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FOLLOW-UP STUDIES OF THE OBSTETRICAL BRACHIAL PLEXUS INJURY

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Stockholm 2006

Cover: Pictures made by Kerstin Westerberg

Published and printed by Karolinska University Press
Box 200, SE-171 77 Stockholm, Sweden

ISBN 91-7140-912-2

”Medan handen arbetar vidgas blicken”
Aristoteles tolkad av Anders Ehnmark
i novellen ”Morfars yxa”

To all the children and adolescents with OBPP
and their parents,
and to my dear family Anders, Albin and Josefin.

ABSTRACT

Aims: The overall aims of these studies were to investigate the influence of different kinds of treatment of the brachial plexus lesion, and to study functioning and participation in adolescents with OBPP.

Methods: Study I involved 247 children with obstetrical brachial plexus palsy (OBPP) of different severity, some of whom had been operated on, with nerve reconstruction being carried out during the first year of life, and with others not having been operated on. All participants were examined at five years of age using a protocol to evaluate the motor and sensory function including range of motion, grip strength, dexterity, tactile sensibility, hand preference and bimanual activity. In Studies III and IV, 59 adolescents were clinically assessed according to the protocol used in Study I, and the results were compared. In Study II, 51 adolescents who had participated in Study I and 116 age-matched adolescents answered a questionnaire concerning their daily life, school performance and friendships.

Results: The overall shoulder activity was better in the nerve-reconstructed group than in the non-operated group at 5 years of age. The groups had not been randomised and were not completely comparable, but the difference was significant and indicates a better range of shoulder motion after nerve reconstruction. The time of the operation, whether it took place before or after 6 months of age, did not influence the result.

A decrease in grip strength and bimanual function was found in children/adolescents with C5-6 lesions. Sixty-eight percent of the children/adolescents with right-sided OBPP were left-handed. Children with complete OBPP had a more severe disability with impact on grip strength, dexterity and sensibility as well as on some ADL functions.

In the long time follow-up, Study III, we found that active joint motion in the shoulder and hand function, especially grip strength, generally remained unchanged or improved somewhat, whereas a slight but significant deterioration occurred in the elbow function. Shoulder surgery resulted in considerable improvement of the shoulder function. Children/adolescents who had undergone nerve reconstruction had a similar profile of change as the non-operated group.

We could not find any relationship between differences in the ROM and participation in sports, even if some of the adolescents who participated extensively in sports at a competitive level had improved both their shoulder and arm function without having an operation.

Considerable EMG changes in the deltoid can be seen in OBPP, even in those who had recovered fully, and the changes deteriorate with time.

The sensibility is considerably less affected than motor function in young people with OBPP.

The majority of the children/adolescents (75 %) did not perceive that they had any problems at all as far as ADL were concerned. This applied to 85 % of the participants with C5-6 involvement and 70 % of them in the C5-7 group.

Adolescents with OBPP, in our society, report that they live a typical teenage life. However, indications of distress and worry related to the disability should not be overlooked.

LIST OF PUBLICATIONS

I. **Strömbeck C**, Krumlinde-Sundholm L & Forssberg H. (2000) Functional outcome at 5 years in children with obstetrical brachial plexus palsy with and without microsurgical reconstruction. *Developmental Medicine &Child Neurology* 42:148-157

II. **Strömbeck C**, Fernell E. Aspects on activities and participation related to body structure and function in adolescents with obstetrical brachial plexus palsy: a descriptive follow-up study. *Acta Paediatrica* (2003) 92:740-746

III. **Strömbeck C**, Krumlinde-Sundholm L, Remahl S & Sejersen T. Long-term functional follow-up of a cohort of children with obstetrical brachial plexus palsy; I. Functional aspects. Accepted for publication in *Developmental Medicine &Child Neurology*

IV. **Strömbeck C**, Remahl S, Krumlinde-Sundholm L, & Sejersen T. Long-term functional follow-up of a cohort of children with obstetrical brachial plexus palsy; II. Neurophysiological aspects. Accepted for publication in *Developmental Medicine &Child Neurology*

CONTENTS

LIST OF ABBREVIATIONS

2PD	Two-point discrimination
ADL	Activity in daily life
AHA	Assisting hand assessment
AMS	Active movement scale
C5-8	Cervical segmental levels 5-8
CMAP	Compund muscle action potential
CT	Computer tomography
EMG	Electromyography
ENeG	Electroneurography
ICF	International classification of functioning
MCV	Motor conduction velocity
MRI	Magnetic resonance imaging
MUAP	Motor unit action potential
NAP	Nerve action potential
OBPI	Obstetrical brachial plexus injury
OBPP	Obstetrical brachial plexus palsy
PEDI	Paediatric Evaluation of Disability Invetory
qEMG	Quantitative electromyography
QST	Quantitative sensory test
ROM	Range of motion
SD	Standard deviations
SEP	Sensory evoked potential
SNAP	Sensory nerve action potential
Th1	Thoracal segmental level
WHO	World Health Organisation

1 OBSTETRIC BRACHIAL PLEXUS INJURY

1.1 ANATOMY

The brachial plexus is formed by the five spinal nerves C5, C6, C7, C8 and Th1, forming three trunks, the upper (C5-6), the middle (C7) and the lower trunk (C8-Th1). These nerves are combined to form the terminal nerves, the axillary, musculucutaneus, radial, median and ulnar nerves. An obstetrical brachial plexus injury (OBPI) is caused by traction of the nerves during delivery, mostly caused by complications like shoulder dystocia or instrumental delivery(1, 2). In breech deliveries, bilateral injuries are more common, and the injury is often more severe, involving root avulsions (3, 4). Paralysis of the phrenic nerve (C3, C4, C5) is sometimes seen, especially after breech deliveries (5).

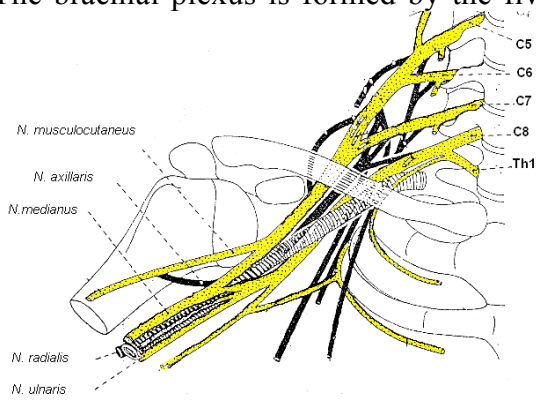


Figure 1. The brachial plexus.

C6			C8		
C5		C7		Th1	
Serratus ant			Flexor digitorum superficialis et profundus		Thenar
Deltoid	Biceps brachialis	Flexor carpi rad		Flex poll long	Hypothenar
Supra-spinatus	Brachioradialis	Triceps			
		Extensor carp			
Infra-spinatus	Supinator	Ext dig	Ext poll	Ulnar intrinsic	
	Teres major	Latissimus dorsi		Flexor carpi ulnaris	
Pectoralis major					

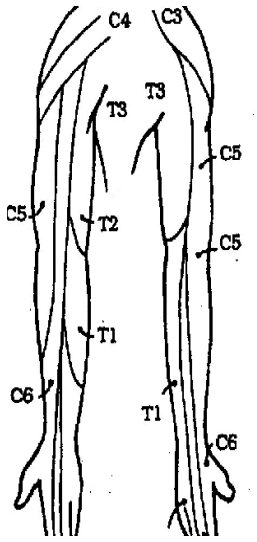
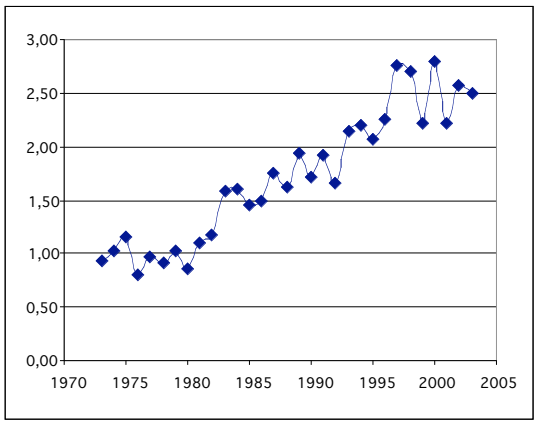


Figure 3. Schedule for motor and sensory innervations of the arm and hand (modified from Narakas' *The Paralyzed Hand*, p 124)

1.2 INCIDENCE AND RISK FACTORS

The incidence of obstetric brachial plexus injury is between 1-5 promille in countries with well-developed obstetric services (6-10). In Sweden, the incidence of OBPI has increased from about 1‰ in 1973 to about 2.5‰ in 2003 according to the Swedish Medical Birth Register. A birth weight above 4.5 kg and shoulder dystocia seem to be the strongest risk factors (1). With birth weights above 4.5 kg, the incidence is more than 1.5 %, and, above 5.0 kg, there is an incidence of 4.3% in our Swedish material

(11). In Sweden about 250 children are born with OBPI every year and about 60 of these children will have sequelae from the injury



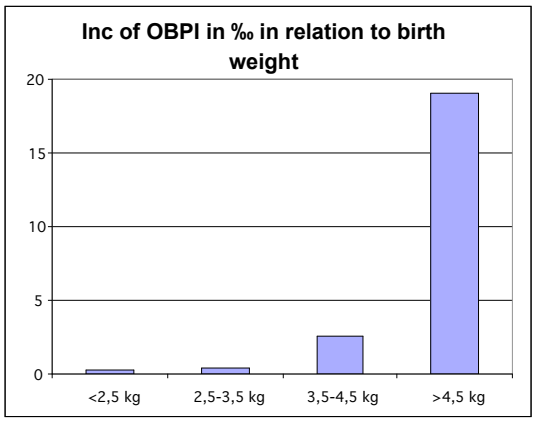


Figure 2a. **Figure 2b.**

Figure 2 .a The incidence of OBPI for 1972 to 2002. **b**. The incidence of OBPI for different birth weights for 1990 to 2003.

1.3 CLASSIFICATION

The OBPI was first described by Smellie in 1765, but it was not until a century later, in the 1870s that Duchenne (12) and Erb (13) were to introduce the injury involving C5-6 (the upper trunk) and sometimes C7 (the middle trunk), often called Erb-Duchenne´s palsy. In 1885 Klumpke (14) published a manuscript in which the lesion of the lower trunk (C8-Th1) was described and the significance of Horner´s sign (i.e., ptosis and miosis) in these cases. Though isolated lesion of the lower trunk is extremely rare (15), complete OBPI, involving C5-Th1, is seen in 4-19 % of all plexus injuries (9, 10).
Narakas introduced a classification into four groups based on the neurological outcome 2-3 weeks after birth, in which the injury is classified according to the number of injured nerves and the severity of the nerve injury. This is the classification we have used in our studies, although we have combined Groups III and IV (16).

Narakas' classification of Obstetrical Brachial Plexus Palsy		
Group I	C5-6	Paralysis of the shoulder and biceps
Group II	C5-7	Paralysis of the shoulder, biceps and forearm extensors
Group III	C5-Th1	Complete paralysis of the limb
Group IV	C5-Th1	Complete paralysis of the limb with Horner's syndrome

Table I. Narakas' classification of OBPP.

1.4 CONSEQUENCES OF AN OBPP

The outcome of an OBPI depends of the severity of the lesion of the nerve fibres. In the mildest forms, neurapraxia and axonotmesis, the prognosis is good and motor function returns within weeks to months. In the more severe lesions, involving

neurotmesis and root avulsion, the nerve is disrupted or pulled out of the spinal cord, and in these cases spontaneous recovery cannot be expected.

Figure 4. Baby with left-sided upper OBPP.

A C5-6 lesion is often associated with a milder form of nerve injury, and about 75% of children with this OBPI have full function restored (10, 17, 18), mostly within the first six months of life, although some do not recover completely before one year of age. C5-6 lesions occurring as a result of breech deliveries often have one or both nerves avulsed, and the prognosis in these cases is less favourable. In cases with complete lesions, there is almost always one or more root avulsion, generally C8. When Horner's sign is seen it indicates a more severe injury, with involvement of the sympathetic system. Patients with complete lesions with or without Horner's sign never get fully restored (19).

Children with severe nerve injury will have a persistent obstetrical brachial plexus palsy (OBPP). Nerve damage always results in a motor impairment, but also, especially when complete lesions have occurred, an impairment of sensory function. Severe nerve lesions are always associated with reduced growth of the arm or hand. The muscles involved are often thinner and give a thinner profile to the arm and shoulder. The muscular imbalance also influences the growth and development of the joint, increasing the risk of subluxation, especially in the shoulder joint.

C5-6 involvement results in impaired function of the shoulder, elbow and forearm. Such involvement is recognisable in a newborn child as a flaccid arm in adducted position and medial rotated with no activity in the elbow joint. When C7 is also involved, the wrist and fingers are flexed and pronated and when the lesion is complete, the arm and hand are completely flaccid.

Improvement in the function of a child with OBPP may continue for the first two or three years of life, and the outcome differs considerably, depending on the severity of the nerve injury.

The typical sequalae noticed after a lesion involving C5-6(7) is a depressed shoulder, often internally rotated with decreased flexion and abduction, accompanied by a slightly flexed elbow and a slight decrease in pronation/supination. When lifting the hand to the head the arm will often be abducted, with the elbow sticking out (known as the trumpet sign). This is caused by decreased external rotation of the shoulder or decreased function of the biceps. When C7 is injured, the extension of the arm, wrist and fingers decreases, the arm and fingers are more flexed and the forearm more often pronated. The impact on the sensory function and bimanual activity is usually low.

A complete lesion involves the entire arm and the typical sequale is usually a depressed shoulder with the arm in adduction, a flexed elbow and the hand supinated or, eventually, the arm just hanging loosely. The impact on sensory function and bimanual activity is high.

2 NEUROPHYSIOLOGY OF OBPP

The most common investigations conducted to diagnose neuromuscular diseases in clinical neurophysiology are EMG (electromyography), ENeG (electroneurography) and the QST (quantitative sensory test).

2.1 EMG

The motor function with the soma of the alfa motor neuron located in the CNS is studied from the ventral horn of the spinal cord through the spinal nerve, the plexus and all the way to the motor end plate. EMG is used to investigate the motor unit, i.e. the alfamotor neuron and the muscle fibres innervated by it. In the muscles of the arm, each motor neuron innervates about 300-400 muscle fibres. After an axonal lesion (axonotmesis) denervation activity or spontaneous activity is generally observed in the form of fibrillation potentials and/or positive sharp waves within 7-10 days (1-3 weeks) of the lesion being formed. After an axonal lesion, the motor units will be remodellated through collateral reinnervation, thereby enlarging the motor unit. For example, a single muscle innervated by 500 alfamotor neurons that has been lesioned in a plexus injury, with only 20 alfamotor neurons remaining, might have these 20 motor units enlarged 25 fold to give clinically normal motor activity. Thus, after successful reinnervation, the same number of muscle fibres are active as before injury (20). The EMG findings in this case will show motor unit potentials with very high amplitudes and increased duration, implying a neurogenic lesion. Plenty of polyphasic unstable motor unit action potentials (MUAP) (subacute neurogenic lesion) are indicative of ongoing reinnervation, whilst an inactive picture with enlarged stable MUAPs (neurogenic inactive lesion) is evidence of complete collateral reinnervation. At last, to confirm the estimation of MUAPs, the interference pattern is helpful. A full interference pattern at maximal voluntary force indicates a normal number of motor units, while a more soarce coverage indicates axonal loss.
The denervation-reinnervation process seems to be speedy in the newborn child compared to the situation at any other stage of life (21). Denervation activity is rare and is evident already just a few days after the axonal lesion at birth, in contrast to older children and adults, where it is only apparent weeks after the injury. The collateral reinnervation is quicker too, and might be complete after only a month or two, compared to 3-6 months, later on in life (22). One might speculate that the immature nervous system and the short distances in the arm and between the muscle cells is of importance for the process of reinnervation (22). The dimensions of the alfamotor neurons, including both axons and myelin sheaths are roughly comparable in newborn babies, children and adults.
Most clinicians use EMG, eventually in combination with ENeG, to decide the severity of the lesion and support decisions concerning nerve reconstruction (23, 24). The question of the predictive value of EMG is discussed in many articles. There are two major explanations to the sometimes too favourable EMGs that are obtained. Van Dijk noted that the muscle fibres of a three-month-old baby are 3.3 times smaller than that of an adult. This means that a cross-sectional area contains about 11 times more muscle fibre in the infant and, therefore, when a needle with the same pick-up area is used, about 11 times more MUAPs will be recorded for infants than for adults, and the EMG will be over optimistic (25). The second major explanation comes from Brown et al who suggested that a poorer outcome than expected could be caused by the impaired motor unit activation due to the absence of normal movements and accompanying sensory and proprioceptive input generally experienced early in life.

Their explanation is that the brain and the spinal cord do not undergo the activity-dependent changes leading to normal motor neuron recruitment (26).

2.2 SENSORY FUNCTION

The soma of the somatosensory neuron is located in the dorsal root ganglion, which can be seen as an enlargement of the dorsal root, just proximal and partly protruding into the intervertebral forearm. A short proximal axon in the dorsal root connects the soma with the dorsal horn of the spinal cord, while the distal axon goes through the spinal nerve, plexus, and peripheral nerve until it reaches the sensory receptor. Thus, most peripheral nerves contain both motor axons with efferent signals on their way to the muscle fibres and sensory axons with afferent signals on their way to the spinal cord and the brain. In contrast to the motor side, the sensory side are grouped in different sensory pathways, for example, the larger myelinated axons for touch and proprioception (measured with ENeG) and the smaller unmyelinated or thinly myelinated axons for temperature (measured with QST). These two techniques will be discussed briefly here, with the emphasis of the discussion being to specify what each technique can tell us about the peripheral nerve lesion.

2.2.1 ENeG

ENeG has the advantage of being a non-invasive method, and is a fast and an almost painless technique for mapping both sensory and motor function in several peripheral nerves. The contra lateral arm can be used as the control and, in contrast to EMG and QST, the method is not dependent on any contribution from the child. Motor function is measured with the amplitude of the compund muscle action potential (CMAP), and the motor conduction velocity (MCV) as the most important components. Sensory function is assessed with the sensory nerve action potential (SNAP) and by recording the sensory conduction velocity (27). In general, low SNAPs indicate an axonal lesion, which is most commonly found in association with a plexus injury. On the whole, there is correlation between the degree of amplitude decrease and axonal loss.
In the conduction block a slight compression of the nerve affects individual sensory nerve fibres focally in, approximately, 2-3 nodes of Ranvier (< 3 mm distance) by blocking the nerve impulse. If the conduction block is 100%, no signals can pass this segment of the nerve. Thus, if such a block is located in the upper part of the brachial plexus, parts of the arm are completely paretic and there is a total loss of perception. A conduction block or nerve apraxia will be spontaneously restored in 6-8 weeks after the injury. This phenomenon is seen in the mildest form of OBPP. There is no way to get absolute confirmation that conduction block is the cause of paresis, but a normal sensory and motor ENeG, with CMAPs and SNAPs showing no difference between the left and right arms, an EMG lacking denervation activity and the loss of or a decrease in voluntary activity are highly indicative of conduction block. A more complicated situation arises when there is a combination of an axonal lesion and a partial conduction block. A decrease in the conduction velocity indicates demyelinisation. In patients who tolerate ENeG well, it is possible to extend the examination in an attempt to distinguish between a lesion of the upper and the lower part of the plexus. It can, for example, be helpful to investigate the medial and lateral part of the cutaneus antebrachii nerves representing different parts of the brachial plexus.

2.2.2 QST

The quantitative sensory test (QST) charts the thresholds of sensitivity to cold and warmth, where the sensitivity to cold represents thinly myelinated axons (A_ fibres) and to warmth, the unmyelinated axons (C fibres). This investigation may be performed on the uptake area of individual sensory nerves or on separate dermatomes. QST has the advantage of being easy to perform, does not cause any discomfort and is more like a "competition" than a medical examination.

3 CEREBRAL AND SPINAL PLASTICITY

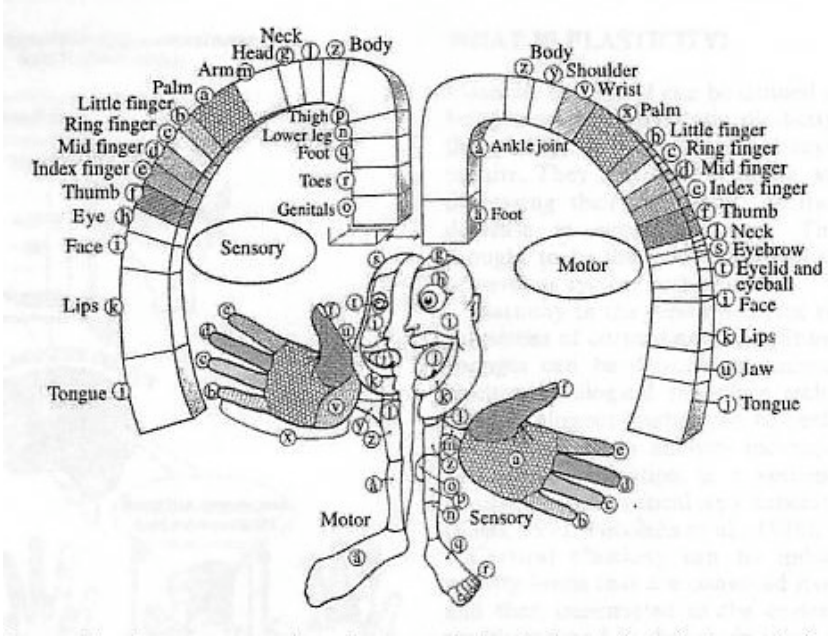


Figure 5. The cortical body map with reference to sensory (posterior to central sulcus) and motor (anterior to central sulcus) functions (from G. Lundborg, "Brain Plasticity and Hand Surgery: An Overview", Journal of Hand Surgery, 2000).

The cerebral representation of the arm and hand in both the motor and sensory cortex is formed during development and maintained by activation of the input pathways. Despite its early formation, the representation of the body parts in the motor cortex is not permanent, but can be altered during motor learning and after injury (28-30). The plasticity of the cerebral cortex can be taken advantage of when the activity level of the peripheral nerves changes, and then transmitted to the cortex where cortical synapses respond to the changes by altering/adapting their strength or efficacy. Well known examples of this plasticity are the cortical remodelling arising as a result of the increased sensory input caused by using Braille or after training with, for example, intensive piano playing, and the down regulation of sensory capacity of the hand in patients with severe spasticity and contracture of the hand resulting in decreased use of the hand. This mechanism is of importance for the training undertaken after injuries to either the central nervous system or the peripheral nerves. In constrained-induced therapy, where the unaffected hand is covered and the patient is forced to use the affected hand (31), expansion may be induced in the contralateral cortical area controlling the affected hand as well as the ipsilateral areas (32, 33).
In a peripheral nerve injury, like an OBPI, there is a loss of both motor and sensory function with an influence on the ventral and the dorsal roots, spinal interneurons, and at cortical and subcortical levels. In spontaneous recovery and after nerve reconstruction there will always be an axonal misdirection, which is followed by a functional synaptic reorganisation of the motor as well as the sensory cortex, giving cortical reorganisation. When sensory relearning takes place, many authors have found that simultaneous use of other senses with that of touch, like sight, hearing and smell as well as bilateral training (34, 35) might improve the cortical reorganisation and the clinical results.

Age seems to be of importance for nerve repair and, for example, young children are capable of better sensory relearning after nerve injuries than adults, with the optimum capacity being at less than 5-10 years of age. This age- dependent recovery of sensibility seems to be based on the same process as learning a new language (34).
Examples of central plasticity after an OBPI are the cortical rearrangement after nerve transfer and neurotisations. A common operation in patients with OBPP is tendon transfer from the latissimus dorsi to the biceps muscle to improve elbow flexion, or to the humerus to improve the external rotation of the shoulder. These changes in muscle function induce plasticity in cortical areas projecting to the functionally relevant muscles (36). The switch of handedness and the good sensibility are other examples of cortical plasticity.
An example of spinal plasticity, called “luxury innervation”, has been described by Vredeveld (37). He found that most children with an OBPI of C5-6 with complete avulsion of both roots (n=14) had normal biceps function at 4 months of age, in contrast to a group also comprised of those with a traumatic lesion to C5-6 that had occurred later in life, where no function of the biceps was seen. In a third group of patients, comprised of those with an OBPI of C5-7 and with avulsion of C7 (n=3), no biceps function was seen. This finding of Vredeveld is confirmed by studies of Korak et al., who found that selective injury to C5-6 in newborn rats gave permanent loss in corresponding motor neuron pools and that this loss was partly compensated by the adjacent C7 motor neuron contribution to biceps muscle, which increased four fold. In 4 week old rats, this increase in C7 adjacent motor neurons was not observed when the preservation of the C7 pathway no longer exists because of the natural apoptosis (38). The increase in C7 adjacent motor neurons was not seen when C7, C8 or Th1 was involved in the lesion and is a sign of efficient peripheral plasticity that is exclusive to the neonatal period.

4 SENSORY ASPECTS

There are plenty of mechanisms that are important for the sensory system, including the modality, the localisation, the intensity and the duration of the stimuli. Looking at the modality of touch, four different types of mechanoreceptors are involved. These are the slowly adapting Merkel cells, the Ruffini endings, responding to a sensation of pressure, while the rapidly adapting Meissner's and the Pacinian corpuscles detect velocity and acceleration. The Merkel cells and the Meissner's corpuscle have the smallest receptive fields and are most sensitive to pressure. The signals from these receptors are transformed through a large number of relay nuclei that give complex information to the sensory cortex. The receptive fields of central neurons have inhibitory as well as excitatory components. Inhibition occurs at each relay of the nuclei of the dorsal column. Inhibitory interneuron activity narrows the discharge zone and sharpens the ability to distinguish between the stimuli from two points to as little as about 1 mm. This lateral inhibition enhances the contrast between two close points at which contact or pressure is applied and enables two points to be differentiated from one another despite the fact that the receptive fields overlap (29).

5 THE INTERNATIONAL CLASSIFICATION OF FUNCTIONING

International Classification of Functioning, Disability and Health (ICF)(39) is WHO's framework for health and disability. The ICF classifies the function and disability associated with health conditions, with the focus on health and functioning rather than on the disability. The components *body function/body structure* and *activity* and *participation* are parts in an interactive model where *environmental factors* and *personal factors* can influence each other and the other components. The system is intended for use on an individual level, as well as on an institutional and a social level.

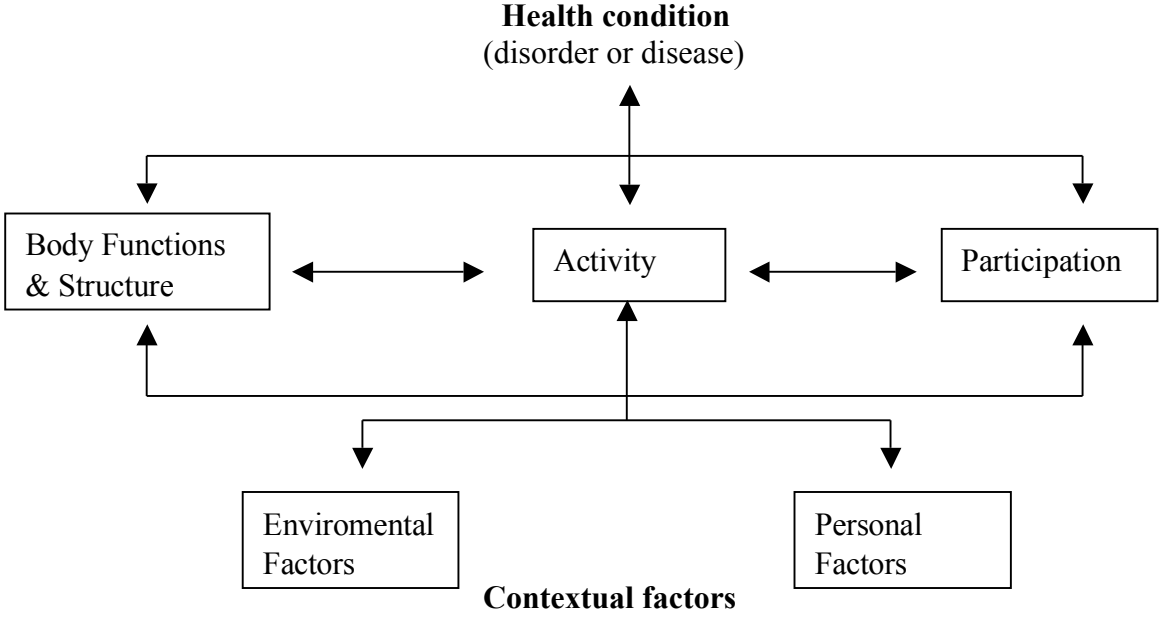


Figure 6. The principle of the International Classification of Functioning.

Body functions are defined as physiological functions of the body systems and *body structures* refers to the anatomical construction. In OBPP, the lesion represents the body structure, and the ROM (range of motion), grip strength, tactile sensibility, EMG and QST are measurements of body function. These aspects are the most commonly studied of OBPP, especially the number of lesioned nerves, the severity of the nerve lesion and the ROM of the shoulder, arm and hand, and are almost always present in articles about the OBPP and its treatment.

Activity is defined as the execution of tasks by or actions of an individual. Functional sensibility and activity in daily life (ADL) are aspects of this. The ADL is likely to be strongly influenced by the severity of the lesion, which determines the possibility to move the arm and hand and the ability to use the hand and have a functional grip. As we see above, other factors also will influence the activity, such as the *health* of each individual, including the presence of other impairments or cognitive difficulties, *personal factors* related to the capacity and motivation of each person, and the influence of *environmental factors*, like peers and teachers who support training of the impaired arm and hand. Special forks and knifes and easily handled zips are also examples of environmental factors that can improve a person's capacity to perform an

activity. The perspective of activity was studied by Gjørup in the sixties and by Hoeksma in 2004 (6, 40). Hoeksma found that when the parents were invited to assign ADL problems a value on a visual analogue scale ranging from 0 (no problems) to 100 (severe difficulty) 24 of them indicated that their child have no difficulty (0) and 14 parents assessed their child to have a level of difficulty performing a task of between 1 and 10. In her study in Denmark in the sixties, Gjörup found that the majority of the patients, 71 out of 89 participating in the investigation, with the most severe OBPP had no problems eating or dressing and just five and 19, respectively, had problems bicycling and swimming. Ho et al used the Paediatric Evaluation of Disability Inventory (PEDI) to try to discriminate between the self-care ability of children with OBPP and their peers, and to distinguish between different levels of severity of OBPP. They found that the PEDI could not discriminate between the children with OBPP without hand impairment and their peers, but it could differentiate between those with OBPP for whom the hand was involved and their able-bodied peers (41). Study III in this thesis also indicates good activity in children/adolescents with OBPP.

Participation refers to involvement in life situations, which, for young people involves attending school or going out to work, leisure time and friendship. In the ICF, activities and participation are divided into different domains each of which is considered to be of importance, such as different aspects of learning, communication, mobility, personal care, life at home, social interactions, education, work, and economic well-being and social life.

A person's body function and their level of activity influence the level of participation. As mentioned previously, it is also influenced by environmental factors like school environment, teachers and the specific aid that a person receives, and personal factors like cognition and motivation. The participation of teenagers and adults with OBPP has not been studied very often. Gjørup performed an extensive study of adults with OBPP, conducted by questionnaires, in Denmark in the 1960s (40). No correlation was found between the severity of the OBPP and the individual' social situation. The author concluded that persons suffering from OBPP live a life, which superficially, is like that of the rest of the population. However a more detailed investigation showed slight differences that were almost imperceptible to others, revealing that several participants felt "out of it"(to cite Gjørup).

Bent et al (42) studied factors determining participation by young adults with a physical disability and concluded that having a disability may limit participation, but is not necessarily synonymous with a poorer quality of life.

Study II in this thesis supports the findings that the participants have a very good level of participation in society, even though we found indications of distress and worry related to the disability.

6 TREATMENT

6.1 CONSERVATIVE TREATMENT OF OBPP

There are two initial approaches to the nerve injury that underlies OBPP, a conservative one and operation involving nerve reconstruction. The conservative treatment includes passive range of motion therapy, mostly performed by the parents, and is intended to avoid contractures and to stimulate the use of the hand in play and during the performance of everyday activities. In Sweden the parents are put in contact with a physiotherapist, on the delivery ward, who gives instructions about passive range of motion therapy. Children with sequelae from the OBPI will then be put in contact with their Local Habilitation Team where they see the physiotherapist once or twice a year. The role of the physiotherapist is to encourage and support the parents and, to ensure that children who are afflicted are encouraged to use their arm actively whilst performing pleasurable or everyday activities, The fact that this contact is maintained, albeit with low frequency, emphasises the importance of stretching to avoid contractures, and of training that can be implemented alone or with assistance from parents to get motor and sensory input and improve the function of the arm and hand.
Sometimes splints have to be used to stretch shortened muscles, often in the elbow or the metacarpophalangeal joint, and the splints might be used for a period of two or three months. Sometimes just one period of splint is needed but sometimes the periods have to be extended or repeated. The splints may also be used to facilitate the use of the hand, for example stabilising the wrist to get a more functional grip. Children with complete OBPP may need other compensatory equipment, e.g to enable them to feed themselves and to write.

6.2 SURGICAL TREATMENT OF OBPP

Surgical intervention to reconstruct nerves was first attempted at the beginning of the 20th century (Kennedy 1903 and Clarke 1905)(43), but fell out of favour owing to high postoperative mortality and poor results. Systematic surgical repair with modern techniques began in the late 1970s and was attempted because of safer infant anaesthesia and improved surgical techniques. Both Narakas (44, 45) and Gilbert (46, 47) reported useful results from nerve reconstruction involving nerve transfer and grafting in patients with an OBPI. Gilbert and Tassin described the natural history of a conservatively treated population and proposed that the Mallet score (48) should be used in comparison with the results of conservative treatment. They found that children with C5-6 and C5-7 lesions who had undergone nerve reconstruction had better shoulder function than children with equivalent nerve damage who had not been operated on (49, 50). Nerve reconstruction was argued to be performed before one year of age whereupon restoration of the lesion will continue for at least two years after the operation. There is still some controversy regarding the indication and timing for operation in infants with C5-6(7) lesions (Narakas' classification group I and II). The reason for this is that the majority of them will recover spontaneously to the extent that nerve reconstruction is not indicated. Tassin and Gilbert found that all children who had a complete recovery had regained some function before two months of age. Gilbert and many with him recommend nerve reconstruction of the C5-6(7) lesions if there is no biceps activity at the age of three months (3, 47, 51). Our policy is, as in Toronto for example, to perform nerve reconstruction in patients with C5-6(7) lesions if there is inadequate recovery of shoulder and elbow function at 6 to 9 months of age (52). Study I in this thesis is dealing with this problem. If there is

adequate recovery of the shoulder but not the elbow or vice versa, we now usually perform extra-plexual nerve transfers to the part of the limb that has not recovered sufficiently. There is now general agreement that the majority of children with involvement of all five spinal nerves (Narakas' groups III and IV, see Table 1) benefit from surgery.

A large number of secondary surgical procedures for OBPP have been described over the years, including muscle releases, tendon transfers and osteotomies (16, 19). In our service the same surgeon performs both the nerve reconstructions and the so-called secondary surgery to ensure that the selection of the surgical intervention and its timing are optimal. We now often perform surgery of the shoulder joint during the first year, i.e. the surgery is conducted before the nerve injury has recovered. It is sometimes necessary to relocate a dorsally displaced shoulder joint at the same time as a nerve reconstruction is made.

Shoulder surgery. The most common secondary procedure in children with OBPP in our department is the release of internal rotation contracture of the shoulder, which in most cases was achieved by elongation of the subscapularis tendon, sometimes combined with a latissimus dorsi transfer to enhance the power of external rotation (53). In patients who were operated on before 1996, the origin of the subscapularis muscle was released instead (a procedure known as the "subscapularis slide"). We now favour the tendon elongation technique because it is more precise and because it facilitates relocation of the shoulder joint if the head of the humerus is dorsally displaced. Dorsal subluxation/dislocation was noted in 25% of the patients who had undergone subscapularis elongation during an operation in our service.

Figure 7. Child with a right-sided OBPP

Elbow: When patients have insufficient flexion power, with good recovery of the hand, a pectoralis minor to biceps transfer is our method of choice. Complete loss of elbow power is rare in OBPP patients, but when it does, a more powerful transfer is required than that of the pectoralis minor, so a latissimus dorsi to biceps transfer or the Steindler procedure can be considered in this situation. We do not recommend surgical release of extension defects in the elbow. Our preference for this problem is progressive static splinting.

Forearm:. Supination contracture is the most common forearm deformity. We favour rotation osteotomy of the radius, placing the hand in a few degrees of pronation. Occasionally a rerouting of the biceps tendon, as described by Zancolli, is performed to add a motor to drive the pronation(54-56).

Wrist and hand: Wrist extension is essential for the stability and power of a grip, but weakness of the wrist extensors is common in OBPP. In our experience, transfer of the pronator teres alone has provided adequate wrist extension power in about 50% of the patients.

Opponens plasty and correction of finger clawing are other procedures, which can provide a marked improvement of the grip function, when indicated. Tendon transfers of the wrist and hand in OBPP are challenging and technically demanding. The patchy innervation pattern in these patients makes it difficult to identify muscles with sufficient power to function as transfers without causing unacceptable loss at the donor site.

7 THE BRACHIAL PLEXUS TEAM

Since 1986 a national brachial plexus clinic has been situated at Astrid Lindgren Children's Hospital in Karolinska Hospital in Stockholm. The clinic is a collaboration between the unit child neurology and the unit hand surgery units in Stockholm. As mentioned above, about 250 children get an OBP lesion every year and only around 60 of these will have sequelae of the lesion. Most of them have mild sequelae and only about 7-10 children are recommended for surgery involving nerve reconstruction each year. Because of this, a national clinic was started up to centralize the surgical experience, restricting it to one clinic. During the 20 years since its inception we have seen more than 800 children. The first visit generally takes place when an infant is about 3-6 months of age and the children are then regularly followed up at the clinic for at least five years. Standardised assessments of the ROM of the arm and hand are conducted at every visit. Advice concerning treatment is given to the local rehabilitation therapists. When necessary secondary surgery is recommended and performed by the same hand surgeon who performs the nerve reconstructions. At 5 years of age all children, regardless of whether they have been subjected to nerve reconstruction or not, are thoroughly examined to determine their range of motion, grip strength, dexterity, tactile sensibility and bimanual activity. (57). Questions about their activity in daily life are also posed. These data have been used in Studies I and III.

In addition to the clinical work we also arrange for education and seminars to be provided for the parents of children with OBPP, for teenagers and their parents and for professionals.

8 AIMS OF THE STUDIES

The overall aim of these studies was to investigate the influence of different kinds of treatment on the obstetrical brachial plexus lesion and to examine the implications of the interventions on functioning and participation in adolescents with OBPP.

1. We wanted to investigate the functional outcome; i.e ROM in the shoulder, arm and hand as well as grip strength, dexterity, tactile sensibility, bimanual activity and handiness at five years of age in infants with OBPP who had been operated on to reconstruct nerves during their first year of life and to compare their function to a group of children with OBPP who had not been operated on. Moreover, we wanted to see whether the timing of the nerve reconstruction, in particular whether it took place before or after 6 months of age, was of any importance for the outcome.

2. We wanted to examine and describe the development of sequelae in obstetrical brachial plexus palsy (OBPP) and to describe possible differences in the functional outcome occurring from the age of five years to a follow-up, 2-15 years later, and to try to find out if the changes observed were related to the level of sports activity and physiotherapy. We also wanted to investigate if the functional outcome differed for those operated upon with nerve reconstruction or/and secondary surgery.

3. We wanted to investigate the long-term neurophysiological outcome and sensory function in persons with obstetrical brachial plexus palsy (OBPP). Signs for post polio-like syndrome were sought. We also wanted to examine the EMG changes in adolescents who had an OBPI in the newborn period and were completely restored within the first year of life.

4. We wanted to analyse whether activities and participation in daily life differed between adolescents with obstetric brachial plexus palsy (OBPP) and their able-bodied peers.

9 MATERIAL AND METHODS

9.1 PARTICIPANTS

Patients in the plexus clinic 1986-2006
800 patients

247 children — 42 dropouts
247 children and 42 dropouts in **Study I**

45 — 6
51 adolescents in **Study II**, 45 particip. and 6 dropouts in Study I

59 — 11
70 children/adolescents in **Study III and IV**, 59 of whom participates in Study I and 11 who were too young to have been included in Study I

Figure 8. Description of the participants involved in the different studies. The figure shows the number of patients and drop outs in Study I, and how many of these took part in Studies II-IV.

OBP-injury	Study I	Dropouts Study I	Study II	Dropouts Study II	Study III+IV	Dropouts Study III
C5-6 op	**8**	1	4	1	3	1
C5-6 unop	**15**	1	3	1	7	3
C5-6 ER	**106**	15	14	2	31	13
C5-7 op	**24**	4	2	1	6	1
C5-7 unop	**32**	7	10	1	9	5
C5-7 ER	**29**	8	10	5	8	8
C5-8(Th1) op	**27**	5	7	2	4	6
C5-8(Th1)unop	**6**	1	1	0	1	2

Table II. The table shows the lesion and treatment of the participants in each study. The dropouts in studies II-IV are those who were asked to participate in each study, but declined to do so; they are not related to the dropouts in Study I.

Birth — A: 3-7 months, EMG and diagnosis — B: examination at five years of age, Study I — C: 7-20 years old follow up examination EMG and QST, Study III & IV

Figure 9. Timetable for the different assessments and precision of when a diagnosis was made.

The participants to all studies were recruited from the brachial plexus clinic in Stockholm. The diagnosis OBPP has a typical anamneses and is not very difficult to make. The participants were diagnosed on their first visit to the clinic, which occurred during their first year of life and they were classified as having one of three levels of nerve root involvement, C5-6, C5-7 or C5-8(TH1). If there was any other handicap, like mental retardation or cerebral palsy, the child was excluded from the study. In Study I, 247 5-year old children with OBPP from all over Sweden were examined. In studies III and IV, 59 of these children and 11 younger children, living in Stockholm, were re-examined 2-15 years later. The same doctor and occupational therapist examined them all at 5 years of age and at the follow-up and used the same protocol.

In Study II, 51 teenagers from the whole of Sweden, who were born between 1985-87, including a cohort of the children examined in and the dropouts from Study I answered a self-assessment questionnaire concerning their daily life, their performance at school and friendships. The outcome of those with C5-7 lesions, classified before 6 months of age, differs considerably, depending on the severity of the C7 lesion, indicating that children with C7 lesions might be classified in different functional groups. These functional groups provide information on the number of joints that suffer restrictions, i.e., one for either the shoulder or elbow joint, two for shoulder and elbow and three if the wrist and hand are involved in addition to the shoulder and elbow. This means of providing additional information was used in Study II, and it was planned to use it in Study III, but it had to be dropped because restrictions on the size of the article did not allow such of depth analysis.

The dropouts in Study I are less than 20% of the potential sample, and in studies III and IV, 37% of the adolescents asked to take part of the study declined to do so. Characteristic data is presented for the dropouts in both studies. There were equally many dropouts for the different lesion groups in Study I, and in studies III and IV, 8 out of a possible 13 with a total lesion declined to take part in the study. Some of them had moved to another part of Sweden, and others were tired of hospitals and participating in investigations. Although the dropouts represented more than 50% of this group, the remaining patients are representative for the group as a whole. In lesion groups C5-6 and C5-7, less than one third declined to take part of the study. In Study II, the dropouts were equally distributed too, see Table I in Study II.

9.2 INVESTIGATIONS

When the national plexus clinic started in 1986 we decided to follow-up all children at the age of 5 years, regardless of whether they had undergone nerve reconstruction or not. The reason for choosing this age was that the natural healing, as well as the healing undergone subsequent to nerve reconstruction would be expected to be completely finished. At five years of age the children are also more cooperative, which is necessary to obtain reliable results at the examinations.
A new protocol was developed for the follow-up examination at five year of age (57). Mallet's classification of shoulder function, which focuses on functional movements rather than on ROM (48), was not used when we wanted to make a more thorough evaluation of the arm and hand. We have added Mallet's classification, to our protocol subsequently, since it is a commonly used in numerous plexus studies. All children in Studies III and IV have, therefore, been examined with Mallet, but since they were not all examined with it in Study I, we are unable to make any comparisons.

Michelow, Clarke and Curtis presented a grading system for active joint movements against gravity in 1994 (58). The measurements of movements in our protocol were easily translated to this 7-graded system, and we have used this system in our follow-up studies, see Table III. Clarke and Curtis further developed the system to produce the Active Movement Scale (AMS) (52), in which movements made against gravity and movements independent of gravity are included, but our group preferred to use the old 7-graded system since we can't translate the old measurements in Study I to the new system.

Movement	*score*	*Numerical score*
No joint movement	1	0
Flicker of movement	2	0.3
Less than half range	3	0.6
Half range of movement	4	1.0
More than half range	5	1.3
Good but not full range	6	1.6
Full range of movement	7	2.0

Table III. The 7-graded movement scale developed by Michelow, Clarke and Curtis that was used in Study III to evaluate changes in ROM.

Study	ROM	Dexterity	Grip strength	Tactile sensibility	Functional sensibility	Bimanual activity	EMG	SEP	QST
I	X	X	X	X	X	X	X	X	
III	X	X	X			X			
IV				X	X		X		X

Table IV. Specific assessments performed in studies I, III and IV.

9.2.1 Range of motion (ROM)

The range of motion in the different joints was first measured by the occupational therapist of the team, and then reassessed by the neuropaediatrician and the hand surgeon. The values were recorded as pre-stipulated intervals corresponding to the Toronto scale, described above.

In Study I the ROM data were used to establish a point score from 0-3 (0 no movement- 3normal movement) for each movement of the arm and hand. The scores for each movement in a specific joint were summed, giving a specific score/value for the shoulder, the elbow joint and the wrist and fingers. These scores were then used to compare the different subgroups. In Study III we used the Toronto scoring system, giving a maximum score of 2 for each movement. As above, we then summed the different scores in each joint. Our old data corresponded well to the Toronto scale, and it was easy to translate the old values into the new system and compare the two measurements for ROM with one another.

9.2.2 Hand function

9.2.2.1 Dexterity

A timed pick-up test was used to measure dexterity (57). The result was reported as the relative dexterity, given as the ratio between the time taken, in seconds, to accomplish the task with the unaffected arm to the time taken with the affected arm. To eliminate differences that might only depend on handedness, the dexterity of the affected hand was considered to be within normal variation when the ratio was > 0.8. The same test was used in studies I and III and was performed by the same occupational therapist.

9.2.2.2 Grip strength

Grip strength was measured with two different instruments during the many years that these data were collected. The Martin Vigorimeter was used over the first eight years, whereupon the electronic device Grippit replaced it®. By expressing the results for each individual's hands as a ratio, comparisons could be made between the results made with the different instruments, and age-related differences in strength could be eliminated. To eliminate differences that are possibly only depending on handedness, the grip strength of the affected hand was considered to be within normal variation when the ratio was > 0.8.

9.2.2.3 Tactile sensibility

In Study I, the tactile sensibility was tested by touch applied to the arm (covering specific dermatomes), discrimination between 2 points (2PD) and by stereognosis. Proprioceptive sensibility was tested through discrimination between three identical mugs containing different weight. Since all participants, even those with complete OBPP managed to determine the location of touch, we exclude this test in Study IV. All participants in Study I, with the exception of two children with complete OBPP who had undergone nerve reconstruction, managed the proprioception test, we excluded this test in Study IV as well.
The 2PD test was conducted for all fingers, first with a distance of 3 mm between the points, which is considered to be appropriate for normal levels of sensibility (59-61), and then, when the child/adolescent could not discriminate the two points, a distance of 7 mm was tried. This second distance between the prongs was chosen with the intention of testing a separation that was clearly greater, but still within the most sensitive area of the finger pulp. At random, either one or two prongs of the paperclip were very gently pressed on the pulps of the fingers.
The result was noted as: 0 (normal, can discriminate when a distance of 3 mm was used), 1 (somewhat decreased, can discriminate prongs separated by 7 mm, but not 3 mm) and 2 (decreased, 2PD > 7 mm). The result for digit I was considered to reflect C6 innervations (2PDC6) and digit V, C8 innervations. When testing stereognosis, six familiar objects were placed in the hand. These were selected in pairs of similar size and shape to increase the challenge. The result was scored from 0 (could not identify any object) to 6 (could identify all six objects).

9.2.2.4 Functional sensibility

A pick-up test performed with and without looking was used to examine the functional impact of tactile sensibility on motor performance (57, 62). Ten wooden cubes of side length 10 mm were to be picked out of a box (120x120x40 mm) as

quickly as possible. The task was performed under two conditions: first as a test of dexterity, and then with the hand shielded from view. The *difference* in the performance of the same hand with and without looking reflects the somatosensory loss, since locating the objects; grasping and tossing them all require sensory information to guide the motor act. Each hand was tested separately, with the unimpaired hand being tested first. The functional sensibility was given as the ratio between the time taken without looking to the time taken when looking. A ratio of < 2.2 was considered to imply normal functional sensibility (scored as 0), whilst a ratio greater than this implies decreased functional sensibility (scored as 1), and, finally, if the child/adolescent could not perform the test at all without looking, although he/she could do it when able to see the cubes, a score of 2 was given.

9.2.2.5 Bimanual performance

The involvement of the affected hand in the performance of five bimanual activities was classified on a 4-point scale as follows: The level of use was graded as 0 (not used), 1 (assisting without a grip), 2 (assisting with an altered grip) or 3 (assisting with a normal grip). The maximum score for bimanual performance was, therefore, 15 and the result obtained for each child/adolescent was reported as percentage of the maximum score.

9.2.3 Neurophysiological assessments

9.2.3.1 EMG

In Study I a diagnostic EMG was performed between the age of three and seven months to determine which cervical segments were involved in the lesion. The protocol for this included measuring the fullness of the interference pattern and, to some extent, the size of individual motor unit action potentials (MUAPs). The EMG-data were classified in a five-graded scale (1=slight, 2=moderate, 3= severe, 4=very severe lesions and 5=end stage (27). No end stage (grade 5 damage) was identified in any child at this age. A C5-6 lesion corresponds to changes in the deltoid and biceps muscles. A C5-7 lesion can further incorporate a minor degree of change in the extensor digitorum muscle. Changes in the intrinsic muscles point to C8-Th1 lesions.
In the follow-up investigation, Study IV, qEMG investigations were made using a Keypoint apparatus (Medtronic). About 20 motor unit action potentials (MUAPs) were gathered and the occurrence of spontaneous activity was sought out. The aim was to grade the known lesion on a scale of one to five (vide supra) using the MUAP analysis obtained by qEMG. The grading was based on the mean amplitude and duration of the MUAPs gathered and to some extent the interference activity at maximal voluntary activation. In the most severe lesions, which clinically include some muscle atrophy, the MUAPs were grade 5=end stage. A simple protocol involving the routine examination of just two muscles, in contrast to five muscles usually investigated with EMG to define a late onset or traumatic brachial plexus lesion, was chosen to minimize the discomfort for the children and teenagers. The numbers of muscles investigated were occasionally increased for a more thorough investigation. It is also possible to get information about the reinnervation process by studying the MUAPs if they are inactive and enlarged or more varied, as in ongoing collateral reinnervation.

9.2.3.2 ENeG

When electroneurography (ENeG) was carried out, it was performed at the same time as the EMG, measuring motor amplitudes, CMAPs, and sensory amplitudes, SNAPs, as well as the conduction velocity. Low CMAPs imply that there is an axonal lesion, though the CMAP might be normal after an axonal lesion if the collateral reinnervation has been successful, which is why an ENeG must always be combined with an EMG.

9.2.3.3 SEP

Sensory evoked potential (SEP) of the median nerve was examined on the patients in Study I. These examinations were only done for preoperative mapping and the results indicated whether the median nerve was involved or not, but as this was of no clinical use, it is not used any more.

9.2.3.4 QST

In Study IV detection levels of cold and warm sensation were measured with a quantitative sensory test (Senselab, Somedic). A standard thermode (25 x 40 mm) was placed over the thenar region in the C6 dermatome and over the hypothenar region in the Th1 dermatome. The mean difference from the baseline, 32 degrees Celsius, was determined and used as the parameter for cold and warmth thresholds, respectively (63). In addition, the cold and warmth thresholds were mapped in the C6 and C8 dermatomes in the neck above the paraspinal muscles. A small thermode (25 x 35 mm) was used for this. Thus, the dermatomes were examined both in relation to the dorsal and the ventral ramii of the spinal nerve. The normal values taken for the dorsal ramii are based on 33 measurements of the healthy side, and are 3.2º C for cold sensation and 4.8º C for warm sensation. Normal threshold values for the ventral ramii for adults in our laboratory are 2.5º C for cold sensation and 3º C for warm sensation. In a recent paper from Anand and Birch (64) the threshold levels used for QST were 2.3º C for cold sensation and 3.8º C for warm sensation; however they did not report the background for these limits. In Study IV we use the threshold levels from a study ongoing in our department. These values are based on 70 adolescents (aged 18) used as healthy controls in the ongoing study (T. Brismar, personal communication). The values obtained are 1.5º C for cold sensation and 2.9º C for warm sensation.

9.2.4 CT-myelography

In Study I, all infants for whom nerve reconstruction had been recommended underwent preoperative computer tomography (CT) myelography to look for pseudo-meningocele implying root avulsions. Owing to the frequent false negative and false positive findings from the CT myelography we stopped using this form of investigation for a while. Nowadays, as the reliability of the technique has been improved, we have taken up this investigation again. Other authors have also found that a significant number of avulsions do not show any evidence of pseudomeningcele (65). Magnetic resonance imaging (MRI) of the plexus gives less radiation and some authors believe that this investigation will be more used preoperatively (65, 66). The problem in our clinic is the longer anaesthesia needed in the MRI.

9.3 QUESTIONNAIRE FOR SELF ASSESSMENT

In Study II we used a self-assessment questionnaire ("Ansula"), based on the Anser-System (67). This questionnaire was devised by Dr Mel Levine of the Clinical Centre for the Study of Development and Learning at the University of North Carolina at Chapel Hill, USA. The questionnaire was translated into Swedish by two psychologists, Ewa Isberg and Margareta Kihlgren (personal communication). As we found that the type of questions centred on several daily activities and aspects relating to participation, making it ideal for the ICF framework, we decided to use it and to create an age-matched comparison group. The questionnaire has two parts: 1) statements concerning the child's apprehension in terms of attention, school work (reading, spelling, writing and mathematics), leisure time and self-esteem, and 2) free questions regarding different kinds of abilities, difficulties, fears and preferences in daily life and friendships. Free questions concerning school were excluded since they were covered by the first part of the questionnaire.

10 STATISTICS

In Study I, the ROM in the shoulder, elbow and hand is expressed as a percentage of the ROM of the unaffected arm. The results are presented in box-plot graphs showing the median and, the minimum and maximum values. The Mann-Whitney U-test for non-parametric values was used to test the statistical difference between groups. $P \leq 0.05$ was considered to be statistically significant.

In Study III the results for the ROM are presented as the mean and standard deviation (SD), median and percentiles (P_{25} and P_{75}) along with data relating to the number of participants whose general ability had improved, remained unchanged or deteriorated. The changes in ROM and strength between five years of age and the follow-up were analysed with the Wilcoxon Matched Pairs Test and the Sign Test. The Mann-Whitney U test was used to analyse changes in the ROM of the shoulder between the group on whom an operation had been conducted and the others. The Spearman Rank Order Correlation was used to measure the association between the changes in the outcome variables and the participants' characteristics (their age, whether they had undergone shoulder surgery or not, their level of physical activity and the level/position [and severity] of their lesion). A p-value of 0.05 was considered to be statistically significant.

In Study IV the mean and standard deviation (SD) of the QST threshold values and the amplitude and duration of the EMG are presented. The Spearman Rank Order Correlation Test was used to measure the correlations between the shoulder abduction score and qEMG, between qEMGidi and the grip strength, and between qEMGidi and QSTC8 for the children who had undergone nerve reconstruction., as well as between different sensory tests. The Wilcoxon Matched Pairs Test and the Sign-Test have been used to measure the changes of EMG between the age of 3 –7months and the follow-up. A p-level of 0.05 was considered to be statistically significant.

In Study II, the Pearson Chi-square analysis was used to determine the statistically significant differences in school achievement and Kruska-Wallis ANOVA and the Mann-Whitney U-test were used to reveal differences in attention, leisure time activities and self-esteem. Free questions were taken into account, but the data were not subjected to a statistical examination.

11 PRESENTATION OF THE STUDIES

11.1 STUDY I

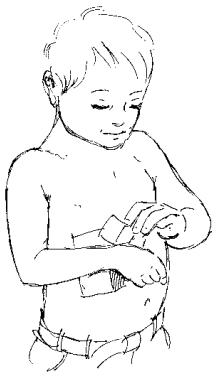


Figure 10. Five year old boy with a right-sided OBPP.

Study I involved 247 children with Obstetrical Brachial Plexus Palsies (OBPP) who were allocated to different groups according to the nerves lesioned, i.e., C5-6, C5-7 and C5-C8(Th1). Each group was further divided into three subgroups, comprised of those for whom nerve reconstruction had been performed, those who were not operated upon, but for whom a full recovery was not accomplished, and "early recovers", comprised of children who had some marked improvement in the function of the biceps and the deltoid before three months of age, see Table IV. The children were examined at 5 years of age according to a special protocol testing the sensory and motor function of the hand, including the Range of Movement (ROM), grip strength, dexterity, tactile sensibility, hand preference and bimanual activity. Our original intention was to randomise children in comparable groups and to perform a controlled study, but this was not possible due to parent's compliance. We believe that, on the whole, the children who received primary surgery were those who had had more severe injuries.

For the prognostic information we found that the children who recovered completely started to regain function within the two first months of life, and in 80% of them this was already evident within the first month.

The ROM of the shoulder for those with C5-6 palsies was significantly better in the group comprised of those who had been operated on, but otherwise there were no differences between the two groups. Neither the timing of the operation, whether it took place before or after 6 months of age, nor the number of avulsions in upper plexus palsies did influence the outcome. We found that several patients with a late recovery (in whom biceps activity was only evident after 3 months of age) no longer fulfilled the criteria for nerve reconstruction at the age of six months. This study does not support the idea that children with no activity of the biceps and the deltoid should be operated on at three months of age, as has been claimed by other authors. Rather, it favours waiting until at least six months to see whether spontaneous recovery will occur.

As far as the hand function is concerned, there is a decreased function in the pick up test, grip strength and bimanual function for those with C5-6 lesions and those with C5-7 lesions, operated on and not operated on. This is remarkable, at least in the C5-6 OBPP, where the hand function and the bimanual activity were expected to be normal. In some cases the results could be attributed to the decreased shoulder rotation, which result in the arm being in a non-functional position often rotating internally; this is sometimes found in combination with decreased supination. This decreased grip strength in the C5-6 group and the hand preference could be caused by increased instability in the shoulder, which would prevent normal use of the affected hand and normal development of its grip strength. It also indicates the importance of a well co-ordinated shoulder and lower arm function for the development of a normal hand function.

The group with complete injuries (C5-Th1) had most root avulsions and their hand function was most significantly correlated to the number of avulsions.

OBP-injury	No. of patients	No. of drop outs	**No. of patients**	old for op	declined operation	LR+	Patients with restored function
C55-6 op	9	1	**8**				
C5-6 unop	16	1	**15**	2	4	1	
C5-6 ER	121	15	**106**				67
C5-7 op	28	4	**24**				
C5-7 unop	39	7	**32**	9	1	6	
C5-7 ER	37	8	**29**				
C5-8(Th1) op	32	5	**27**				
C5-8(Th1) unop	7	1	**6**				

Table V. Participants and drop outs in Study I. Old for op are patients older than one year when admitted to the clinic, LR+ are patients with late recovery (activity in biceps after 3 months of age).

11.2 STUDY II

Figure 11. Teenage girl with a left-sided upper OBPP with "trumpet sign".

The aim of this study was to analyse whether activities and participation in daily life differed between adolescents with obstetric brachial plexus palsy (OBPP) and their able-bodied peers. With the intention of investigating this, fifty-one teenagers born between 1985 and 1987 with OBPP and a comparison group, consisting of 116 age-matched adolescents from a socio-economically and socio-culturally representative area, answered a self-assessment questionnaire concerning their daily life, school performance and friendships.

We found that teenagers with OBPP did not consider themselves to have more attention-related problems than the teenagers in the comparison group, and they estimated themselves to be good or very good at the different tasks involved in their schoolwork, just as often or sometimes more often than those with whom the comparison was being made. Moreover, the adolescents with OBPP did not differ from the comparison group with respect to the time devoted to activities that the subject had chosen by him or herself. The free question revealed no differences between the groups and demonstrated that the most popular activities were "being with friends" or "doing sport".

Differences were, however, found in the levels of self-esteem in activities involving motor performance, with self-esteem being significantly lower in teenagers with the most severe type of OBPP. This was particularly surprising given that the subjects spent the same amount of time performing activities of their choice involving motor performance as the controls.

The most common answer to what the respondents worried about in all groups was "nothing". In the OBPP groups, the second most common answer were "Fear that something might happen that might damage either my affected or unaffected arm". Our conclusion is that, although teenagers with OBPP in our society report living a typical teenage life, indications of distress and worry related to their disability and therefore need to be taken into consideration.

11.3 STUDIES III AND IV

Figure 12. A teenage boy with a right-sided upper OBPP.

In Study III we reported and described the development of established sequelae in obstetrical brachial plexus palsy (OBPP) over a period of time and discuss possible differences in the functional outcome occurring from the age of five years to a follow-up, taking place 2-15 years later. In Study IV we report on the long-term neurophysiological and sensory aspects of OBPP.

A cohort of 70 children/adolescents (age 7-20), 35 male and 35 female, with OBPP of various degrees of severity and a mean age of 13 years and 6 months (SD 4.25 years) were monitored. Thirteen of the 70 participants underwent nerve reconstruction before one year of age. Six of the participants with C5-6 lesions had been fully restored before one year of age. Sixty-eight of the children were examined at five years of age using a standard protocol where the Range of Motion (ROM), grip strength, dexterity and bimanual activity were considered, with the same tests, combined with a quantitative EMG (qEMG) and a quantitative sensory test (QST) being conducted at the follow-up. Tests for functional sensibility and 2 point discrimination for C6 and C8 were performed. Differences in the outcome between the age of five and the actual follow-up were studied.

Active joint motion in the shoulder and hand function, and especially the grip strength, tended to remain unchanged or to improve somewhat, whereas a slight, but significant, deterioration occurred in the elbow function. A relation between differences in the ROM and participation in sports was sought, but the relationship was not significant and did not allow us to draw any conclusions on causality. Shoulder surgery resulted in considerable improvement of the shoulder function. Children/adolescents who had undergone nerve reconstruction had a similar profile of change as the group comprised of those who had not been operated on.

We conclude that the observed decrease in elbow function, and a commonly occurring restriction in external rotation in the shoulder, together with individual variations for the long-term outcome, motivates a continued regular follow-up of children with OBPP beyond the pre-school years.

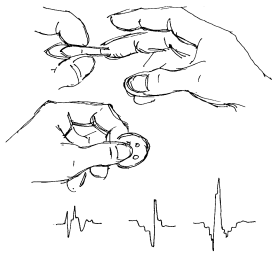


Figure 13. Test of 2PD, stereognosia and picture qEMG.

In Study IV we found that, two of the six patients who were completely free of clinical symptoms, revealed grade 3 changes on qEMG of the deltoid at the follow-up. The other four who were free of clinical symptoms, revealed less changes of the qEMG (grade 1). In conclusion, the study shows that considerable qEMG changes in the deltoid can be seen in those with OBPP, even when they have shown a full functional recovery.

All participants, including those who functionality had been fully restored, displayed abnormal changes in the qEMG of the deltoid. The EMG abnormalities were more evident at the follow-up (at 7-20 years) than at the initial examination made at 3-7 months of age; and this difference was significant ($p = 0.003$).

The qEMG abnormalities were more widespread for the interosseii, including both normal patterns and severe atrophy-related changes (grade 5) and, in contrast to the situation with the deltoid, the EMG changes did not alter over time between the initial

assessment and the follow-up. No significant improvement was observed in the EMG for the interosseii for those who had undergone nerve reconstruction

Sensibility was markedly less severely affected than motor function. Despite the existence of severe lesions with root avulsions of C8-Th1, all participants experienced sensibility in their hand. All felt cold and warmth, even if the threshold values were elevated on average. The ability to discriminate, as measured by 2PD, was more severely impaired. The results of the various methods used correlated well for the most severe lesions. This was especially true of deviations in 2PDC8 and functional sensibility, which proved to be useful methods for indicating impaired sensibility. Of the tests used for sensibility, functional sensibility best estimates global hand function, whilst 2PDC8 was the measure that best correlated to functional sensibility.

We observed signs not only of peripheral plasticity, but also of central plasticity. This includes a switch of handedness, and the surprisingly good sensibility.

12 SUMMARY

The children who recovered completely started to regain function within the two first months of life, and 80% of them within the first month.

The overall shoulder activity was better in the group comprised of those who had undergone nerve reconstruction than in the group made up of those who had not been operated on. Despite the low numbers of participants, the difference was significant. The time, at which the operation took place, i.e., whether it occurred before or after 6 months of age, did not influence the result.

A decrease in grip strength and bimanual function was found in children/adolescents with C5-6 lesions.
In Study I 28% of those with a right-sided C5-6 plexus lesion were left-handed and in the C5-7 group, 65% of those with right-sided lesions were left-handed. This result was confirmed in Study III, where 68% of the children/adolescents with right-sided OBPP were left-handed. Of the six adolescents, who had recovered fully, three had a right-sided lesion, one of whom was left-handed.
In the long term follow-up presented in Study III we found that active joint motion in the shoulder and hand function, especially the grip strength, generally remained unchanged or improved somewhat, whereas a slight but significant deterioration was evident in the elbow function. Shoulder surgery resulted in considerable improvement in the shoulder function. Children/adolescents who had undergone nerve reconstruction had a similar profile concerning change to those who had not been operated on.
We could not find any relationship between differences in the ROM and participation in sports, even when some of the adolescents who participated extensively in sports at a competitive level had improved both their shoulder and arm function without having an operation.

Considerable EMG changes can be seen in those with OBPP even in when they have recovered fully.
The EMG changes in the deltoid deteriorate with time.

Sensibility is considerably less affected than motor function in young people with OBPP.

The majority of children/adolescents (75%) did not perceive that they had any problems at all as far as ADL were concerned. This was true of 85% of the participants with C5-6 involvement and 70% of participants in the C5-7 group.

Adolescents with OBPP report living a typical teenage life today in our society. However, indications of distress and worry related to the disability ought/need to be considered.

13 DISCUSSION

These studies are all about the follow-up and treatment of OBPP. During the twenty years over which data have been collected the incidence has not decreased, but rather, increased. Efforts have been made among the obstetricians to identify and handle different risk factors (1, 2, 11, 68). The concern shown to the mothers of children with OBPP, the information given and the handling of the next pregnancy have been much better during these 20 years. Also there has been an improvement in the care of the children with OBPP.

13.1 METHOD

13.1.1 Sensibility

Medical investigations differentiate between the ability to discern touch and the ability to discriminate whether a touch is restricted to one point, or is made at two close points simultaneously. As mentioned above, Study I indicated that all children could localize touch, which is why we excluded this test in Studies III and IV. Anand and Birch used Semmes-Weinsteins monofilament to determine the touch threshold (64), but we expected identification of low threshold values to be a prerequisite for the ability to discriminate between a touch from one or two points, the 2PD test. Since this test is even more sensitive, we preferred to perform the 2PD test. The results of the various methods used correlated well for the most severe lesions. This was especially true of deviations in 2PDC8 and functional sensibility, which proved to be useful methods for indicating impaired sensibility. Of the tests used for sensibility, functional sensibility provides the best estimate of global hand function, whilst 2PDC8 was the measure that best correlated to functional sensibility.
The test known as QST dorsal was thought to differentiate between root avulsions and nerve lesions like neurotmesis. However, it seems to have a very low sensitivity for root avulsions. For example, in 12 out of 13 patients who had undergone nerve reconstruction, one had values for warmth that deviated from the norm, but all the others had normal values, even though we know that eight of them had a root avulsion of C6 or C8 or both.

13.1.2 The questionnaire for self-assessment

Questions might be posed concerning the choice of questionnaire and, in particular, why we did not use some of the alternatives available. With the intention of depicting the different areas of functioning in as broad a manner as possible, we chose the "Ansula" questionnaire (67). Clinical teams in Sweden have used the form to gain information on participation for children with neuropsychiatric disorders but, at the time the research presented here commenced, it had not been used for research. As a result of this, we had to create an age-matched comparison group to obtain a Swedish reference for the statistical calculations. We discussed whether it would be possible to use the Swedish SF-36 Health survey, but the questions posed were directed towards more severely handicapped children than those] with OBPP, and the activity-related questions seemed somewhat irrelevant to these adolescents, with questions like can you manage stairs and can you walk one kilometre, being included. A Swedish version of the Child Health Questionnaire, designed to measure physical and psychosocial functioning, exists (64, 69), with one version that was written for the children and another for the parents, but as we preferred to focus on participation, these were not considered to be ideal for this investigation. The Ansula questionnaire is intended to find out about the youngsters' own views of their schoolwork and their

social participation. Other potentially suitable questionnaires in the ANSER system intended for use in gathering the opinions of teachers and parents exist, and we considered to use these, however that would for practical reasons not be possible to perform for the control group. Since this system by that time was not validated for the Swedish population we preferred to have a control group of able-bodied teenagers. For completeness, it should be mentioned that there are some questionnaires specifically focusing on self-esteem in children and adolescents, but as "Ansula" enabled us to obtain broader information about the participants' overall daily life situation, it was believed to be a more sound choice.

13.2 PROGNOSIS AND TREATMENT

Our studies confirm earlier conclusions of the favourable prognosis for C 5-6(7) lesions. When activity in the biceps and the deltoid are regained within the first two months of life, there is a good chance of complete recovery. C5-6 lesions have the most favourable outcome, probably partly because of the "luxury innervation" observed for C7, and in Sweden these patients rarely need to have an operation involving nerve reconstruction. Less than a handful of children with C5-7 lesions undergo nerve reconstruction at the age of 6-12 months in Sweden each year. They seem to obtain better shoulder function as a result, as has been found in other studies (70). Though, the time at which the operation takes place, that is, whether it is undertaken before or after six months of age, does not influence the result in our studies. Thus, although infants with complete OBPP should undergo nerve reconstruction, and in these cases there is no reason to wait for the child to be more than three months when the operation takes place, it is recommended that the outcome of other children be awaited until six months before deciding whether to operate or not.

Even though nerve reconstruction during the first year of life seems to help children with severe OBPPs, secondary surgery involving shoulder surgery, tendon transfer and osteotomias help a larger number of children, and these operations are much more common than nerve surgery in Sweden. Study III revealed that children/adolescents who had undergone shoulder surgery had significantly better shoulder function, and a thorough long-term follow-up of these children is going on in the department of hand surgery in Stockholm.

Physiotherapy is the traditional treatment for OBPP. The physiotherapist's role in encouraging the parents to pursue their child's treatment regularly and over an extended period is of importance, and many parents have requested more physiotherapy, but we have not found that there are better results for those children who receive more physiotherapy. Typically, difficulties arise in adolescence when children no longer want to attend a physiotherapist or do the stretching recommended by their parents. The challenge at this age is to encourage them to take responsibility for their care. When a group of teenagers with OBPP was asked about a message to their parents a frequent response was to get more stimulation from them to train. It is not unusual for deterioration to be observed in the elbow extension during early adolescence, and teenagers should be made aware of this and be informed about how best to combat it. Two adolescents doing extensive physical training did not deteriorate in the same way as those who do not engage in such strenuous activity, and they were more aware of their bodies.

13.3 SENSIBILITY

Children and adolescents with an OBPP that includes C5-6(7) are able to use their hand and will also use and train its sensibility. Nevertheless, 60-80% (71, 72) of those

with right-sided OBPI are left-handed. Is that because their arm is weaker, has impaired sensibility or is it the suggested developmental apraxia caused by defective motor programming in early infancy, as suggested by Brown et al (26)?
It appears to be important to start training sensory function as soon as possible after nerve injuries have occurred (34, 64, 73). When practising sensory therapy we tend to stimulate other senses more with children, for example, singing songs using different words for different fingers, painting the fingers in different colours, etc. The intensive stretching recommended during the first year of life might not only prevent contractures, but also make the infant aware of the limb by stimulating perception, and improving/and reinforcing motor- and sensory programming.
Despite the fact that the sensibility is severely impaired in children with complete OBPP, their motor functions is always affected to a much greater degree than the sensibility. All children we have seen with complete OBPP have gained some sensibility and can localize touch, even when they have four root avulsions. Thus, as patients will not use a hand on until they are able to feel with it, it might not be until two, three or even more years have passed since they underwent nerve reconstruction that they will start to use the affected hand. All felt cold and warmth, even if the threshold values were elevated, findings which are in line with results from Anand & Birch (64). It was the ability to discriminate, as measured by 2PD, which was more severely impaired. Lateral inhibition might not be sufficiently effective after severe OBPI to enable the finest 2PD, although it does evidently allow satisfactory stereognosis.
Our results are in line with previous results indicating that sensory neurons are better able to survive injury than motor neurons in neonatal rats in which selected nerves had been lesioned (74). Further, for their survival, motor neurons appear to be dependent on trophic factors from their target cell, a mechanism that is less important for sensory neurons. In the young, sensory neurons always project to several spinal segments (75), in contrast to motor neurons, are restricted to 2-3 segments. Thus, one can speculate that this represent a general form of “luxury” innervation for the sensibility referred to above. Finally, we speculate that the receptive fields of single sensory neurons may enlarge more substantially than the motor unit following nerve lesion.
To sum up, we need to be more aware of the need for sensory training even for those with C5-6(7) lesions, rather than only focusing on ROM and muscle strength.

13.4 EMG

The EMG changes found in the fully restored teenagers are of interest. As mentioned above the motor unit might be enlarged 25 fold (20)and these six teenagers must have had an axonotmesis, rather than only a conduction block, since their recovery went on for at least three months before they had regained all function. Are these young persons more likely to suffer pain and more vulnerable to exhaustion in the arm that had been affected in adulthood? One of the boys whose function had been fully restored within the first six months of life and who did not remember on which side he had his OBPI, participated in a follow up investigation when he was 17 years old. He recounted how, some weeks before in a gym, he had done hard strength training after which his right arm was stiff and he couldn’t stretch it properly. Two or three days after this occasion he was completely restored and an EMG performed some weeks later revealed Grade 3 EMG changes of the deltoid in his right arm where he had had an OBPI. Should we recommend this young man not to exercise with such intensity? If he continues to do so, is there a risk of exhaustion like that in the post polio syndrome? This is an issue for further research.

There is a deterioration of the EMG of the deltoid from the age of 3-7 months to the follow-up 2-15 years later, but not of the EMG of the interosseii. One explanation for this is that the deltoid was involved for all children/adolescents, but only those with severe C5-7 lesions and complete lesions registered changes to the EMG of the interosseii, and those with complete lesions all exhibited Grade 4 changes to the interosseii at 3-7 months of age. In the C5-7 group, three of 15 participants had EMG changes of Grade 3-4 in the first months of life and seven of 24 had EMGs of Grade 3-4 at the follow-up, which is not a significant deterioration. This difference between the EMG changes in the deltoid and the interosseii might also be attributable to the relative distance from the lesion. In the regenerative process, fewer motor neurons are expected to succeed in reaching the intrinsic muscles than the shoulder muscles.
The deterioration of the qEMG of the deltoid, that is evident in all those who have suffered an OBPI, again raises the question of the advice that should be given to young people with OBPP concerning exercise.

13.5 ACTIVITY AND PARTICIPATION

The majority of the children/adolescents (75%) did not perceive that they had any problems at all as far as ADL were concerned. This corresponds well to the findings of Hoeksma (8) and Ho (41). All participants managed well with their schoolwork, including using the computer, and, with just three exceptions, all those at school attended the physical education classes even if they could not manage all elements. To sum up, the participation in society is good and the teenagers with OBPP seem to live a typical teenage life. Having established this, however, it is important to note they are very much aware of their handicap and they are often worried that something might happen to either of their hands or arms.

14 FUTURE

Interest in OBPP is extensive and so far we have seen plenty of reports of the natural outcome, the prognosis and the results of surgery. Numerous obstetrical studies have been conducted and, in the southwest of Sweden, at least four studies have recently been published (1, 2, 11, 68). Over the last year, interest in sensibility and function has increased (6, 34, 41, 64); studies about cerebral and spinal plasticity and relearning after periphery nerve injuries have probably contributed to this.

My coming study is in collaboration with assisting professor Gunnar L. Olsson, department of child anaesthesia in Astrid Lindgren Childrens' Hospital. We have an ongoing research programme about pain in adults with OBPP. Children and adolescents with OBPP rarely report suffering pain (64), although in our patient group we have some patients with neuropatic pain, especially when that have a fever. Of these, two have a complete OBPP and one has a severe C5-7 lesion. All three have undergone nerve reconstruction. They all describe a burning pain in the forearm and hand and a need for medication for it. When asking young people about pain quite a number of them admit that they do experience some, often in the shoulder or upper arm after physical exercise. This disappears shortly after they finish training. The ongoing study is searching for problems related to the increased pain in adults with restored and non-restored OBPP.

Together with occupational therapist Lena Krumlinde I also want to disseminate the results of our studies in the local habilitation teams working with the patients in their locality. As mentioned above, we regularly hold seminars for therapists training children with OBPP, but we also want to start a study to see whether it is possible to avoid specific problems, for example, the flexion contracture in the elbow.

A new method for measuring how effectively the affected hand is used for bimanual activities, the Assisting Hand Assessment (AHA), has been developed by one of the occupational therapists in the team, Lena Krumlinde-Sundholm (59, 60, 61?). The AHA provides a new perspective on hand function tests by recognizing the different roles the two hands play in bimanual performance. The affected hand generally serves as a non-dominant hand, so it does not need to be as quick or as accurate as a dominant hand. The AHA measures how effectively the affected hand assists and, interestingly, children with OBPP are usually very clever at using the affected hand to assist, even if they have severely affected hand function. The AHA is used in conjunction with traditional measures, such as grip strength, and used in this way it is able to provide complementary information on the functional use of the hand/arm. It is necessary to have a standardised method for evaluation to confirm changes that take place during development and to examine the impact of interventions. We are planning to conduct a longitudinal investigation to follow children with OBPP using the AHA.

The hand surgeon of the plexus team, Dr. Tomas Hultgren, who has been in charge of the surgical treatment of OBPP patients in Sweden since 1996, is conducting a detailed follow up of the outcome for and clinical results of 200 OBPP patients who had been operated on, undergoing shoulder surgery between 1996-2006. Evaluation of the long-term effects on mobility and function is done in collaboration with one of the team's occupational therapists, Birgitta Lindqvist. The development of the

shoulder joint following surgery is analysed using radiological techniques. As an important part of this study, the first group of patients who were operated on can now be thoroughly evaluated 10 years after receiving their initial treatment.

Thus, despite the growing body of literature on OBPP, there are several areas where we find it important to increase the knowledge.

15 ACKNOWLEDGEMENTS

So many persons have supported me, encouraged me and advised me through all the years I have been working with children with obstetrical brachial plexus palsy. I really want to thank all who have contributed to this thesis in any way, and in particular, I would like to mention the following:

All of the children and teenagers with OBPP and their parents, for your interest and willingness to participate in all studies.

My supervisor, Associate Professor Thomas Sejersen, for your support and belief in my work. Thank you for all the nice lunch-meetings and discussions, and for encouraging me when I had doubts about my work.

Professor Thomas Carlstedt who introduced me to the field of obstetrical brachial plexus palsies, and with whom I started up the plexus team and commenced the follow-up studies before he left for England.

Professor Hans Forssberg, who introduced me to the field of research and was the co-author of my first article. Thank you for all your support for my work with OBPP and for enabling me to work with OBPP even when I was in charge of the open ward and at Sachs Childrens' Hospital.

Associate Professor Sten Remahl, my co-supervisor, for introducing me to neurophysiology, for your support and for all those interesting discussions over the years.

My co-author Lena Krumlinde Sundholm for fruitful collaboration during the past 20 years. We have planned studies, discussed results, written articles, had lectures, travelled and laughed together. Thank you for your friendship and support.

Associate Professor Elisabeth Fernell, my co-author, for your interest, encouragement and friendship.

Hand surgeon Tomas Hultgren for your help and support, especially concerning surgical knowledge and writing about this in my articles.

The members of the Plexus team, Tomas Hultgren, Lena Krumlinde Sundholm, Carin Allert, Birgitta Lindqvist and Annika Johnson for all these years of instructive and joyful collaboration.

Airi Jantuneen for all the work you have done to ensure that the schedule is as near ideal as it can be for the children and the plexus team alike!

Hans Forssberg, Per Åmark and Kerstin Dahlström the past and present heads of the Department of Neuropaediatrics at Astrid Lindgren Children's Hospital for creating a scientific environment thereby offering the opportunity to further research whilst caring for patients.

All my colleagues in the Department of Neuropaeditrics. You are a great! I am especially grateful for your support and understanding when I have been out of clinical work during my research.

Per Sandstedt, the head of Sachs Children's Hospital, and Eva Esscher, former head of the Neuropaediatric Department in Sachs Children's Hospital for supporting me and encouraging me to continue my work with OBPP during the years I worked there. My thanks, too, go to my then colleagues Lena Starck and Kerstin Sars-Zimmer for support during those years.

Ulrika, Carina and Kristina for being such nice and helpful secretaries.

My dear aunt, Kerstin Westerberg, for your perfect illustrations.

Elisabeth Berg for support with all the statistical issues.

Suzy Lidström for quick and instructive revision of the English text.

Eva Åström, Katarina Wide and Suzanne Marcus for being good colleagues and great friends. Thank you for your support and encouragement and the enjoyable dinners we have had together.
All other good colleagues, in Stockholm and on the west coast, with or without sailing boats, for your friendship and for giving me inspiration, joy and the energy to finish this thesis. Thank you Nina for all help when everything seemed chaotic.
My dear parents Jan-Olof and Margareta Strömbeck who always have supported me and believed in me, and my dear brothers Carl-Magnus, Jan-Paul and Peter for your love and understanding. My sister My for being such a good friend and sister. Thanks for all the help and support and all the laughs and good times we have had together.
My dear Anders for your support and enthusiasm. You have always supported me, encouraging me to fulfil this work, even though you didn't realise this was a marathon run…
My beloved children Albin and Josefin for all your support, and help with computer problems. And for all the joy you have brought to me and for reminding me about the most important things in life.

These studies have been supported by Frimurare Barnhuset in Stockholm, Norrbacka-Eugenia Stiftelsen, Stiftelsen Samariten, Stiftelsen Solstickan, Stiftelsen Sunnerdahls handikappfond, Stiftelsen Sven Jerrings Fond and Riksförbundet för rörelsehindrade Barn och Ungdomar. Without this funding, this thesis would not have been possible to fulfil.

16 REFERENCES

1.Mollberg M, Hagberg H, Bager B, Lilja H, Ladfors L. High birthweight and shoulder dystocia: the strongest risk factors for obstetrical brachial plexus palsy in a Swedish population-based study. Acta Obstet Gynecol Scand 2005;84(7):654-9.

2.Christoffersson M, Kannisto P, Rydhstroem H, Stale H, Walles B. Shoulder dystocia and brachial plexus injury: a case-control study. Acta Obstet Gynecol Scand 2003;82(2):147-51.

3.Slooff AC. Obstetric brachial plexus lesions and their neurosurgical treatment. Clin Neurol Neurosurg 1993;95 Suppl:S73-7.

4.Geutjens G, Gilbert A, Helsen K. Obstetric brachial plexus palsy associated with breech delivery. A different pattern of injury. J Bone Joint Surg Br 1996;78(2):303-6.

5.Ubachs JM, Slooff AC, Peeters LL. Obstetric antecedents of surgically treated obstetric brachial plexus injuries. Br J Obstet Gynaecol 1995;102(10):813-7.

6.Hoeksma AF, ter Steeg AM, Nelissen RG, van Ouwerkerk WJ, Lankhorst GJ, de Jong BA. Neurological recovery in obstetric brachial plexus injuries: an historical cohort study. Dev Med Child Neurol 2004;46(2):76-83.

7.Hardy AE. Birth injuries of the brachial plexus: incidence and prognosis. J Bone Joint Surg Br 1981;63-B(1):98-101.

8.Hoeksma AF, Wolf H, Oei SL. Obstetrical brachial plexus injuries: incidence, natural course and shoulder contracture. Clin Rehabil 2000;14(5):523-6.

9.Bager B. Perinatally acquired brachial plexus palsy-a persisting challenge. Acta Paediatr 1997;86(11):1214-9.

10.Sjoberg I, Erichs K, Bjerre I. Cause and effect of obstetric (neonatal) brachial plexus palsy. Acta Paediatr Scand 1988;77(3):357-64.

11.Mollberg M, Hagberg H, Bager B, Lilja H, Ladfors L. Risk factors for obstetric brachial plexus palsy among neonates delivered by vacuum extraction. Obstet Gynecol 2005;106(5 Pt 1):913-8.

12.Duchenne G. De l'Éléctrisation Localisée et de son Application à la Pathologique et à la Thérapeutique. Paris:Balliere 1872:357-62.

13.Erb. Uber eine eigenthumlich Lokalisation von Lähmungen im Plexus brachialis. Vehr Natur Med 1874;2:130-137.

14.Klumpke A. Klumpke's paralysis. 1885. Clin Orthop Relat Res 1999(368):3-4.

15.Al-Qattan MM, Clarke HM, Curtis CG. Klumpke's birth palsy. Does it really exist? J Hand Surg [Br] 1995;20(1):19-23.

16.Narakas AO. The paralysed hand. Edinburgh: Churchill Livingstone; 1987.

17.Wolf H, Hoeksma AF, Oei SL, Bleker OP. Obstetric brachial plexus injury: risk factors related to recovery. Eur J Obstet Gynecol Reprod Biol 2000;88(2):133-8.

18.Goel SP, Agarwal RP, Garg BK, Mathur SK. Nerve injuries in neonates. J Indian Med Assoc 1989;87(6):132-4.

19.Birch R. Birth lesions of the brachial plexus. In: Livingstone C, editor. Surgical Disorders of the Peripheral Nerves. Edinburgh; 1998.

20.Roeleveld K, Sandberg A, Stalberg EV, Stegeman DF. Motor unit size estimation of enlarged motor units with surface electromyography. Muscle Nerve 1998;21(7):878-86.

21.Mancias P, Slopis JM, Yeakley JW, Vriesendorp FJ. Combined brachial plexus injury and root avulsion after complicated delivery. Muscle Nerve 1994;17(10):1237-8.

22.van Dijk JG, Pondaag W, Malessy MJ. Obstetric lesions of the brachial plexus. Muscle Nerve 2001;24(11):1451-61.

23.Bisinella GL, Birch R. Obstetric brachial plexus lesions: a study of 74 children registered with the British Paediatric Surveillance Unit (March 1998-March 1999). J Hand Surg [Br] 2003;28(1):40-5.

24.Papazian O, Alfonso I, Grossman JA. [Neurophysiological assessment of children with obstetric brachial plexus palsy]. Rev Neurol 1998;27(156):263-70.

25.van Dijk JG, Malessy MJ, Stegeman DF. Why is the electromyogram in obstetric brachial plexus lesions overly optimistic? Muscle Nerve 1998;21(2):260-1.

26.Brown T, Cupido C, Scarfone H, Pape K, Galea V, McComas A. Developmental apraxia arising from neonatal brachial plexus palsy. Neurology 2000;55(1):24-30.

27.Stålberg E, editor. Clinical Neurophysiology of Disorders of Muscle and Neuromuscular junction, Including Fatigue
Handbook of Clinical Neurophysiology: Elsevier; 2003.

28.Jenkins WM, Merzenich MM, Recanzone G. Neocortical representational dynamics in adult primates: implications for neuropsychology. Neuropsychologia 1990;28(6):573-84.

29.Kandel ER JT. Principles of neural science. Third ed. New York: Elsevier Science Publishing Co; 1991.

30.Lundborg G. Brain plasticity and hand surgery: an overview. J Hand Surg [Br] 2000;25(3):242-52.

31.Eliasson AC, Krumlinde-sundholm L, Shaw K, Wang C. Effects of constraint-induced movement therapy in young children with hemiplegic cerebral palsy: an adapted model. Dev Med Child Neurol 2005;47(4):266-75.

32.Taub E, Uswatte G, Elbert T. New treatments in neurorehabilitation founded on basic research. Nat Rev Neurosci 2002;3(3):228-36.

33.Ro T, Noser E, Boake C, Johnson R, Gaber M, Speroni A, et al. Functional reorganization and recovery after constraint-induced movement therapy in subacute stroke: case reports. Neurocase 2006;12(1):50-60.

34.Lundborg G, Rosen B. Sensory relearning after nerve repair. Lancet 2001;358(9284):809-10.

35.Lundborg G. Richard P. Bunge memorial lecture. Nerve injury and repair--a challenge to the plastic brain. J Peripher Nerv Syst 2003;8(4):209-26.

36.Chen R, Anastakis DJ, Haywood CT, Mikulis DJ, Manktelow RT. Plasticity of the human motor system following muscle reconstruction: a magnetic stimulation and functional magnetic resonance imaging study. Clin Neurophysiol 2003;114(12):2434-46.

37.Vredeveld JW, Blaauw G, Slooff BA, Richards R, Rozeman SC. The findings in paediatric obstetric brachial palsy differ from those in older patients: a suggested explanation. Dev Med Child Neurol 2000;42(3):158-61.

38.Korak KJ, Tam SL, Gordon T, Frey M, Aszmann OC. Changes in spinal cord architecture after brachial plexus injury in the newborn. Brain 2004;127(Pt 7):1488-95.

39.WHO. International classification of functioning, disability and health. Geneva: World Health Organization; 2001.

40.Gjorup L. Obstetrical lesion of the brachial plexus. Acta Neurol Scand 1966;42:Suppl 18:1-80.

41.Ho ES, Curtis CG, Clarke HM. Pediatric Evaluation of Disability Inventory: its application to children with obstetric brachial plexus palsy. J Hand Surg [Am] 2006;31(2):197-202.

42.Bent N, Jones A, Molloy I, Chamberlain MA, Tennant A. Factors determining participation in young adults with a physical disability: a pilot study. Clin Rehabil 2001;15(5):552-61.

43.Kennedy R. Suture of the brachial plexusin birth paralysis of the upper extremity. British Medical Journal 1903;1:298-301.

44.Narakas AO. The treatment of brachial plexus injuries. Int Orthop 1985;9(1):29-36.

45.Narakas A. Brachial plexus surgery. Orthop Clin North Am 1981;12(2):303-23.

46.Gilbert A, Khouri N, Carlioz H. [Birth palsy of the brachial plexus--surgical exploration and attempted repair in twenty one cases (author's transl)]. Rev Chir Orthop Reparatrice Appar Mot 1980;66(1):33-42.

47.Gilbert A, Brockman R, Carlioz H. Surgical treatment of brachial plexus birth palsy. Clin Orthop 1991(264):39-47.

48.Mallet J. [Obstetrical paralysis of the brachial plexus. II. Therapeutics. Treatment of sequelae. Priority for the treatment of the shoulder. Method for the expression of results]. Rev Chir Orthop Reparatrice Appar Mot 1972;58:Suppl 1:166-8.

49.Gilbert A, Tassin JL. [Surgical repair of the brachial plexus in obstetric paralysis]. Chirurgie 1984;110(1):70-5.

50.Tassin JL. Paralysies Obstetricales du Plexus Brachial. Evolution Spontanee, Resultats des Interventions Reparatrices Precoses. Paris: Univerisity Paris VII; 1983.

51.Hentz VR, Meyer RD. Brachial plexus microsurgery in children. Microsurgery 1991;12(3):175-85.

52.Clarke HM, Curtis CG. An approach to obstetrical brachial plexus injuries. Hand Clin 1995;11(4):563-80.

53.Birch R. Obstetric brachial plexus palsy. J Hand Surg [Br] 2002;27(1):3-8.

54.Zancolli EA, Zancolli ER, Jr. Palliative surgical procedures in sequelae of obstetric palsy. Hand Clin 1988;4(4):643-69.

55.Al-Qattan MM. Elbow flexion reconstruction by Steindler flexorplasty in obstetric brachial plexus palsy. J Hand Surg [Br] 2005;30(4):424-7.

56.Ishida O, Sunagawa T, Suzuki O, Ochi M. Modified Steindler procedure for the treatment of brachial plexus injuries. Arch Orthop Trauma Surg 2006;126(1):63-5.

57.Krumlinde-Sundholm L, Eliasson AC, Forssberg H. Obstetric brachial plexus injuries: assessment protocol and functional outcome at age 5 years. Dev Med Child Neurol 1998;40(1):4-11.

58.Michelow BJ, Clarke HM, Curtis CG, Zuker RM, Seifu Y, Andrews DF. The natural history of obstetrical brachial plexus palsy. Plast Reconstr Surg 1994;93(4):675-80; discussion 681.

59.Moberg E. Objective methods for determining the functional value of sensibility in the hand. J Bone Joint Surg Br 1958;40-B(3):454-76.

60.Menier C, Forget R, Lambert J. Evaluation of two-point discrimination in children: reliability, effects of passive displacement and voluntary movements. Dev Med Child Neurol 1996;38(6):523-37.

61.Cope EB, Antony JH. Normal values for the two-point discrimination test. Pediatr Neurol 1992;8(4):251-4.

62.Krumlinde-Sundholm L, Eliasson AC. Comparing tests of tactile sensibility: aspects relevant to testing children with spastic hemiplegia. Dev Med Child Neurol 2002;44(9):604-12.

63.Fruhstorfer H, Lindblom U, Schmidt WC. Method for quantitative estimation of thermal thresholds in patients. J Neurol Neurosurg Psychiatry 1976;39(11):1071-5.

64.Anand P, Birch R. Restoration of sensory function and lack of long-term chronic pain syndromes after brachial plexus injury in human neonates. Brain 2002;125(Pt 1):113-22.

65.Birchansky S, Altman N. Imaging the brachial plexus and peripheral nerves in infants and children. Semin Pediatr Neurol 2000;7(1):15-25.

66.Miller SF, Glasier CM, Griebel ML, Boop FA. Brachial plexopathy in infants after traumatic delivery: evaluation with MR imaging. Radiology 1993;189(2):481-4.

67.Isberg E, Kjellman B. Multidisciplinary assessment of children with deficits relating to attention, motor activity and perception: evaluation of the ANSER model. Child Care Health Dev 1999;25(5):359-76.

68.Christoffersson M, Rydhstroem H. Shoulder dystocia and brachial plexus injury: a population-based study. Gynecol Obstet Invest 2002;53(1):42-7.

69.Andersson Gare B, Ruperto N, Berg S, Hagelberg S, Jonsson NO, Magnusson B, et al. The Swedish version of the Childhood Health Assessment Questionnaire (CHAQ) and the Child Health Questionnaire (CHQ). Clin Exp Rheumatol 2001;19(4 Suppl 23):S146-50.

70.Gilbert A. Long-term evaluation of brachial plexus surgery in obstetrical palsy. Hand Clin 1995;11(4):583-94.

71.Yang LJ, Anand P, Birch R. Limb preference in children with obstetric brachial plexus palsy. Pediatr Neurol 2005;33(1):46-9.

72.Strombeck C, Krumlinde-Sundholm L, Forssberg H. Functional outcome at 5 years in children with obstetrical brachial plexus palsy with and without microsurgical reconstruction. Dev Med Child Neurol 2000;42(3):148-57.

73.Birch R. The brachial plexus: 1. J Hand Surg [Br] 1992;17(5):495-7.

74.Schmalbruch H. The effect of peripheral nerve injury on immature motor and sensory neurons and on muscle fibres. Possible relation to the histogenesis of Werdnig-Hoffmann disease. Rev Neurol (Paris) 1988;144(11):721-9.

75.Ygge J. Central projections of the rat radial nerve investigated with transganglionic degeneration and transganglionic transport of horseradish peroxidase. J Comp Neurol 1989;279(2):199-211.