a clinical trial, and therefore the concept of “clinical equipoise” was introduced. This was defined as “genuine uncertainty within the expert medical community – not necessarily on the part of the individual investigator – about the preferred treatment”. 59 Whether clinical equipoise or uncertainty of all individual participants is the moral underpinning of the randomised controlled trial, is still a matter of debate. 60

The main obstacle to a randomized study on conservative versus surgical treatment of OBPL is equipoise between the two treatment arms judged by the participating physicians. By now, individual surgeons have surgically treated many OBPL patients. They have surgically encountered neuroma tissue or root avulsions. Surgeons conclude that spontaneous recovery from such severe lesions cannot be expected. Nerve reconstruction was frequently performed in such cases, and the good results convinced these surgeons even more about the correct choice of the applied therapy.

On the other hand, different surgeons may have performed nerve reconstruction without much success, or seen profitable results from an expectant attitude.

Thus the surgeon develops either a more assertive or a more reluctant attitude. It is not known which percentage of OBPL patients eventually undergoes surgery, nor if this percentage varies between hospitals, regions or countries.

Furthermore, non-surgical physicians might be reluctant to refer their patient to a surgeon, not being convinced of the merits of nerve reconstruction, and subsequently see some extent of spontaneous recovery in their patients. The condition of “clinical
Summary and Discussion

equipoise” may also depend on what is considered as the expert medical community. We suppose that within the surgical OBPL community there is general acceptance of nerve surgery, while in a non-surgical community a more reluctant attitude is upheld. This might be due to referral bias in their personal medical practice: surgeons probably only encounter a selection of severely injured infants, while non-surgical physicians may see many patients with spontaneous recovery.

The assertive or reluctant attitude of the treating physicians interferes with the condition of equipoise. The surgeon may believe that he or she is performing surgery that may not help the patient, or that he or she is withholding surgery that may help. Randomization is not possible.

Timing of nerve surgery

Basic research has convincingly shown that a delay between nerve lesion and repair diminishes the functional result. Over the past years, the outcome benefits of early repair in adult brachial plexus lesions have been advocated. There is no good reason to assume that timing of surgery is not a significant factor in OBPL. In Chapter 4, we could not show this in our own series. Other authors, however, report a better recovery when nerve repair is performed early.

An early intervention implies performing nerve surgery at around three months of age. Gilbert uses absent biceps function at three months of age as an indication for surgery. Other authors advise waiting longer, as sufficient spontaneous recovery may still occur after this point in time. As the speed of neurological spontaneous recovery diminishes with time, most authors do not advise waiting for longer than 6 months.

The optimal timing of surgery probably lies between three and six months. If an early moment is chosen, the surgical findings could reveal a mild / axonotmetic lesion with expectation of spontaneous recovery. Surgical reconstruction is then not indicated. If a later moment is chosen, denervation time is longer for those infants who need repair, and this has a negative effect on the outcome of nerve surgery. Both strategies have their own errors.

In the LUMC strategy our aim is that if there is an error, it will consist of failing to find neurotmesis or avulsion during surgery rather than letting such lesions go unoperated or delaying surgical reconstruction. If the quality of shoulder and elbow joint movements is doubtful, surgical exploration is advised.

Future directions

A number of directions can be outlined for further research to improve the outcome of infants with an OBPL.
1) **Prevention of the lesion**

Two measures which potentially reduce the incidence of OBPL have already been discussed. These are to abstain from vaginal delivery in breech presentations, and better education to improve management of shoulder dystocia. Another challenge in obstetric research would be reliable identification of high-risk cases, both ante-partum and during delivery.

2) **Early referral**

Prognosis for the majority of infants with OBPL is good; for these infants specialized therapy is not indicated. The remaining 20% to 30% of infants are at risk for life-long limitations, and an active treatment attitude is warranted, which usually implies referral to a specialized centre. The difficulty is to identify at an early age those patients who are at risk for incomplete recovery. The algorithm that we describe in Chapter 7 is a first step that can aid primary and secondary care physicians to refer patients at an early stage. The implementation of a widely recognized algorithm that can be used in the routine care of these infants would be a major step forward. In our opinion, the Leiden three item test could be used as a first step to reach this goal. The development of an additional test which can be uniformly used in specialized centres to determine who should be operated, and when, is a major challenge for the future. In any case, when severe lesions are detected early, nerve surgical therapy can be applied without delay. The effect of early surgery should be analysed.

3) **Improvement of diagnostics**

If non-invasive diagnostic techniques could be improved, surgical exploration as a diagnostic step would not be necessary. Additionally, if the diagnosis of a severe nerve lesion could be made at an earlier age, the resulting shorter delay between lesion occurrence and nerve repair might improve results.

a) **Improvement of imaging**

From the nineteen-eighties onwards, patients with brachial plexus lesions have been tested on the occurrence of root avulsions by myelography, and later CT-myelography. CT-myelography is, in our opinion, still the gold standard. With improvements in MRI-scanning technique, it is probable that, in the near future, this will be as reliable in detecting root avulsions as CT. Another target would be imaging of the architecture of the neuroma itself, using MR-neurography, or MR-fibre tracking. Alternatively, imaging of the motorneurone pool in the spinal cord might reveal additional information. Pre-operative and intra-operative ultrasound might be helpful for structural images of the peripheral nerve lesion.

b) **Improvements in electrodiagnostic studies**

In this thesis we have discussed extensively the use of needle EMG and the application of intra-operative nerve conduction studies. (Chapters 6 to 8) In our view it will be difficult to improve the diagnostic value of these two modalities due to the patho-
physiology of OBPL. Intra-operative SSEPs and MEPs have been applied to assist the intraoperative diagnosis of root avulsions, but these two measures probably do not increase the diagnostic algorithm of a good quality CT-myelography. Transcranial magnetic stimulation is difficult in young children, but this might be a challenge for further research.

c) Histological examination
Currently we use frozen sections to examine myelin content of the proximal stump to assess its suitability as a graft lead-out. Additionally, it is employed to assess the presence of neuroma tissue in the proximal and distal stumps and to indicate whether further resection is necessary to provide undamaged intraneural architecture of the proximal and distal stumps. A per-operative objective automated quantitative axon count could help in the choice of an appropriate outlet for nerve grafts. Additionally, more uniform quantification could aid in the comparison of results between centres.

4) Different targets of therapy

a) Improvement of nerve regeneration
At present, experimental work is being performed aimed at improving nerve outgrowth using gene therapy. Development and design of artificial nerve grafts has been a subject of continuous research for many years. Hopefully this will eventually result in a clinical application. Alternatively, electrical stimulation has shown a beneficial effect on nerve regeneration in carpal tunnel syndrome. The application of electrical stimulation after nerve repair should be subject to further investigation.

b) Study of bony deformities
An experimental model has been developed which mimics the effects of denervation of shoulder muscles on the gleno-humeral joint. This might lead to therapeutic approaches for a better functional outcome.

d) Botulin toxin therapy
Especially in the treatment of contractures and co-contractions, botulinum toxin was embraced by many physicians, however, without proper evaluation of its effect or indications.

e) Improvement of central control
It was postulated that functional impairment after brachial plexus lesions is in part due to defective motor programming in early infancy, which was called developmental apraxia. Extensive training focussed on cortical plastic rewiring has not been studied in OBPL, but might be an interesting research topic.
5) Optimization of currently available surgical techniques

As this thesis is written from a nerve surgeon’s perspective it is logical that this direction will be discussed in more detail. The recommendations discussed for nerve reconstructive surgery may similarly apply to secondary orthopaedic operations.

It is essential that infants with OBPL are treated by a team, involving nerve surgeons, orthopaedic surgeons, paediatric physiotherapists, rehabilitation specialists, and occupational therapists. In the past twenty years, such a team was formed at the LUMC. The patients are assessed in a weekly scheduled multidisciplinary outpatient clinic.

The primary aim of refining surgical techniques or surgical strategies should be improvement of patient outcome. Surgical studies with good methodological quality are needed to achieve this goal.

OBPL is a relatively rare condition and it is, therefore, mandatory that centres work together to develop treatment strategies. Because meetings and congresses usually have a relatively small number of participants, an open unrestricted dialogue is possible. A first important step would be to express and report surgical results in a uniform way. Although such initiatives have been expressed by various surgeons at many meetings, practice has unfortunately not changed. It is of paramount importance that a generally accepted classification of results is agreed upon, preferably combining neurological outcome with patient-derived outcome scales.

Only after uniform evaluation modalities have been agreed upon, a next step is possible, which is pooling of data and comparison of different treatment options among participating centres. This would imply a certain willingness to share data. Preferably prospective data should be collected.

A third step would be to perform multicentre, randomized studies. The difficulties in setting up such studies have been discussed. Probably only a small proportion of clinical dilemmas is suitable for a randomized trial. The use of distal nerve transfers, for instance, instead of repair of the proximally located nerve lesion has become very popular in adult brachial plexus surgery. It is open to discussion whether this should also be introduced in obstetric lesions, because proximal repair of nerve lesions seems to yield superior results in infants than in adults. A subject of further study could be to compare pectoral nerve transfer to ulnar/median fascicular nerve transfer for biceps reanimation and to improve results of external rotation. In cases where spontaneous recovery of biceps function occurs, but failure of recovery of external rotation, a study could be performed to compare early muscle transfer to delayed neurotisation of the suprascapular nerve using an accessory nerve transfer.

The difficulty is that many surgeons have already devised a management strategy for certain clinical dilemmas, and must be willing and able to perform another surgical procedure than the one they are accustomed to. An important topic would be to compare reluctant and assertive attitudes concerning timing of surgery, i.e. a comparison of whether selection for surgery should take place at three months or six months of age. Such a study was initiated, but re-
Results have not been published or presented yet. Depending on the results of these data, participants (and non-participants) might be encouraged to join a randomized trial between these two strategies. The question remains whether the aforementioned difficulties can be solved: equipoise for patients, equipoise for surgeons, standardization of surgical technique, inclusion bias, and standardization of evaluation. We fear this is not likely, although this should be the ultimate goal. Such an analysis would not only lead to an advance of evidence level, but also to an improvement in care of infants with OBPL.

Assuming it is unlikely that international multicentre studies will be performed in the near future, regional or national collaboration could be a starting point. Such partnership may be less affected by patient and doctor attitude which facilitates collaboration.

Hopefully, with uniform evaluation and cooperation between centres, the better scientific quality of evidence will ultimately improve the nerve surgical treatment strategy for infants with OBPL.
Table 1: PubMed search for all surgical series

<table>
<thead>
<tr>
<th>1st author</th>
<th>year</th>
<th>technique</th>
<th>n</th>
<th>evaluation</th>
<th>outcome*</th>
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<tr>
<td>shoulder</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Gilbert</td>
<td>1991</td>
<td>Mallet</td>
<td>241</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Mallet 3/4/5 (C5-C6 lesions) 80/96; Mallet 3/4/5 (C5-C6-C7 lesions) 61/81; Mallet 3/4 (total lesions) 41/64</td>
<td></td>
</tr>
<tr>
<td>Birch</td>
<td>2005</td>
<td>Mallet (sum-score)</td>
<td>87</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>Mallet &gt;=13: 29/87; Mallet 11/12: 42/87; Mallet &lt;= 10: 16/87</td>
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<tr>
<td>Terzis</td>
<td>2008</td>
<td>degrees</td>
<td>67</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>30 patients: mean abduction 127°, mean external rotation 62°; 37 patients required additional shoulder surgery</td>
<td></td>
</tr>
<tr>
<td>Lin</td>
<td>2009</td>
<td>Erb palsy: grafting</td>
<td>48 vs. neurolysis 8</td>
<td>56</td>
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<td>Berger</td>
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<td>Mallet</td>
<td>51</td>
<td></td>
<td></td>
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<td></td>
<td>Mallet 1-2-3-4-5 (C5-C6 lesions): 0-1-2-3 resp.; (C5-C7 lesions): 0-0-8-10-1; (total lesions): 2-0-4-0-0</td>
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<td>modified Mallet</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>6 good / 17 fair / 3 poor</td>
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<td>18</td>
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<td></td>
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<td>clinical improvement: [reconstruction] 15/16; no improvement [no reconstruction of apparently normal nerve]: 2/2</td>
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<td>Mallet</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>abduction grade 4: 3; abduction grade 3: 3; external rotation grade 3: 4; external rotation grade 2: 2</td>
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<td>Grossman</td>
<td>2004</td>
<td>combined with bypass grafting to the SSN (7/11) or XIN-SAN transfer (1/11)</td>
<td>11</td>
<td>modified Gilbert shoulder score</td>
<td>grade 5: 6/11; grade 4: 4/11; grade 3: 1/11</td>
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<td>Pondaag</td>
<td>2005</td>
<td>external rotation after SSN grafting (65) vs. transfer (21)</td>
<td>86</td>
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<td>degrees, Mallet</td>
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<td>van Ouwkerk</td>
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<td>SAN-SSN transfer</td>
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<td>56</td>
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<td>deltoid &gt;= MRC3+; 49/56; Mallet abduction grade 4: 37; mean abduction 109°; 34 had secondary surgery</td>
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<td>Tse</td>
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<td>external rotation after SSN grafting (106) vs. transfer (71)</td>
<td>177</td>
<td>AMS</td>
<td>mean AMS for external rotation: [grafting] 2.2 vs. [transfer] 3.0; no difference grafting or transfer</td>
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## Summary and Discussion

<table>
<thead>
<tr>
<th>1st author</th>
<th>year</th>
<th>technique</th>
<th>n</th>
<th>evaluation</th>
<th>outcome*</th>
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<tr>
<td><strong>shoulder &amp; elbow flexion</strong></td>
<td></td>
<td></td>
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<td>Laurent</td>
<td>1994</td>
<td></td>
<td>50</td>
<td>MRC</td>
<td>deltoid &gt;= M3: 86%; biceps &gt;= M3: 95%; (upper palsy only)</td>
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<td>El-Gammal</td>
<td>2010</td>
<td>total palsy: proximal function</td>
<td>35</td>
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<td>28</td>
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<td>20</td>
<td>MRC</td>
<td>good recovery (MRC 4 or 5): deltoid 80%, biceps 55%, external rotation 25%</td>
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<td>13</td>
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<td>Xu</td>
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<td>Kawabata</td>
<td>2001</td>
<td>ICN-MCN</td>
<td>31</td>
<td>MRC</td>
<td>MRC 4: 26/31; MRC 3: 3/31; MRC 2: 2/3</td>
</tr>
<tr>
<td>El-Gammal</td>
<td>2008</td>
<td>ICN transfer to various targets</td>
<td>46</td>
<td>AMS</td>
<td>elbow flexion AMS 6 or 7: 29/31</td>
</tr>
<tr>
<td>Terzis</td>
<td>2009</td>
<td>elbow flexion after grafting or various transfers</td>
<td>54</td>
<td>MRC, degrees</td>
<td>M4 to M5: 27; M3+ or M4: 15; M2+ or M3: 10; &lt;=M2: 2; average flexion 108°</td>
</tr>
<tr>
<td>Noaman</td>
<td>2004</td>
<td>ulnar-MCN transfer</td>
<td>7</td>
<td>MRC</td>
<td>biceps M5: 2/7; MRC 4: 2/7; MRC 3: 1/3; MRC 2: 2/7</td>
</tr>
<tr>
<td>Al-Qattan</td>
<td>2002</td>
<td>ulnar-MCN transfer</td>
<td>2</td>
<td>MRC / AMS</td>
<td>MRC 5/5: 2/2; AMS 7/5: 2/2</td>
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<tr>
<td>Blaauw</td>
<td>2006</td>
<td>hypoglossal nerve transfer</td>
<td>6</td>
<td>MRC</td>
<td>MRC &gt;= 3: 4/6; serious co-contractions tongue-arm</td>
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<tr>
<td>Kawano</td>
<td>2007</td>
<td>delayed ICN-MCN transfer</td>
<td>3</td>
<td>MRC</td>
<td>MRC &gt;3: 3/3</td>
</tr>
<tr>
<td><strong>hand</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Haerle</td>
<td>2004</td>
<td>27/73 had also secondary surgery to the hand</td>
<td>73</td>
<td>Raimondi</td>
<td>Raimondi 2: 16; Raimondi 3: 24; Raimondi 4: 16; Raimondi 5: 16</td>
</tr>
<tr>
<td>Gilbert</td>
<td>1991</td>
<td></td>
<td>64</td>
<td></td>
<td>useful hand function 19/64</td>
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</table>
### Table 1 – continued

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Year</th>
<th>Technique</th>
<th>n</th>
<th>Evaluation</th>
<th>Outcome*</th>
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</thead>
<tbody>
<tr>
<td>Lin</td>
<td>2009</td>
<td>total palsy: grafting 44 versus neurolysis 8</td>
<td>52</td>
<td>AMS</td>
<td>AMS 6 or 7 for abduction: [neurolysis] 1/8 vs. [grafting] 9/44; AMS 6 or 7 for flexion: [neurolysis] 2/8 vs. [grafting] 10/44; AMS 6 or 7 for finger flexion [neurolysis] 5/8 vs. [grafting] 40/44</td>
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<tr>
<td>Birch</td>
<td>2005</td>
<td>47</td>
<td>Raimondi</td>
<td>Raimondi 4 or 5: 27/47; Raimondi 3: 17/47; Raimondi &lt;= 2: 3/47</td>
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<tr>
<td>El-Gammal</td>
<td>2010</td>
<td>total palsy: hand function</td>
<td>35</td>
<td>AMS, Raimondi</td>
<td>AMS 6 or 7 finger flexion: 61%; Raimondi 3 or better: 18/35; finger extension 46%</td>
</tr>
<tr>
<td>Kirjavainen</td>
<td>2008</td>
<td>all patients</td>
<td>105</td>
<td>Raimondi</td>
<td>mean score: (C5-6 lesions) 4.57; (C5-7 lesion): 4.26; (total lesions): 2.16</td>
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<tr>
<td>Kirjavainen</td>
<td>2008</td>
<td>patients with total palsy</td>
<td>25</td>
<td>Raimondi</td>
<td>Raimondi 3 or 4: 11.</td>
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<tr>
<td>Dumont</td>
<td>2001</td>
<td>20</td>
<td>AMS</td>
<td>useful shoulder function: (total palsy) 4/20; useful hand: (if pre-operative hand function was absent) none</td>
<td></td>
</tr>
<tr>
<td>Pondaag</td>
<td>2006</td>
<td>13</td>
<td>Raimondi</td>
<td>Raimondi &gt;= 3: 9/13</td>
<td></td>
</tr>
<tr>
<td>Berger</td>
<td>1997</td>
<td>6</td>
<td>Raimondi</td>
<td>Raimondi 1-2-3-4-5: 3-1-2-0-0 resp.</td>
<td></td>
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<tr>
<td>various</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>good or excellent: 89%</td>
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<tr>
<td>Ashley</td>
<td>2007</td>
<td>global results</td>
<td>63</td>
<td>Motor Score Composite (mean of MRC-scores)</td>
<td>IR5: 0%, IR4: 17%, IR3: 61%, IR2: 22%, IR1: 0%</td>
</tr>
<tr>
<td>Badr</td>
<td>2009</td>
<td>global results</td>
<td>16</td>
<td>impairment rating: 1 (flail) - 5 (normal)</td>
<td>IR5: 0%, IR4: 17%, IR3: 61%, IR2: 22%, IR1: 0%</td>
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<tr>
<td>Chen</td>
<td>2007</td>
<td>contralateral C7 to MCN / median nerve / radial nerve</td>
<td>7</td>
<td>MRC</td>
<td>substantial synchronous motion of donor limb 3/7; biceps M4: 3/4; wrist and finger flexion M3 or M4: 3/7; triceps and wrist extensors M4: 1/1</td>
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<tr>
<td>Pondaag</td>
<td>2008</td>
<td>various end to side repairs</td>
<td>20</td>
<td>MRC</td>
<td>good recovery: 7/20; failure: 5/20</td>
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<tr>
<td>Terzis</td>
<td>2010</td>
<td>triceps after grafting or transfer</td>
<td>55</td>
<td>MRC</td>
<td>M4 to M5-: 20; M3+ or M4-: 17; M2+ or M3-: 2; &lt;=M2-: 6</td>
</tr>
</tbody>
</table>


In case surgeons or groups present their patient-series in different papers, only one of these papers is mentioned in this table.

* outcome is presented as number of patients (n) or percentage (%): outcome1: n1; outcome2: n2 or outcome (group1): n1; (group2): n2 or outcome [technique1]: n1 vs. [technique2]: n2
Summary and Discussion


Fu SY, Gordon T. Contributing factors to poor functional recovery after delayed nerve


93 Al-Qattan MM. The outcome of Erb’s palsy when the decision to operate is made at 4 months of age. Plast Reconstr Surg 2000 December;106(7):1461-5.


