Functional Outcomes of Triple Nerve Transfers Compared to Traditional Nerve Grafting in Upper Trunk Obstetrical Brachial Plexus Injuries

by

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Abstract

Children with obstetrical brachial plexus injuries may experience difficulties in some or all functional domains defined under the International Classification of Function. It can result in partial or complete paralysis of the arm. Secondary complications may include limb length discrepancy, and changes to the shoulder including glenoid deformity and posterior subluxation of humeral head. In addition to impacting body structure and function of the children, brachial plexus injuries can also affect the overall health and psychosocial condition of the children and their parents.

In an effort to improve their arm function, different surgical options have been tried. Nerve reconstruction using sural nerve graft, popularized in the 1960s, still remains the gold standard. Although nerve transfers are widely done in the adult population with upper trunk brachial plexus injury, its role in children with obstetrical upper trunk brachial plexus injuries remains unclear.

The main goal of this thesis is to evaluate the efficacy of the triple nerve transfer surgical procedure by comparing the functional outcomes and healthcare costs in a cohort of children with upper trunk brachial plexus injury. Fourteen children who received triple nerve transfers were compared to twelve children who received sural nerve grafting procedure using the Active Movement Scale as the primary outcome measure. We found that the triple nerve transfer group demonstrated significantly higher scores in shoulder external rotation, elbow flexion and forearm supination 2 years post operatively. In addition, they also demonstrated high scores on the Assisting Hand Assessment that measures how effectively the children can use the involved hand in bimanual activities.

In terms of healthcare cost, the triple nerve transfer surgical technique required less surgical time, shorter hospital length of stay and less frequent need for secondary orthopaedic procedures. Based on these findings, we conclude that triple nerve transfers could be a useful option in the armamentarium of treatment for upper trunk obstetrical brachial plexus injuries.

Preface

This thesis is an original work by Kathleen O'Grady. The research project, of which this thesis is part, received research ethics approval from the University of Alberta and University of Calgary Research Ethics Board, Project Name Peripheral Nerve Injuries in Alberta, No Pro00008901, October 6, 2016.

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Table and Figures

List of Abbreviations

AHA	Assisting Hand Assessment
AMS	Active Movement Scale
BPOM	Brachial Plexus Outcome Measure
BMRC MMT	British Medical Research Counsel Manual Muscle Testing
ICF	International Classification of Function
OBPI	Obstetrical Brachial Plexus Injury
PEDI-CAT	Pediatric Evaluation Disability Inventory Computer Adaptive Test
PODCI	Pediatric Outcome Data Collection Instrument

Chapter 1: Epidemiology and pathophysiology of obstetrical brachial plexus injuries

Clinical vignette

Clara is a 9 month old second child of the family. She was born full term, weighing 10 pounds 9 ounces. Her mother was healthy with no history of gestational diabetes or hypertension. Her first child weighed 7 pounds 2 ounces and had no complication with delivery. Clara's birth was complicated by shoulder dystocia. Shortly after birth her parents noticed that Clara could not move her right arm. After 3 weeks she was able to move her fingers, thumb and wrist but she continued to show marked weakness in her shoulder, elbow and forearm. She was subsequently referred to a brachial plexus clinic. After a physical exam and EMG studies at 5 weeks of age, she was diagnosed with an upper trunk brachial plexus injury.

Clara received regular rehabilitation from an occupational therapist. Although she showed some improvement, at 9 months of age, she was still unable to get her hand to her mouth without using trick movements with her shoulder known as the trumpet sign. At that point, her affected arm was 2 cm shorter than her other limb. Scapular winging was evident when she tried to move her shoulder into flexion and cross adduction while reaching up for objects. While performing bimanual tasks, she often reached across the table to grab objects with her left hand with little participation from the right arm. When she did try to use the right arm, due to a lack of elbow flexion and forearm supination, she often had to use compensatory movements to handle objects. Therefore, for many bimanual tasks like taking off a hat, trapping a large ball or pulling to stand, Clara *performed these tasks one handed. For those reasons, along with Clara's family, a decision was made to proceed with a nerve repair operation.*

Introduction

The challenge that Clara faces is a common scenario seen in children with obstetrical brachial plexus injuries. The type of nerve injuries sustained can range from the mildest form, neurapraxia that would spontaneously resolve to the most severe form with total root avulsion with little to no chance of recovery. The roots, trunks and branches can be damaged at different levels and to varying degrees, resulting in different combinations of functional deficits in the affected arm. Among them, upper trunk injury is the most common. Commonly known as Erb's palsy, it primarily impacts shoulder and elbow movements, namely shoulder flexion, abduction, external rotation, elbow flexion and forearm supination. The addition of middle trunk involvement to an upper trunk injury can also affect shoulder internal rotation, elbow extension, forearm pronation, wrist extension, finger extension and thumb extension. Total plexus injuries, the most severe form, affect the entire arm and hand including grip impairment.

In this chapter, the prevalence and types of obstetrical brachial plexus injury in North America and Europe will be reviewed. It will address how these types of injuries impact the function of the child based on the International Classification of Function framework. Several outcome measures have been developed that look at all aspects of the International Classification of Function, including impairment, activity and participation. Environmental and personal factors will impact outcome. The most robust outcome measures that have good construct validity will be discussed in detail. The inter-rater and intra-rater reliability of these measures will also be examined and the outcome measure will be placed within the ICF framework.

Peripheral nerve reconstruction surgical options for children with obstetrical brachial plexus injuries that meet the criteria for surgical intervention will be discussed. Of particular relevance to this thesis is the comparison of the current gold standard surgical approaches in the adult population to the current state of surgical options for the obstetrical brachial plexus population. Lastly, the current state of intervention will be compared to possible future surgical options within the obstetrical brachial plexus population. This will provide the rationale for future research into new surgical techniques that may be more effective at improving the function of the affected limb in children with obstetrical brachial plexus injuries.

Incidence and Prevalence of Obstetrical Brachial Plexus Injuries

The incidence of obstetrical brachial plexus injuries in Canada has been recently reported by Coroneos and colleges in a 2015 publication as 1.24 per 1000 live births and was consistent from 2004-2012 (Coroneos et al., 2015). There have been many studies across Europe and the United States on the incidence, recovery rates and presentation of different types of obstetrical brachial plexus injury. In a recent systematic review of 63 publications by Chauhan and his colleagues, 53 of them have sufficient information to calculate the rate of obstetrical brachial plexus injury. The overall reported rate was 1.4 per 1000 live births with a range of 0.1 to 6.3. The U.S. publications reported 1.5 per 1000 vs 1.3 per 1000 in other countries. Twenty-nine of those articles reported rates of obstetrical brachial plexus injury for vaginal deliveries separately from caesarean section deliveries. The rate was 1.6 per 1000 vaginal deliveries with a reported range of 0.1 to 8.1. The rate of obstetrical brachial plexus injury from the US was 1.8 vs. 1.1 from other countries for vaginal deliveries. With almost 2 million vaginal births, there were over 3000 obstetrical brachial plexus injuries. Seven publications also provided the rate of obstetrical brachial plexus injury with caesarean delivery with an average of 0.3 per 1000 caesarean births. The average rate was 0.3 in the US versus 0.5 per 1000 caesarean births elsewhere in other countries (Chauhan et al., 2014).

Walsh and his colleagues did a prospective study over a 10-year period. Interestingly, they found despite the fact that the incidence of caesarean sections had increased over that 10 year period, the incidence of obstetrical brachial plexus injury had remained the same (Walsh et al., 2011). When all the subtypes are combined, the literature showed that 75% of obstetrical brachial plexus injuries recover completely without intervention implying that they are either neurapraxic or mild axonotmesis injury (Type 1-2 Sutherland injury) (Andersen et al., 2006). The remaining 25% that do not demonstrate full recovery will require a range of treatment. This may include occupational and physical therapy, Botox injections, serial casting, primary surgeries including nerve grafting and nerve transfer or a combination of both procedures, tendon transfer and releases and lengthening and possible bony surgeries (Abzug & Kozin, 2014).

A permanent obstetrical brachial plexus injury is defined as an impairment of range of motion and strength of the affected limb lasting more than 12 months. Chaugan cited 15 publications (8 from the US and 7 from other countries) with the reported rate of permanent injuries. Out of the 91% in the US and 95% in other counties that were followed for the year, only 10% were permanent injuries in the US and 19% in other countries. If the children that were lost to follow up were assumed to have permanent injuries, then 18% of injuries in the US and 23% in other countries would be deemed permanent (Chauhan et al., 2014). The numbers vary slightly as to the type of obstetrical brachial plexus injury in the literature. The general consensus is that upper trunk or classic Erb's palsy represents 40-60% of all obstetrical brachial plexus cases. Upper and middle trunk involvement represent 20-30% of cases and total brachial plexus injuries (flail limb with or without Horner's sign) account for the remaining cases. Klumpke palsy (only lower trunk) are rare, accounting less than 1% of cases (Abzug & Kozin, 2014) (Hale et al., 2010).

Definitions and subtypes of obstetrical brachial plexus injuries

Obstetrical brachial plexus injuries are defined as a flaccid paresis of the arm at birth. The newborn infant has limited active range of motion of that arm. The different types of perinatal brachial plexus injuries were first categorized by Narakas and later expanded by Al-Qattan. Upper trunk injuries, also known as Erbs Palsy, involve the C5 and C6. This results in weakness of shoulder external rotation, abduction, elbow flexion and forearm supination. Sixty to 80 % show spontaneous recovery of shoulder and elbow movements. An upper and middle trunk injury, also known as Extended Erbs Palsy involves C5, C6 and C7. In addition to the presentation of an upper trunk injury, it also includes loss of elbow extension, some loss of shoulder internal rotation and pronation and some loss of wrist, finger and thumb extension. Initially Naraka described these types of injuries as having only 60 % of spontaneous recovery. Al-Qatan sub-divided this population into Extended Erb's Palsy with early recovery of wrist extension and no early recovery of wrist extension. He reported that spontaneous full recovery was higher in the subset that had early recovery of wrist extension in the first two months. The spontaneous recovery rate was between 76 to 94 % for the former population and 18 - 45% for the latter population. Lower trunk brachial plexus injury is extremely rare in perinatal cases and involves the C8 and T1 roots. This clinically presents with a flaccid hand and intrinsic minus posture. Lastly, complete brachial plexus injury involves all 5 nerve roots resulting in a flail limb with or without Horner sign. The prognosis is poor with little chance of spontaneous recovery after the first three weeks (Narakas, 1987) (Al-Qattan et al., 2009) .

Classifications of severity of injury to the nerve fibres

There are two classifications of nerve injuries, one described by Seddon and the other by Sunderland. Both are widely used. Sunderland classified peripheral nerve injuries into 5 categories. Level 1 is described as a conduction block and level 2 involves axon and myelin damage. In both cases a complete recovery is expected. Level 3 involves not only the axon but also damage to the endoneurium where recovery will be incomplete and surgery may be warranted. In level 4 the endoneurium is damaged along with the perineurium. Only partial recovery is expected and typically this type of injury requires surgical repair. Level 5 which is a complete disruption of the entire nerve structure will have negligible recovery and will always require surgical repair to have any improvement in the distal target muscles (Walsh et al., 2011) (Pindrik et al., 2013).

In the Seddon classification, there are 3 levels of severity of peripheral nerve injury. Neurapraxia or a conduction block is described as the mildest form of injury. The myelin is injured but it usually recovers in a few weeks. In axonotmesis, the axons are also damaged. Recovery may not be complete as a neuroma may form. In neurotmesis, the most severe form, there is a complete disruption of the nerve. Recovery is rarely complete and surgery is often warranted. If the nerve root is avulsed from the spinal cord there is no chance of recovery and surgery is always recommended (Andersen et al., 2006).

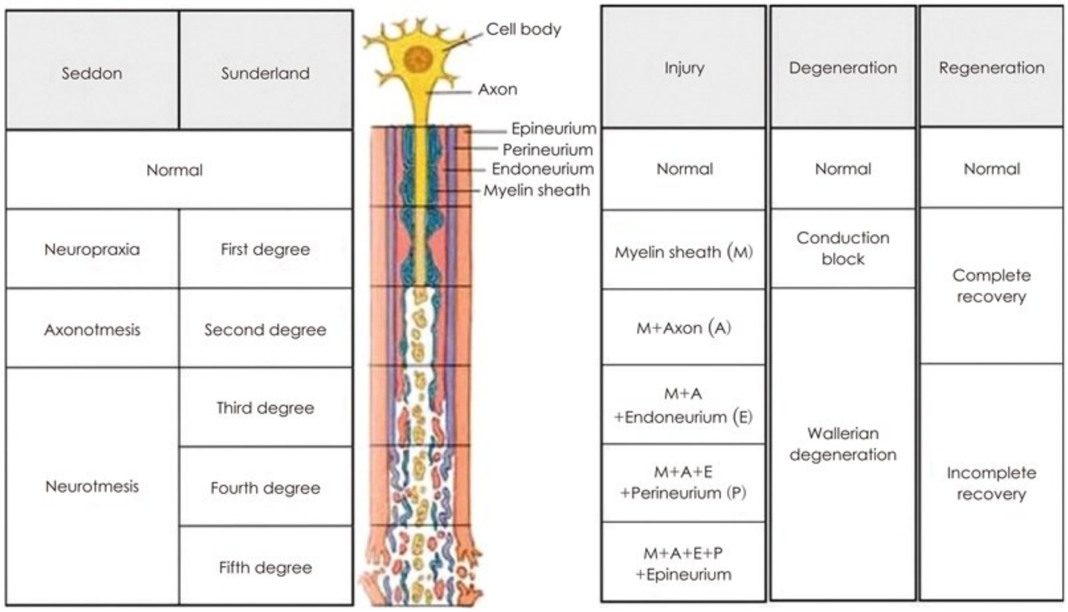

Figure 1. Seddon and Sunderland classifications of peripheral nerve injuries

(source: Google Images Korean Journal Otorhinolaryngol-Head Neck Surg. 2013 Jul;56(7):397-405.)

The physical impairments of obstetrical brachial plexus injury

Children with obstetrical brachial plexus injuries can have a wide variety of physical impairment to body function and structure. Limited passive and active range of motion, weakness, loss of sensation, decreased motor coordination and decreased limb size are common issues among children with obstetrical brachial plexus injuries. In addition to direct functional loss due to denervated or only partially innervated muscles, there are also long term implications to the glenoid fossa. Waters reported that persistent muscle imbalance and soft-tissue contractures can lead to progressive glenohumeral joint dysplasia in patients with obstetrical brachial plexus injury. Glenohumeral dysplasia can occur with glenoid retroversion and posterior humeral head subluxation. Secondary shoulder surgeries such as tendon transfers and arthroscopic joint reduction may be necessary to improve underlying glenohumeral joint dysplasia (Waters et al., 1998). If the muscle imbalance can be mitigated earlier in the child's life, it can potentially reduce some of the secondary deformity to the glenoid fossa and thus the need for secondary procedures.

It is important to address these issues because there is a growing body of research showing that the physical limitations of children can influence how their affected arms function. Recent studies have shown that children with obstetrical brachial plexus injury had lower global functioning compared to their peers (Bae et al., 2009).

Activity/participation limitations and psychosocial impacts of obstetrical brachial plexus injury

Children who have impaired mobility and strength to their affected arm may have difficulties performing everyday activities such as dressing, feeding and self-care. While they may adapt and become independent in these activities over time, it often takes much longer and requires more effort, using the opposite arm to compensate for the affected side. Particularly challenging activities are putting on shirts and pants, buttoning and closing snaps. Washing hair, drying with a towel, and putting on make-up are difficult using only one hand. Adaptation to vehicle and kitchen may be required to perform IADL activities such as driving and meal preparation. Limitations in performing many recreations activities in sports and art are common. Consequently, participation and community engagement are often reduced in children with brachial plexus injury, leading to lower quality of life.

In 2000 a group of researchers examined activity limitations in children with obstetrical brachial plexus injury. They determined that children with obstetrical brachial plexus injury including those with only upper trunk injuries had significantly decreased arm use. In addition to impaired strength and range of motion, they reported that those children had decreased bimanual function resulting in poor scores on pick up tests (Strombeck et al., 2000). Decreased bimanual hand function impacted their ability to perform everyday activities, taking longer and requiring more effort to complete daily activities including dressing, personal care and eating. As the children get older, their IADLS such as meal preparation, driving, and housework are also affected which limit their career choices later in life.

In a follow up study in 2003, Stombeck and Fernell investigated personal and societal cost of obstetrical brachial plexus injury. While teenagers with obstetrical brachial plexus injury had similar interests, activities and social life as their peers, they had lower self-esteem scores and less participation in sports and motor activities (Strombeck et al., 2007).

Sarac (2013) conducted a qualitative study to look at physical function of children with obstetrical brachial plexus injury using the International Classification of Function as a framework. For body functions, these children had difficulties putting their arm above their head. For body image, children frequently listed problems in the perceived size and shape of their arm. They also reported emotional difficulties caused by scars from surgery. In addition, the children report limitation in activities and barriers to participate in sports such as football, dancing, and swimming. Climbing ropes and throwing balls are reported as difficult by the children. The children reported that they can do many things independently but they have to do them differently from their peers. An example provided by the children is washing their hair one handed (Sarac et al., 2013). This could potentially lead to long-term sequelae such as repetitive strain injury to the unaffected arm.

Secondary impairments from shoulder dystocia and difficult delivery

In a prospective cohort study of 38 infants with obstetrical brachial plexus injury, Buitenhuis and her colleagues concluded that children with obstetrical brachial plexus injuries have a higher incidence of central neurological developmental problems (Buitenhuis et al., 2012). Central neurological developmental problems can directly impact independence in activities of daily life and participation within their environment.

Children's participation levels within their community are impacted by their obstetrical brachial plexus injuries and this can place a burden on the parents and the family unit. These consequences are cumulative and do not decrease as the child ages (Firat et al., 2012). In a recent study that examined the quality of life of children with obstetrical brachial plexus injury and its association with demographic characteristics, injury pattern and functional status, Akel and his colleagues found that children with obstetrical brachial plexus injury scored significantly lower on the quality of life survey (CHQ-PF28). While gender did not significantly affect the scores, side of the injury and lower scores on Active Movement Scale scores of shoulder and elbow movements did result in lower scores in the HRQL survey (Akel et al., 2013).

To help minimize the functional impairment of children with obstetrical brachial plexus injury and to maximize their ability to participate in activities in their home and school environments, surgical intervention may be necessary. There are many standardized outcome measures to evaluate surgical intervention. The outcomes can help guide future decisions for other children with similar injury. It is critical that those outcome measures reflect all 3 domains of the International Classification of Function. The following is a detailed description of each of those domains and their functional implications.

Outcome measures in obstetrical brachial plexus injuries: International Classification of Function

Evaluating the health of a child using the International Classification of Function provides a useful framework to evaluate how a particular condition may lead to an impairment of body function. The injury can also impact the way in which these children may carry out activities taking personal and environmental factors into account. The ICF outlines areas of impairment (which include body structures and functions), activities (defined as actions and tasks executed by individuals) and participation (defined as involvement in life situations).

Body structure and function outcome measures

Impairment represents a loss of body functions that have physiological as well as psychological dimensions ("International Classification of Functioning, Disability and

Health," 2001). In obstetrical brachial plexus injuries, neuromusculoskeletal and movement are affected resulting in a loss of joint mobility and muscle power. To quantify this, Impairment of Body Function and Structure Measurement Tools are the most commonly used. For many centres, this involves physical examination of the infant over a period of time to document the natural history and recovery after nerve surgeries. Other commonly used impairment evaluation tools are needle electromyogram (EMG) and nerve conduction studies. EMGs can measure electrical activity of muscles at rest and during contractions. The presence of recruitable motor unit potentials (MUPS) at one month was found to be a good indicator of spontaneous recovery (Van Dijk et al., 2012).

Many assessment tools that measure impairments of the affected limb in children with obstetrical brachial plexus injury have been developed. In addition to good validity and reliably, the selected tool must be appropriate for the developmental age of the child. Examples include the Medical Research Council Grading Scale, the Modified Mallet classification, the Toronto Score Test and the Hospital for Sick Children Active Movement Scale. Of these, only the Modified Mallet, the Toronto Score Test and Active Movement Scores have been shown to have good to excellent inter and intra rater reliability (Hale et al., 2010).

Active Movement Scale (AMS)

In particular, the AMS has proven to be a reliable tool for evaluating infants with obstetrical brachial plexus injury. This is an 8-point scale with 0 representing no movement and 7 representing full movement. It measures specific movement in the infant's affected limb both with gravity eliminated and against gravity. In addition to good intra and inter rater reliability, it can be used as a pre and post outcome measure after surgical interventions (Curtis et al., 2002). It is widely used in most major centers across Canada.

Modified Mallet Scale

As children that approach preschool years, they can follow commands more reliably. At that age, the Mallet and Modified Mallet scales can be used to evaluate their shoulder movements. It evaluates the child's ability to move the affected limb in various functional positions on command. In these scales, a 5 point score is used with 0 being not testable and grade 5 representing normal movement. The movements assessed include shoulder internal rotation to touch the belly button, hand to small of the back, hand to mouth, hand to nape of neck (Abzug & Kozin, 2014). One drawback is that this tool cannot be applied to infants as they are not old enough to follow commands. Consequently, it is primarily used to evaluate the effectiveness of secondary interventions or to track the long-term results of primary repair (Gilbert, 2009).

British Medical Research Council manual muscle testing grading scale (BMRC MMT)

Another measurement tool that is widely reported in the literature is BMRC-MMT grading scale. It is a 6-point scale (0 no contraction to 5 normal power) that test movement of the muscles with gravity eliminated, against gravity and against resistance. While widely used in the adult population and older children, it is not a practical tool when evaluating infants. Its reliability was found to be low in children with neuromuscular disorders (Escolar et al., 2001).

Activity and participation outcome measures

Historically most measures used to evaluate outcomes in treatment for children with obstetrical brachial plexus injury focus on the child's impairment. In contrast, of greater real life relevance are activity limitations and participation restrictions that could have a major impact on quality of life. Examples of these include restrictions in lifting or carrying objects, fine hand use (picking up and grasping) and driving such as riding a bicycle or driving a motor vehicle later in life. Self-care limitations include difficulties in washing oneself, toileting, dressing, eating, meal preparation and doing housework. With their functional importance, few studies have looked at activities of daily living or participation within one's community (Chang et al., 2013). Studies that evaluated the psychosocial well-being of the child are also very limited. Well validated and reliable instruments to quantify activity and participation include the Pediatric Evaluation of Disability Inventory (PEDI and PEDI –CAT versions), Assisting Hand Assessment (AHA) and the Paediatric Data Collection Instrument (PODCI) (Bialocerkowski et al., 2013; Chang et al., 2013).

In addition, the Brachial Plexus Outcome Measure (BPOM) has been shown to have good construct validity (Ho et al., 2012a). The following is a detailed description of the activity and participation evaluation tools.

Pediatric Evaluation of Disability Inventory (PEDI-CAT)

The Paediatric Evaluation Disability Inventory Computer Adaptive test (PEDI-CAT) measures 4 functional areas which includes daily activities, mobility and social/cognitive function and responsibility. The responsibility area measures the extent the caregiver or child takes responsibility for managing complete multi-step life tasks. It can be used with children and youth (birth-20 years) with a variety of physical or behavioural conditions. It has demonstrated that it is a good valid and reliable assessment (Dumas & Fragala-Pinkham, 2012). The original Paediatric Evaluation of Disability Inventory (PEDI), which was designed for children ages 4-7 years, was evaluated for its application to assess children with obstetrical brachial plexus injury. It was found that children with hand impairment had a deficit in the self-care ability compared to their typical peers but the PEDI could not discriminate between the performance of children with upper trunk injuries and their typical peers (Ho et al., 2006). The PEDI-CAT may have a larger longitudinal impact as it may detect change in children with upper trunk injuries in the self-care and responsibility domains into adolescence. The PEDI and PEDI CAT are norm referenced tests and may not be sensitive enough to detect change over time around a specific surgical intervention. In addition, changes in the overall score may not be equated to a specific surgical intervention.

Pediatric Outcomes Data Collection Instrument (PODCI)

The PODCI (2-18 years) is a questionnaire which assesses children's overall health, pain and ability to participate in normal activities and vigorous activities. Previous studies using this tool have found that children with obstetrical brachial plexus injury had lower global and upper extremity function scores on the PODCI compared to their age-match peers (Bae et al., 2008). The PODCI could potentially be used to measure baseline function and postoperative functional gains for children with obstetrical brachial plexus injury for secondary procedures (Huffman et al., 2005). Many of the questions that specifically looked at how a child's arm functions and how that impacts activities of daily living and participation are more applicable to older children. This tool may not be sensitive enough to evaluate function in toddler and preschool age children after a primary nerve surgery and cannot be used a pre measure before a primary nerve surgery.

Assisting Hand Assessment (AHA)

The AHA measures how effectively the involved arm is actually used in bimanual activity. It falls within the activity domain of the ICF and is a valid and reliable instrument for use with children with obstetrical brachial plexus injury between ages 18 months and 12 years. Inter and intra rater reliability is excellent. The tool is sensitive to change. (Krumlinde-Sundholm et al., 2007). The Assisting Hand Assessment is a play based objective observational assessment. Mobility in the activity domain of the ICF such as lifting, reaching, holding objects and fine manipulative hand use during typical performance is assessed. The assessment addresses what children actually do with their assisting hand (affected side). The assessment does not address best capacity like many of the active range of motion measures but typical performance during age appropriate activities. Higher scores represent better performance (total is 100 logit units). Also a change in 5 points represents a statistically significant change, which can be used as a pre and post surgical, or rehabilitation measure. A limitation of the tool is that while it may be effective in evaluating change around secondary procedures which are usually performed after the age of two, it cannot be used as pre measure prior to a nerve surgery. A decision is often made no later than 9 months of age to proceed with a primary nerve surgery. The infants are too young to be evaluated by this measure. Recently there has been the creation of a mini AHA that can be used on children with hemiplegia starting at

8 months of age. In the future, this tool may prove to be effective as a preoperative assessment. Normative data on the young obstetrical brachial plexus injury is needed.

Table 1: characteristics and clinical utility of assessment					
Measure	**Target Pop.**	**Type of impairment/ activity measured**	**Primary Purpose**	**Perform / Capacit y**	**Clinical Utility**
Active Movement Scale	Infants to 3yrs with OBPI	Impairment measure evaluating active range of motion in gravity eliminated and against gravity positions	Impairment	Capacity	Used to track natural recovery over first year; pre and post primary nerve surgeries
Modified Mallet Scale	Children with OBPI 3yrs-adult	Measuring active range of motion of the shoulder and elbow	Impairment	Capacity	Assess shoulder and elbow function and as pre and post secondary procedures
BMRC	Children aged 6yrs-adult	Measuring AROM and strength	Impairment	Capacity	Used to assess strength of older children and pre and post secondary procedures in late cases
PEDI CAT	Children 0-20yrs	Measures self-care, mobility, social cognitive and responsibility (adaptive behaviour)	Activity Participatio n	Typical Perform	Parent or child completed questionnaire
PODCI	Children ages 2-18 yrs	Measures potential changes in overall health, pain and ability to participate in normal daily activity, as well as more vigorous activities	Activity Participatio n	Typical Perform	Parent or adolescence completed questionnaire
AHA	Children with a unilateral	Measures how effectively the child uses	Activity	Typical Perform	Therapy led play session. Raw scored

	disability 18mo-12 yrs	affected arm in bimanual activities			converted to percentages and logits
BPOM	Children with OBPI age 4-19yrs	Measures affected arm function and adaptive movements using functional activities	Activity	Typical Perform	Activity led session by therapist with individual and total scores recorded (for quick screen in clinic)

Table 1. Impairment and Activity represent the area that the tool is classified under the ICF. Typical performance represents how the child normally performs the activity. Capacity represents the best performance or movement the child can complete.

Brachial Plexus Outcome Measure (BPOM)

A new assessment tool that looks at the activity and participation domains of the ICF is the BPOM. It is specifically designed to evaluate the quality of upper extremity movement. Eleven activities were selected to measure the deficit movement patterns in children with obstetrical brachial plexus injury 4-19 years of age. A 5-point scale is used. The lowest number (0) indicating the child cannot complete the task to the highest score (5) representing that the child can complete the task with normal movement patterns. In addition, the self-evaluation scale evaluates how the arm works and looks in everyday life and is a qualitative evaluation. This tool has practical use in a clinical setting for preschool and school-age children and has good internal consistency and excellent construct validity when measuring the upper extremity function. It was strongly correlated with the AMS. Intra and inter rater reliability and the validity in measuring changes in upper extremity performance pre and post interventions is underway (Ho et al., 2012b).

Summary of Measurements

The optimal impairment outcome measure to evaluate the effectiveness of a primary nerve surgery in infants and young children with obstetrical brachial plexus injury is the AMS, as the Modified Mallet and the MRC can only be used in preschool and school age children so cannot be used a primary nerve surgery preoperative measure.

The AHA cannot be used as a pre measure prior to a primary nerve surgery. It can be used to evaluate the typical use of the affected limb during functional activities in very young children. This tool can capture arm function of the assisting hand as young as 18 months of age unlike PODCI which is has limited utility in pre school population. The PEDI CAT may not be sensitive enough to evaluate changes over time as an adaptive measure in infants. The BPOM which will likely prove to be an effective tool to evaluate activity limitation in older children cannot be used as a pre measure around early surgical intervention and may not be used in children 3 and younger.

Nerve grafts versus nerve transfers in upper trunk brachial plexus injuries: Adult and pediatric population

Traumatic brachial plexus injuries (TBPI) in the adult population have been reported in many epidemiological studies. It has an incidence of 1.75/100,000 in major cities. The most common cause of such injuries is motor vehicle accidents. There is a much higher rate in young men compared to women (Flores, 2006). Brachial plexus injuries as a result of MVA's are often closed traction injuries that occur at a high velocity. As a result many of the these TBPI involve avulsions of multiple nerve roots (Faglioni Jr et al., 2014). Pain is widely reported in traumatic injuries and is reported to be as high as 70 to 80 %. In an Italian study neuropathic pain was reported in 50 % of patients. Not surprisingly, the higher the reported pain scores the lower the quality of life scores and the higher the depression rating scale scores (Ciaramitaro et al., 2010). Neurolysis and nerve grafting procedures were standard of care for many years. Sural nerve grafts to reconstruct the plexus are used where there are available donor roots. Isolated nerve transfers were used where donor nerve roots were not available as in the case of multiple root avulsions. Nerve surgeries to reconstruct the plexus involved exploring the brachial plexus and using donor nerve sural nerve grafts to reconstruct the plexus. Nerve grafts proved to be more successful in improving bicep function than shoulder function. One study reported 57 % of patients obtaining a MRC 3 or greater (full active movement against gravity) for elbow flexion (biceps) but only 24 -30 % of patients achieve M3 for shoulder abduction and external rotation (deltoid and supraspinatus and infraspinatus muscles) (Kandenwein et al., 2005). Outcomes of nerve grafts in the upper trunk where one root was avulsed (C5 or C6) were not significantly different than if both roots were intact. Patients had some improvement of elbow flexion and extension but outcomes around shoulder abduction and external rotation were less favourable (Bertelli & Ghizoni, 2008).

In cases where donor roots were available, grafts in combination with nerve transfer to reinnervate target muscles has been described. The nerve transfer graft combination surgery was used to improve outcomes when possible. Patients that had injuries where both techniques could be used had the best function (Bertelli & Ghizoni, 2010). The transfers reduced the time for reinnervation. Nerve grafting procedures alone represent a longer time for the nerve to reach its target muscle. It can take 2-3 years for the muscles to become reinnervated with grafts because the peripheral nerves regenerate only at a rate of 1-3 mm per day. In many proximal injuries, the nerve has a great length to grow to reach its target muscles. Furthermore, the regenerating axons must cross 2 coaptation sites, which may decrease the number of axons reaching the targeted muscles. A common complication with an axonal injury is that some axons may end up in the wrong target muscle due to mismatch reorganization at the site of injury. This may lead to co-contraction of asynergistic or antagonistic muscles that may lead to limited active movement.

In addition to sural nerve grafting procedures, contralateral C7 transfers have been used to repair brachial plexus injuries in the adult population. The C7 nerve root is considered to be redundant and may be dispensable. However, weakness in the triceps on the donor side has been reported. In 5 % of cases sensory deficits also occur. In rare cases, there is also loss of wrist extension on the unaffected side (Songcharoen, 2008). In this procedure, the C7 root on the unaffected arm is transected at the level of its division. It is passed under the chest through a subcutaneous tunnel to the contralateral side with sural nerve grafts or a vascularized ulnar nerve graft placed across the chest to bridge the gap between the donor and the recipient infraclavicular plexus nerve. This type of proximal transfer is intended for improving elbow flexion and extension along with hand function. It has been done in conjunction with other extraplexal donor nerves such as spinal accessory nerve, phrenic nerve and intercostal nerves to improve shoulder external rotation and wrist extension. Neurotization of the suprascapular, radial, thoracodorsal and musculocutaneous nerves is often done along with C7 contralateral transfer. Gao et al. reported modest improvement of MRC 3 or greater in 66 % patients for elbow flexion and in 20 % for elbow extension. For wrist and finger flexors an MRC 3 was obtained in

68 % (Gao et al., 2013). A prospective study comparing total and hemi-contralateral (either anterior division for sensory or posterior division for motor) C7 nerve transfers demonstrated that hemicontralateral C7 transfers had fewer donor site complications but total C7 nerve root transfers had better hand function on the affected side (Tu et al., 2014). Terzis studied 56 patients with post traumatic root avulsion brachial plexus injuries that underwent total contralateral C7 transfer and found that 20% have MRC 3 or greater in deltoid, 52% in bicep, 24% triceps and 34% in wrist and finger flexors and 20% for wrist and finger extensors. She reported minimal donor morbidity and concluded it is a safe procedure that can be used for reconstruction of several nerves and for future free muscle transfers (Terzis & Kokkalis, 2009) . Zhang and Gu reported that as no single muscle is innervated by C7 alone and that dividing it will not cause permanent sensory or motor deficiency in the donor arm. They reported temporary sensory loss in D2- D4 on the donor side and reduced grip strength for the first 3 months but this resolved over time. They stressed the importance of not transecting C7 too distally or permanent donor site complications of reduced sensation and weakness might occur as fibers from upper and lower trunks may be injured (Zhang & Gu, 2011). This surgical technique has been used for adults with root avulsion or lower trunk involvement. Contralateral C7 nerve transfers involve bridging grafts. The long regeneration distances can take 2-3 years for nerve innervation to reach the hand. The patients may have to move their unaffected arm synchronously with the affected side to elicit functional movement. Because there are many activities that require asymmetrical movement from the affected and non-affected arm, this can be a major functional impediment. For adults with upper trunk injuries that do not involve the lower trunks,

contralateral C7 nerve transfer are not indicated because it has a higher complication rate than isolated nerve transfers.

Nerve transfers within the affected limb have been widely used in the adult population as nerve grafting alone has not yielded satisfactory results. Nerve transfers may be the only viable option for patients with multiple nerve root avulsions in the upper trunk. Single, double or triple nerve transfers to restore elbow and shoulder function in patients with upper trunk injuries have been widely reported in the literature. Isolated nerve transfers were report in the early 1990s as an alternative surgery to nerve grafting procedures.

History of nerve transfers to improve elbow flexion in the adult population

Restoration of elbow flexion using nerve transfers has been widely reported. As previously reported, nerve transfers have several advantages including donor nerve being closer to the end organ. This results in a shorter distance for the axons to travel, which increases chances of early muscle innervation. In addition, nerve transfers only requires one surgical coaptation instead of two (one for donor grafts in addition to primary surgical repair site) (Bhandari et al., 2009) . There are instances where nerve transfers may not be appropriate. A suitable donor may not be found. In the case of isolated upper trunk injuries there are several options for nerve transfers to restore shoulder and elbow function. The most favourable results have been reported for restoration of elbow flexion. In 1994 Oberlin reported nerve transfer that involved successful innervation of the biceps by fascicular neurotisation from a flexor carpi ulnaris branch of the ulnar nerve. He reported no donor morbidity. Many studies have reported similar findings to Oberlin in the adult population. In 2005 Mackinnon described nerve transfer where a portion of a median nerve was transferred to the brachialis branch of the musculocutaneous nerve and ulnar branch transferred to the bicep branch of musculocutaneous. She reported favourable results for elbow flexion (4 out of 5 MRC) in all 6 patients (Mackinnon et al., 2005). A follow up study by Carlsen and colleagues compared a single nerve transfer which only involved the ulnar nerve transfer to biceps branch to musculeocutaneous to the above mentioned double nerve transfers. Objective torque measurements and the Disability of Arm Shoulder and Hand (DASH) questionnaire along with MRC grading were used as outcome measures. The authors concluded that there was no statically significant difference between the two procedures in terms of outcomes. However both groups demonstrated improvement on all the outcome measures (Carlsen et al., 2010). Ferraresi reported the results on 180 patients with the medial cord to musculocutaneous nerve transfer. In this study the patient has common brachial plexus palsy, which had multiple nerve root avulsions. They used two donor fascicules from flexor carpi ulnaris, flexor carpi radialis and occasionally flexor digitorium profundis. With the exception of patients that had 4 root avulsion, sixty seven percent had a satisfactory result for elbow flexion (M3 or greater) (Ferraresi et al., 2014). Other nerve branches such as intercostal medial pectoral and phrenic nerves have been used as donors to improve elbow flexion, however as mentioned previously the most widely reported with the best results for upper trunk injuries remains the ulnar or median nerve donors to musculeocutaneous to improve elbow function.

History of nerve transfers to improve shoulder abduction and flexion in the adult population

To improve shoulder abduction, nerve transfer from medial head of triceps and anconeus to axillary nerve innervated deltoid has been demonstrated to yield satisfactory results. Bertelli looked at this nerve transfer for isolated axillary nerve injuries. The patients had improved strength and endurance in shoulder abduction (Bertelli & Ghizoni, 2014). In a previous study, 10 patients that received nerve transfers to restore elbow flexion, shoulder abduction and external rotation were evaluated 2 years after surgery. As these patients have avulsion injuries, proximal stumps were not available for grafting. Nerve transfers included cranial nerve XI to suprascapular nerve, ulnar fascicles to biceps motor branch and triceps long or lateral head motor branches to axillary nerve. The patient's range of motion and strength all improved with no demonstrable donor site morbidity. There is no donor site morbidity as the transferred fascicles are considered redundant. There are remaining compensatory muscles for wrist flexion (eg. FCR) and elbow extension (eg. lateral and medial heads of triceps) (Bertelli & Ghizoni, 2004).

Triple Nerve Transfers

In adults with upper trunk injuries, the triple nerve transfer procedure which involves the spinal accessory (donor) to suprascapular nerve (recipient), medial head of triceps branch of radial nerve (donor) to axillary nerve and fascicles flexor carpi ulnaris branch of ulnar nerve (donor) to musculocutaneous nerve to biceps is now widely used in many centers and yield the best functional results to improve shoulder and elbow movement and strength in traumatic upper trunk injuries. This procedure is not only exclusively used in avulsion injuries where nerve grafting is not available, but can also be used with neuromentisis or axonal type injuries. The neuroma does not need to be excised but rather bypassed with the transferred nerve closer to motor or sensory end organs. This technique reduces operative time and minimizes the risk of downgrading function as the nerves are not excised and grafted (Moore, 2014). Nerve transfers for this type of injury may become the standard of care in the future.

A systematic review comparing nerve transfers and nerve grafting for traumatic brachial plexus injuries supported nerve transfer over nerve grafting procedures especially if the donor nerve root or trunk is not optimal for grafting. A recently published systematic literature review looking at Pubmed and Embase databases was conducting comparing nerve grafting, nerve transfers and combination of approaches in upper brachial plexus injuries in adults. They concluded that the Oberlin procedure which involves the transfer of a branch of the ulnar nerve that innervates flexor carpi ulnaris (donor) to musculocutaneous nerve (recipient) is significantly better than nerve grafting alone to improve elbow flexion and forearm supination. The systematic review also found that patients had better strength and active range of motion in shoulder abduction following nerve transfers vs nerve grafting or combined techniques (Ali et al., 2015).

As nerve transfers have been used to improve function in the adult population with upper trunk injuries with over 20 years of published data with favourable results, there has been growing support to investigate this technique within the paediatric population. There is a growing body of evidence within the literature that single, double or triple nerve transfers can be an alternative to the traditional exploration of the plexus and nerve grafting to treat children with upper trunk obstetrical brachial plexus injury.

Nerve surgery in obstetrical brachial plexus injuries

Nerve surgery vs. conservative management

There is still debate as to what level of deficit must be present to recommend nerve-grafting surgery and when the surgery should be performed. Pondaag and Malessy recently investigated the evidence for nerve repair in obstetrical brachial plexus injury population. After an extensive review of the literature they concluded that no randomized control trial comparing surgical reconstruction verses conservative treatment has been conducted. They identified 9 papers that compared different treatments. They concluded that in many of these studies, children with total plexus injuries had better outcomes with surgical intervention that involved reconstruction of plexus with nerve grafts than those who had non-operative management. Reinnervation of the hand was poor in children that did not have surgical intervention. Recommendation for surgery in children with upper trunk plus or minus middle trunk involvement is dependent on the rate of recovery of biceps between 3-6 months. Children who did not have rapid recover of biceps function by 3 months or plateaued biceps function by 6 months, would fare better with surgical intervention then non-operative treatment. There was no consensuses in the literature for the cut-off point to recommend surgical intervention for isolated upper trunk brachial plexus injuries (Pondaag & Malessy, 2014). In 2014 Ali conducted a meta-analysis comparing the outcome (elbow flexion as the primary indicator) in children that did not have surgery versus children that received nerve grafting surgery at 3, 6 and 12 months. They also analyzed the quality of life of these children. The author suggested that decisions around surgery should be made on a case-by-case basis. Randomized control trials are not possible for this population as it is not ethically feasible to randomly assign infants to different treatment arms. Nerve grafting was just as effective between 6-9 months as a surgery that occurred at 3 months (Ali et al., 2014). There is a growing consensus that for children with upper trunk brachial plexus injuries, it is best to wait until 6-9 months of age before making a decision about nerve surgery (Abzug & Kozin, 2014). There is a lack of good comparative evidence between natural recovery for children with axonotmesis type injuries compared to nerve surgery. There is broad agreement that children with total plexus injuries, root avulsions and neurotmesis injuries do better with surgery as there is little likelihood of spontaneous recovery. Clinically, these types of injuries can be evaluated by MRI (avulsion), EMG studies, and physical examination where there is a plateau of active range of motion between 3-9 months. Mild axonotmesis injuries that spontaneously recover hand to mouth function (Cookie Test) and shoulder flexion, abduction and external rotation over half range of motion against gravity between 6-9 months of age often do not require nerve grafting surgery. Only a small number of these patients (<10%) require any type of nerve surgery (Badr et al., 2009). Bain indicated that children with upper trunk injuries occupy a "grey zone" between 3 and 9 months of age. Children exit the grey zone if they can achieve scores greater that 6 (over half ROM against gravity) in elbow flexion using the Active Movement Scale as an assessment tool (Bain et al., 2009). These children do not require surgery. Children that plateau between 6-9 months of age and score <5 on AMS in elbow flexion are recommended for nerve grafting surgery.

Nerve grafting versus neurolysis

Once a decision is made that a child would benefit from a nerve surgery, there is still debate about what type of surgery would most benefit the child. Historically, the gold standard of treatment for children with upper trunk obstetrical brachial plexus injury has been harvesting sural nerves and grafting those nerves to available donors from the brachial plexus. In 1998 Capek and Clarke reported better functional outcomes for children that had neuroma resection and sural nerve grafts compared to neurolysis alone. Twelve months after the operations, the children that received the nerve grafts had higher scores on the AMS than children who had neurolysis (Capek et al., 1998). This was further supported by their follow up study in 2009 (Lin et al., 2009). They stated that neurolysis should be abandoned in favour of nerve grafting. The comparison was made between pre and post AMS grading and not a direct comparison between the end result of neurolysis and grafting (Pondaag & Malessy, 2014).

Nerve grafting has been far more successful in the obstetrical brachial plexus injury population than in the traumatic brachial plexus injuries in adults. There are several reasons for this. These include the size of the infant and the mechanism of injury. The forces associated with brachial plexus injuries during a delivery are far less than in high velocity closed traction injuries like in motor vehicle accidents. In infants, the distance from the nerve roots of the plexus and the end organs is much shorter. Infants also have a robust ability to heal from traction injuries. Therefore, not surprisingly, nerve grafting for children with obstetrical brachial plexus injuries has been regarded as the gold standard for children with upper trunk and pan plexus injuries when surgical intervention is deemed necessary (Hale et al., 2010). For children with pan plexus injuries this remains the only option to improve arm function, as suitable donor nerves for transfers are not often available. In cases where a suitable donor nerve may be available, nerve transfers might be performed (eg. spinal accessory to suprascapular nerve). This can allow sparing of sural nerve grafts for use in the lower trunks where they are needed to improve hand function. Nerve grafting in upper trunk injuries have yielded favourable results for elbow flexion (MRC >3) even in children with avulsion of a C6 root (Malessy & Pondaag, 2014). A factor that may affect optimal muscle function after nerve grafting is that axons may end up in the perineurial tissues between the fascicles bundles. Those axons may not end up in their original fascicles due to fascicular mismatch between the proximal and distal stumps. This can be evident with co-contraction where the same nerve may stimulate for example, both elbow flexion and extension. As well, the denervation time is prolonged with supraclavicular injuries close to the nerve roots (Malessy & Pondaag, 2011).

In recent years nerve transfers have been gaining popularity for children that sustain traumatic brachial plexus injuries and for children with obstetrical brachial plexus injuries where multiple nerve root avulsion may preclude brachial plexus reconstruction via nerve grafts (Abzug & Kozin, 2014). While nerve grafts could potentially supply sensory axons to de-innervated skin territories, distal nerve transfers offer a rich supply of motor axons, coupled with only a single coaptation site close to the target muscles. This offers a potential advantage of faster recovery that may help prevent glenoid deformity as muscle balance is restored earlier. This in turn may lead to a reduction in secondary procedures such a osteotomies and tendon transfers (Seruya et al., 2015). Furthermore, distal nerve transfer negates the need for a second surgical site by harvesting sural nerves from the legs to be used as grafts. This reduces the likelihood of secondary complication, reduces OR time and length of stay in hospital. Since nerve transfers have proven to be more effective in the traumatic adult population, it stands to reason that similar results may be possible in the traumatic pediatric population.

Contralateral C7 nerve transfers in the traumatic and obstetrical brachial plexus population

The C7 contralateral nerve transfers were investigated when reconstructing brachial plexus injuries that were traumatic in nature along with nerve grafts and nerve transfers. Chim and colleagues concluded that there was no difference in nerve transfers and nerve grafts but contralateral C7 as a donor for nerve transfers in reconstruction of shoulder abduction yielded poorer results in this population (Chim et al., 2014). In the obstetrical brachial plexus injury population C7 contralateral transfers have not been used for children with upper trunk injuries. Surgical techniques like neurolysis, neuroma resection and nerve grafting and nerve transfers offer acceptable outcomes with less risk of donor site morbidity.

Isolated nerve transfers

Isolated nerve transfer in the obstetrical brachial plexus injury population was first described in the late 1980s. For children that presented late for primary nerve grafting repair or where suitable donor nerve roots were not available, nerve transfers were performed to improve shoulder external rotation, flexion, abduction and elbow flexion and forearm supination.

Nerve transfer for elbow flexion

Several donors were used to improve elbow flexion, including but not limited to intercostal nerve transfers and flexor carpi ulnaris fascicle nerve transfer to musculocutaneous nerve (El-Gammal et al., 2008; El-Gammal et al., 2014). Medial pectoral donor nerve or intercostal donor nerves have been transferred to the musculocutaneous recipient where a viable stump (C5and C6) for donor nerve grafts could not be used. Favourable results of 88% achieving a MRC greater than 3 were reported (Pondaag & Malessy, 2014).

Nerve transfers for external rotation

Nerve transfers have also been used to improve shoulder external rotation in children with obstetrical brachial plexus injury. Initially spinal accessory nerve was transferred to suprascapular nerve to allow sural nerve grafts to be used to reconstruct other parts of the plexus. Tse and colleagues conducted a study where comparing the nerve grafting from C5 to suprascapular nerve, to nerve transfer of spinal accessory to suprascapular nerve. Shoulder external rotation was evaluated starting with the elbow flexed and the arm resting against the abdomen, (AMS evaluation of shoulder external rotation). There were no differences with external rotation AMS scores between the nerve grafts and nerve transfers (Tse et al., 2011). They reported that both surgeries yield poor results of external rotation. However when allowing for compensatory movement many of the children can bring their hand to their mouth and reach their head with either surgery (Pondaag et al., 2005). In a follow up study Malessy reported similar outcomes in shoulder external rotation comparing nerve grafting and nerve transfers. In this study spinal accessory nerve was transferred to suprascapular nerve for children that had a neurotmesis of C5 and an avulsion of C6 nerve roots (Malessy & Pondaag, 2014). Rucheksnman reported optimal results for spinal accessory to suprascapular nerve transfers when including shoulder abduction in measuring external rotation of the shoulder. Of note the transfers were combined with Botox injection of pectoris major and lattismus dorsa or surgical release of the pectorals major. The author acknowledged that this could have confounded their results (Ruchelsman et al., 2010). A recent publication compared phrenic nerve communicating branch graft procedure to spinal accessory nerve transfer procedure as to options for donors to suprascapular nerve. They measured external rotation looking at true glenohumeral rotation (AMS measurement) and functional external rotation (allowing for shoulder abduction) and both procedures yield similar results. The authors reported that both surgeries yielded poor result for glenohumeral rotation, similar to that in Pondaag's earlier study. Those children had to use compensatory movements to achieve functional shoulder movement. Grafts were required between the phrenic nerve donor and suprascapular nerve while the spinal accessory nerve can be directly transferred to spinal accessory nerve (Al-Qattan & El-Sayed, 2014).

Nerve transfer for shoulder flexion and abduction

As mentioned previously, the third nerve transfer that has been widely reported in the adult population but only recently used in the obstetrical brachial plexus injury population is the radial to axillary nerve transfer. In the obstetrical brachial plexus injury population it is usually part of a triple nerve transfer (Abzug & Kozin, 2014). Terzis and her colleagues reported good results (>=M3) in 5 children that received intercostal to axillary nerve transfers (Terzis & Kokkalis, 2008). She did not use isolated middle head of triceps as a transfer. To our knowledge there has been no isolated axillary nerve reconstruction studies without additional nerve grafting or nerve transfers in the obstetrical brachial plexus injury population.

Triple Nerve Transfers

While the triple nerve transfers has gained popularity in adults with traumatic brachial plexus injuries, only one study to date has investigated the efficacy of this surgical technique in the obstetrical brachial plexus population, in place of nerve grafting surgical procedure in upper trunk brachial plexus injuries. All children in the study failed the cookie test (<6 on AMS), which were the primary indications for nerve surgery. In the study 10 patients AMS scores were recorded before and after surgery with a final follow up at 24 months. Significant gains on the AMS scores were noted in shoulder flexion, abduction, external rotation elbow flexion and supination. However, this preliminary study did not have a control group that received nerve-grafting procedure (Ladak et al., 2013).

Therefore, we conducted a study comparing a group of upper trunk obstetrical brachial plexus injury patients treated with triple nerve transfers to a similar cohort that received the sural nerve grafting procedures. The results of this study will be discussed in the next chapter.

Chapter 2: Comparison of triple nerve transfer and nerve grafting for upper trunk obstetrical brachial plexus injuries

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Abstract:

Purpose: Upper trunk obstetrical brachial plexus injury (OBPI) can cause profound shoulder and elbow dysfunction. Although neuroma excision with interpositional sural nerve grafting is the current gold standard, distal nerve transfers have potential advantages. The goal of this study was to compare the clinical outcomes and healthcare costs between nerve grafting and distal nerve transfers in children with upper trunk OBPI.

Methods: In this cohort study, children who received triple nerve transfers were followed with the Active Movement Scale (AMS) for a minimum of 2 years. Their outcomes were compared to children who underwent nerve graft reconstruction. The Assisting Hand Assessment (AHA) was administered to the nerve transfer group to evaluate their bimanual hand skills through everyday play activities. To evaluate healthcare utilization, a direct cost analysis was also performed.

Results: Twelve patients who underwent nerve grafting were compared to 14 patients who underwent triple nerve transfers. Both groups had similar baseline characteristics and showed improved shoulder and elbow function following surgery. However , the nerve transfer group displayed significantly greater improvement in shoulder external rotation and forearm supination ($p<0.05$). They also had high AHA raw scores with no significant postop donor morbidity. The operative time and length of hospital stay were significantly lower ($p<0.05$) and overall cost was ~50% less in the nerve transfer group.

Conclusions: Triple nerve transfers for upper trunk OBPI is a feasible option with better functional outcomes for shoulder external rotation and forearm supination, faster recovery and are less expensive compared to traditional nerve graft reconstruction.

Introduction

Obstetrical brachial plexus injuries are common, with an incidence between 0.5 and 3 per 1000 live births (Borschel & Clarke, 2009). While 75% of these cases are neurapraxic in nature and recover spontaneously, approximately 25% of patients have varying degrees of permanent neurologic deficits. Of these, the upper trunk is most commonly affected, resulting in shoulder and elbow dysfunction. This represents roughly 75% of those with permanent injuries (Shenaq et al., 2005).

In addition to nerve dysfunction, potential secondary complications include limb length discrepancy (Bain et al., 2012) and secondary changes to the shoulder that may lead to incongruity of the glenohumeral joint, deformity of the humeral head, and hypoplasia of the glenoid fossa (Waters et al., 1998). These changes could affect body structure and function of the child and place a major psychosocial burden on the family (Akel et al., 2013). They can negatively impact the child's ability to participate in daily activities, thereby compromising their quality of life (Alyanak et al., 2013).

In an effort to improve outcomes for children with obstetrical upper trunk brachial plexus injuries, microsurgical techniques are being continually refined. Distal nerve transfer surgery has become part of the standard armamentarium offered to adult patients with upper trunk brachial plexus injuries. Potential advantages of distal nerve transfers include shorter distance of nerve regeneration, motor to motor nerve coaptation without an intervening sensory nerve graft, and less extensive surgical dissection. Although these procedures are starting to gain popularity in the pediatric population, their efficacy compared to traditional nerve graft reconstruction in obstetrical brachial plexus palsy is not well established. To date, only a few studies have evaluated the potential role of single nerve transfers to restore shoulder or elbow function in patients with upper trunk obstetrical plexus injury. However, those procedures on individual nerves alone cannot be used to replace the additional need for sural nerve graft reconstruction. A recent study examined the combined use of triple distal nerve reconstruction procedure to restore functional deficits in the shoulder and elbow (Ladak et al., 2013). However, that was an uncontrolled study without a comparable group of patients who had nerve graft brachial plexus reconstruction.

The purpose of this study is to fill that important void by comparing a cohort of patients who underwent triple nerve transfer surgery to those treated by the traditional sural nerve grafting procedure. In addition to evaluating their functional outcomes, we also examined differences in healthcare utilization and costs between those procedures. To our knowledge, this has not been done before.

We hypothesize that triple nerve transfer is more efficacious in restoring shoulder and elbow function in children with upper trunk obstetrical brachial plexus injuries and can be achieved at lower direct healthcare costs.

Methods

This study was conducted in adherence to the ethical principles outlined in the World Medical Association Declaration of Helsinki and was approved by the human research ethics board at the University of Alberta and the University of Calgary.

Subjects

A cohort of children with isolated upper trunk obstetrical brachial plexus injuries was recruited. These infants were evaluated at birth and followed at the regional brachial plexus clinics by a multidisciplinary team at the Glenrose Rehabilitation Hospital in Edmonton and at the Alberta Children's Hospital in Calgary. The sural nerve grafting reconstruction patients were recruited from both regional clinics while those who underwent triple nerve transfers were all recruited from the Edmonton regional clinic as the procedure was not offered in Calgary. The inclusion and exclusion criteria were similar in both groups. Written and verbal informed consent regarding the operation was obtained from the parents or guardians.

Selection criteria

The arm function of each child was graded independently using the Active Movement Scale by occupational and physical therapists who were not involved in the surgical management of the children.

Inclusion criteria for the study included:

i) Having an isolated upper trunk injury based on clinical examination findings

ii) Supportive information was sought through needle electromyography evaluation that showed normal EMG activities in the triceps muscle

iii) Normal elbow extension and wrist flexion

iv) A failed cookie test at 9 months of age indicating below full antigravity strength for elbow flexion

Children were carefully examined for evidence of middle or lower trunk deficits. Intraoperative studies suggest that C7 is a prime contributor to the triceps muscle. Therefore, children with elbow extension abnormality were excluded from the study. To eliminate lower trunk deficits, those with wrist and hand abnormalities were also excluded.

<u>Surgical Procedures</u>

Triple nerve transfers

The procedure involves transferring the following nerves:

i) A distal branch of the spinal accessory nerve was used as a donor for the suprascapular nerve to reinnervate the supraspinatus and infraspinatus muscles for shoulder abduction and external rotation. To eliminate the possibility of additional double crush injury to the suprascapular nerve at the spinal notch (Upton & McComas, 1973), a posterior approach was used to expose the suprascapular nerve and to release the scapular ligament (Figure 1A).

ii) A second transfer involves using a motor branch of the radial nerve to the lateral triceps to reinnervate the axillary nerve close to its neuromuscular junction of the mid deltoid muscle to restore shoulder abduction (Figure 1B).

iii) A third transfer was done using a redundant motor branch of the ulnar nerve to the flexor carpi ulnaris muscle and coapt it to the musculocutaneous nerve to reinnervate the bicep brachii muscle to restore elbow flexion and forearm supination. In one case where no dominant flexor carpi ulnaris nerve fascicle could be found, a redundant branch of the median nerve to the flexor carpi radialis muscle was used instead (Figure 1C).

Following surgery, the arm was placed in a modified sling and elastic bandage for immobilization in full shoulder adduction at 90 degrees of elbow flexion for 3 weeks before active physiotherapy was initiated. All of the triple nerve transfer procedures were performed by the same surgical team in Edmonton.

Nerve graft reconstruction

The sural nerve grafting procedures were performed by one of two surgical teams in Calgary or Edmonton. The sural nerve grafts were harvested from both legs. The brachial plexus was exposed via a supraclavicular approach and the neuroma was isolated and excised. Sural nerve grafts were then interposed and coapted using fibrin sealant to reconstruct the upper plexus in an anatomic fashion (see Figure 2). The same post-operative procedure of using a modified sling and elastic bandage to immobilize the child's arm in full shoulder adduction at 90 degrees of elbow flexion was done. Active physiotherapy was initiated after 3 weeks.

Functional Evaluation

Independent therapists at the Glenrose Rehabilitation Hospital and the Alberta Children Hospital who were not involved in the surgical decision process administered the Active Movement Scale as the primary outcome measure. Additionally, to assess spontaneous hand use of the affected arm during bimanual play activities, the Assisting Hand Assessment (AHA) was completed as a secondary outcome measure.

Active Movement Scale

The Active Movement Scale was used to quantify the patient's baseline function and post-operative recovery (see Table 1). This tool was deliberately selected because it was shown to have good inter-rater and intra-rater reliability and has been well validated in this patient population (Curtis et al., 2002). During the evaluation, the child's upper limb movements while at play is quantified on an 8 point ordinal scale: 0 equates to "no contraction visible" and 7 being "full motion present against gravity". Fifteen functional movements of the shoulder, elbow, wrist and hand were measured. In this cohort of upper trunk brachial plexus patients, the movements of particular relevance are: shoulder function (including abduction, flexion, and external rotation) elbow flexion and forearm supination (Table 1).

Data from the triple nerve transfers groups was compared to the nerve graft reconstruction group at 6, 12 and 24 months post-surgery.

Assisting Hand Assessment

In addition, AHA was administered to the nerve transfer population. This was not done on the nerve graft reconstruction patients because a certified therapist was not available at the Calgary site to administer the AHA. This is a hand function evaluation instrument that measures how children with upper limb impairment use the affected hand (assisting hand) collaboratively with the non-affected hand in bimanual play. The test was developed for use with children who have unilateral upper limb impairment such as those with obstetric brachial plexus palsy. The AHA can be used with children 18 months to 12 years of age. It gives a unique perspective of assessing how a child uses their two hands together in a natural play setting that reflects the child's spontaneous and normal way of handling objects. This is of greater functional relevance than only measuring their best capacity to grasp, release or manipulate objects when prompted to use their affected hand. The AHA also has an added advantage in that it has been normed on the obstetrical brachial plexus population (Krumlinde-Sundholm et al., 2007).

<u>Healthcare Cost and Utilization</u>

For the purpose of this study, we only included direct costs because indirect costs such as time spent seeking or receiving care, time off work and unpaid provision of care by family members are nebulous and are therefore much more difficult to account for. Direct costs evaluated included the cost of acute surgical care, diagnostic tests, and visits to physicians and allied health professionals. In the pediatric population, the length of post-operative hospital stay is an important consideration as it has a significant impact on the family with regard to parental time off work and inability to care for other children in the home.

Length of operation and hospital stay

The length of surgery was extracted from the operative case record for each patient. Length of hospital stay was tabulated based on the admission and discharge dates recorded in the patient's chart.

Cost analysis

Direct cost data was collected through review of the medical records for each patient, Alberta Health Care Insurance Plan physician billings and aggregate facility fees from the Canadian Institute for Health Information. To allow accurate comparisons between patients, all costs were reported in 2010 Canadian dollars using the Bank of Canada consumer price index.

Professional fees

The surgeon and anesthesia fees were extracted from the Alberta Health Care Insurance Plan Schedule of Medical Benefits. The relevant fee codes for each operation were selected and a total fee was calculated based on the length of the operation.

Facility fees

The facility fees were determined based on publicly available data from the Patient Cost Estimator (Canadian Institute for Health Information). The facility fee represents the average cost of a standard hospital stay for our patient population in Alberta based on case mix group and resource intensity weight methodology (Canadian Institute for Health Information). This includes cost of the operation, hospital bed, nursing care, laboratory, pharmacy and diagnostic services. It also includes other costs such as administration, information systems, building maintenance and housekeeping. This costing methodology is based on the Canadian Institute for Health Information Management Information Systems Guidelines and Alberta Health Services healthcare cost reporting standards.

Statistical Analysis

Patient demographics were compared using Fisher's exact test and unpaired t-tests. Because of the small sample size, we elected to use the Mann Whitney U-test, a conservative nonparametric statistical method to compare the differences in the Active Movement Scale score between the two surgical groups. To ensure that differences in the individual's baseline performance in both groups were accounted for, we compared changes in the Active Movement Scale scores in each participant 2 years post surgery. Mann Whitney U test was also used to compare surgeon and anesthesia fees between the two procedures. Due to their aggregate nature, facility fees were excluded from statistical analysis. Statistical significance for α was set at less than 5% ($p<0.05$). Statistical analysis was performed using SPSS 19.0 software (SPSS, Inc., Chicago, Ill).

Results

Patient Demographics

Patients in both groups were similar in terms of birth weight, gender, affected limb and age at surgery (see Table 2). Because triple nerve transfers were only offered in Edmonton, all 14 children in that group were recruited from the regional pediatric upper limb clinic in the Glenrose Rehabilitation Hospital. In contrast, the 12 nerve graft reconstruction patients were recruited from the Glenrose Rehabilitation Hospital in Edmonton (3 children) as well as the Alberta Children's Hospital in Calgary (9 children). Each patient was followed for 2 years.

Functional outcomes

Shoulder Function

At baseline, none of the subjects had useful shoulder abduction, flexion or external rotation. The spinal accessory nerve to suprascapular nerve and radial nerve to axillary nerve transfers and the sural nerve grafts procedure resulted in significant improvement in the shoulder abduction, shoulder flexion and external rotation. Based on the Active Movement Scale scores at 2 years post-surgery, there was no significant difference between the two groups for shoulder flexion or abduction. However, the nerve transfer group showed significantly better shoulder external rotation than the nerve-grafting group. At 24 months improvement in individual scores in the transfer group was 2.4 ± 1.2 compared to $.7 \pm 0.7$ in the graft reconstruction group ($p<0.05$). Details of the results are shown in Figure 3 and Table 3.

Elbow Flexion and Forearm Supination

While changes in the Active Movement Scale were similar for elbow flexion (1.7 ± 1.2 in the transfer group verse 2.2 ± 1.5 in the graft group), improvement in forearm supination scores with the triple nerve transfer surgery at (3.4 ± 0.9) were significantly greater than that in the nerve grafting group to (2.2 ± 1.6) ($p<0.05$). Additional details of the Active Movement Scale scores are shown in Figure 4 and Table 3.

Functional hand use for bimanual performance

The AHA was administered to measure how effectively the children in the nerve transfer group could use their affected arm along with their well-functioning arm to perform bimanual tasks. The mean age of the transfer group at the time of evaluation was 3.9 years (range of 1.7 -5.6 yrs). The nerve transfers group had high scores with an average raw score of 81 ± 3.5 logit-based AHA units (out of a total of 100 units). Translated to functioning in daily life, this group of children performed bimanual tasks independently and bimanual play was not affected by their brachial plexus injury. They could move their upper arms fluidly and reach a large range but with limited forearm movements. Grasp and release items and fine motor adjustment items were performed effectively.

Donor-Site-Morbidity

As a measure of donor-site morbidity in the nerve transfer population, the Active Movement Scale scores for elbow extension and wrist flexion were followed as a functional measure of radial, ulnar and median nerve function. Over a 2year period, no significant change in function was found in either elbow extension (6.9±0.1) or wrist flexion (6.8±0.2).

Healthcare Costs

Operative time and length of hospital stay

The duration of the triple nerve transfer procedure was 02:21±00:06 (mean±SE, hh:mm) whereas nerve grafting was 08:39±00:32 ($p<0.0005$, see figure 5). Triple nerve transfer patients had an average hospital stay of 1.1±0.1 days compared to nerve graft patients who had an average stay of 3.3±0.2 days ($p<0.0005$, see Figure 5A).

Professional fees

The mean surgeon fee for the triple nerve transfer was \$2000 ±\$103, compared to nerve graft fee of \$4377±\$312 ($p<0.0005$). Anesthesia fees for triple nerve transfers were \$612±\$21 compared to nerve grafting of \$2026 ±\$176 ($p<0.0005$). Total professional fees are shown in Figure 5B.

Facility fees

The average cost of a hospital stay for triple nerve transfer patients was \$4425 compared to \$8835 for nerve graft patients (see Figure 5B).

<u>Secondary procedures</u>

Seven of the twelve nerve graft patients required subscapularis lengthening. Three of the nerve graft patients required anterior release with a latissimus dorsi and teres major tendon transfer to rotator cuff to improve shoulder external rotation (Hofer procedure). In the triple nerve transfer group, one child had a pectoralis release at the time of the transfer surgery and one child had a pectoralis release at the time of the transfer surgery and 1 child had a pectoralis release and Hofer procedure at the age of 3½ years.

Discussion

In this study we compared the clinical outcomes of a cohort of children with upper trunk obstetrical brachial plexus injury who underwent triple nerve transfers to those who had sural nerve graft reconstruction. While both groups demonstrated gains in motor function on the Active Movement Scale, the triple nerve transfer group demonstrated greater improvement in shoulder external rotation and forearm supination.

Comparisons with published data in the literature

Distal nerve transfers afford the benefit of creating distal coaptations close to the neuromuscular junction with a shorter regeneration time. Nerve transfer surgery with or without nerve grafting has demonstrated good motor outcomes in the adult population (Yang et al., 2012). Nerve transfers in the traumatic pediatric population have also shown favorable outcomes (Chim et al., 2015) The spinal accessory to suprascapular nerve transfer has been widely used as an adjunct to sural nerve graft reconstruction of the brachial plexus (Tse, et al., 2012). Several recent studies have also used isolated nerve transfers in late presenting cases (over one year of age) of obstetrical brachial plexus palsy. The Oberlin procedure has proven to be effective in restoring elbow flexion in that patient population (Hale et al., 2010); (Siqueira et al., 2012). Historically nerve transfers have been used in isolation in the obstetrical brachial plexus injury population with children who present late. Even in those cases, favorable results with nerve transfers are still seen.

A recent study reported that spinal accessory nerve transfers produced superior results compared to cervical root grafting for suprascapular nerve reconstruction in obstetrical brachial plexus injuries (Seruya et al., 2015). Although they did not find any significant difference in shoulder external rotation using the Active Movement Scale, they did show higher scores on the Mallet Scale in the nerve transfer group. One possible explanation for the discrepancy is that the way the shoulder is evaluated with the Active Movement Scale is different from the Mallet Scale. In addition to the traditional method of measuring external rotation with the shoulder in adduction, the Mallet also captures external rotation with the shoulder abducted (hand to nape of neck). One may argue that the Mallet captures shoulder movement in a way that is more relevant to everyday activities. Improvement of the movement of hand to nape of neck would make activities such as putting in a ponytail, washing hair or placing a necklace around the neck easier. In addition compared to the nerve transfer group, Seruya found that the nerve graft group had a two fold increase in secondary shoulder surgery which is similar to our experiences (Seruya et al., 2015). There are a number of potential explanations for this difference. First, it is widely known that children with obstetrical brachial plexus injury have changes to the biomechanics and formation of the glenohumeral joint (Waters et al., 1998). Obstetrical brachial plexus injury cases have been reported to have smaller glenohumeral displacement when performing the Mallet scale and larger scapulothoracic displacement (Russo et al., 2014). They may also have abnormal scapular position, glenohumeral dysplasia and internal rotation contractures. In addition, scapular winging is often reported. Russo recently reported that children with obstetrical brachial plexus injury have limited glenohumeral cross-body adduction which may contribute to scapular winging (Russo et al., 2014). Glenohumeral dysplasia and soft tissue and capsular contractures can occur over time. As the child continues to grow and develop, resulting in more imbalanced muscle forces around the joint, these changes in the shoulder can become more pronounced. Children with obstetrical brachial plexus injury have been shown to have abnormal anteverted glenoscapular version− the glenoscapular angle measured using MRI. This is done by using a bisecting line constructed along the axis of the scapula to connect the medial margins of the scapula to the middle of the glenoid fossa (Kozin, 2004). A negative value indicates glenoid retroversion and a positive value represents glenoid anteversion. Kozin reported progressive loss of external rotation of the glenohumral joint indicative of shoulder malformation in children with obstetrical brachial plexus injury (Kozin, 2004). Indeed, angular deformity and posterior subluxation of the humeral head (coronal deformity) has been widely reported in this population (Clarke et al., 2009). If some of these secondary changes can be mitigated by improving neural innervation to the deltoid and rotator cuff muscles over a shorter period of time, it may reduce the need for secondary shoulder surgeries in the future. It may also reduce secondary contractures and glenoid deformity over time.

Another possible explanation for the greater improvement in shoulder external rotation in Active Movement Scale scores in the distal nerve transfer group may be attributed to the surgical approach used in this study (Ren et al., 2013). In the adult population, Ren and his colleagues showed favorable results using a double nerve transfers for restoring shoulder abduction and external rotation. However in a previous study in the obstetrical brachial plexus injury population comparing nerve transfers (spinal accessory to suprascapular nerve transfers) to nerve grafts, Tse reported no difference in shoulder external rotation (Tse et al., 2011). One potential reason for the difference is that the suprascapular nerve in the earlier study was not decompressed at the suprascapular notch. In contrast the posterior approach used in this study allows to the suprascapular ligament to be released from the suprascapular notch, thereby negating the risk of the double crush injury that may have occurred at the time of delivery. Described by Upton and McComas, they found that the injury to axons at one location could render the nerve more susceptible to injury at another location, such as at a compression site (Upton & McComas, 1973). Indeed, double crush injury affecting the suprascapular nerve at the suprascapular notch in patients with cervical nerve root (C5 C6) injury has been described (Ahlawat et al., 2015). Releasing the ligament may account for the improved scores in external rotation in the triple nerve transfer population.

Finally, a third potential reason for the greater functional improvement is that in distal nerve transfers, only a terminal branch of the recipient nerve is cut. The remaining viable nerve fibers in the native nerve would therefore still provide an intact conduit to reach the target muscle.

Improved forearm supination in the transfer population may be attributable to the fact that the distal donor nerve stump is placed close to the neuromuscular junction. Given the long distance from the nerve reconstruction site in the neck, the length advantage to the elbow and forearm muscles would be even more pronounced with distal nerve transfers.

Healthcare costs and practical considerations

In this study, distal nerve transfer patients have significantly shorter operative times and post-operative hospital stays compared to patients who underwent nerve graft reconstruction. This translates to significantly reduced costs for the health care system in Alberta in terms of fees paid to the surgeon and anesthetist and the overall cost of the hospital stay. Each nerve grafting procedure amounts to one full day of operative time. In comparison, three triple nerve transfer procedures could be performed in the same amount of operative time, potentially reducing the waitlist for these procedures. Shorter hospital stays can also help to alleviate the pressure on hospital beds in acute care facilities.

Perhaps even more importantly is that for the patients and their family, having a shorter hospital stay, less extensive surgery and quicker post-surgical recovery is of paramount importance. These considerations could be major factors that need to be taken into account when the family is trying to make an informed decision about different treatment options.

Potential limitations of distal nerve transfers

A potential argument in favor of sural nerve graft reconstruction is that it would also provide a path for sensory nerve fibers to reinnervate the target tissues. However, as reported anecdotally by parents and through functional observations, there is little difference in limb sensibility between the two groups. There may be several possible explanations for this. First, as pointed out in the previous section, since only a terminal branch of the recipient nerve is cut in distal nerve transfers, the remaining branches would still provide continuity for sensory axons in the proximal nerve to the reach the target tissue. Second, as demonstrated in the adult population, there is substantial reorganization in the somatosensory cortex following peripheral nerve injuries and after surgical reconstruction (Yoshikawa et al., 2012). It is highly conceivable that cortical reorganization in children may also play a significant role in compensating for the loss of peripheral sensory nerve fibers. In practice, we have not seen any cases of inadvertent injury in any of the children as a result of skin hyposensitivity. Hand dexterity for fine manipulation is also not impaired.

Secondly, a potential issue with distal nerve transfers is the concern of donor nerve morbidity. However, we did not find that in this study. A likely reason is that the donor muscles are deliberately chosen on the basis that there are other synergistic muscles that can substitute for the same function. Furthermore, great effort is taken to select a redundant motor nerve fascicle for transfer so that intact fascicles are left behind to minimize the effect on muscle function.

A third limitation of distal nerve transfers is that it would not be a viable option in all cases of brachial plexus injuries. It would only be feasible if there is sufficient preservation of neighboring donor nerves available for transfer. Therefore, it should be considered as a complementary option for nerve graft reconstruction. Distal nerve transfers are a valuable alternative in patient populations such as the one described in this study, but would be less applicable in pan-plexus injuries.

In conclusion, the results of this study support the use of nerve transfers as a potential first-line treatment option for reconstruction of upper trunk obstetrical brachial plexus injuries.

Figure Legends

Figure 2.1. Distal nerve transfers. A) Posterior approach transferring a distal branch of spinal accessory nerve to the suprascapular nerve while also releasing suprascapular nerve the scapular ligament. **B)** Transferring a motor branch of the radial nerve to the lateral triceps to reinnervate the axillary nerve close to its neuromuscular junction in the deltoid muscle. **C)** Using a motor branch of the ulnar nerve to the flexor carpi ulnaris muscle to reinnervate the biceps muscle.

Figure 2.2. Nerve graft reconstruction. Bilateral sural nerve grafts were used to reconstruct the brachial plexus following neuroma excision.

Figure 2.3. Results of restoration of shoulder movements following surgery. While the extent of improvement in shoulder flexion and abduction was similar in both procedures, external rotation was significantly better after nerve transfer surgery (* denotes $p<0.05$). AMS denotes Active Movement Scale.

Figure 2.4. Results of nerve transfers vs grafts in elbow flexion and supination. The layout and notations used are the same as in figure 3. Improvements in both elbow flexion and forearm supination are significant better following distal nerve graft repair.

Figure 2.5. Health costs and utilization. A) Comparison of length of operation (mean $\pm$ se, minutes) and **B**) length of hospital stay (mean $\pm$ std error, days) for triple nerve transfer and nerve grafting. **C**) Comparison of professional and facility fees for triple nerve transfer and nerve grafting in 2010 Canadian dollars. ***$p<0.0005$.

Table 1) Active Movement Scale

Movement	**Score**
Gravity Eliminated	
No contraction	**0**
Contraction without movement	**1**
Movement <1/2 of ROM	**2**
Movement >1/2 of ROM	**3**
Full Movement	**4**
Against Gravity	
Movement <1/2 of ROM	**5**
Movement > ½ of ROM	**6**
Full Movement	**7**

Table 2) Comparison of baseline patient characteristics

	Nerve graft	**Triple nerve transfer**	***p-value***
Gender	6 females 6 males	7 females 7 males	*0.999*[*]
Affected limb	8 left 4 right	4 left 10 right	*0.113*[*]
Birth weight, Grams	3903 $\pm$ 851	3604 $\pm$ 446	*0.145*[^]
Age at surgery, months	11.4 $\pm$ 6.1	11.9 $\pm$ 2.3	*0.935*[^]

[*]Fisher's exact test
[^]Unpaired t-test

Table 3) Comparison of Nerve Transfers (T) (mean ± std error) and Nerve Grafts (G).

Movement	Preoperative Score	Postoperative Scores (6 month	Postoperative Scores (1yr)	Postoperative Scores (2 yrs)
Shoulder abduction	3.6 ±0.3 (T) 3.0.±0.4 (G)	4.1 ±0.3 (T) 3.3 ±0.6 (G)	4.8 ±0.3 (T) 4.9 ±0.4 (G)	5.1 ±0.4 (T) 5.5 ±0.3 (G)
Shoulder Flexion	3.7 ±0.3 (T) 4.1 ±0.4 (G)	4.6 ±0.4 (T) 4.3 ±0.5 (G)	5.1 ±0.4 (T) 5.4 ±0.3 (G)	5.4 ±0.4 (T) 5.8 ±0.2 (G)
Shoulder external rotation	1.9 ±0.3 (T) 1.8 ±0 .4 (G)	2.9 ±0.4 (T) 1.6 ±0.6 (G)	3.8 ±0 .4 (T) 2.1 ±0.5 (G)	4.3 ±0.5 (T) 2.9 ±0.6 (G)
Elbow Flexion	4.4 ±0.4 (T) 3.3 ±0.4 (G)	5.5 ±0.3 (T) 3.2 ±0 .7 (G)	6.1 ±0.2 (T) 5.0 ±0.3 (G)	6.1 ±0.2 (T) 5.5 ±0.2 (G)
Forearm Supination	2.3 ±0.2 (T) 2.3 ±0.3 (G)	4.1 ±0.5 (T) 2.7 ±0.6 (G)	4.9 ±0 .4 (T) 3.7 ±0.5 (G)	5.6 ±0.3 (T) 4.4 ±0 .6 (G)

Figure 2. 1

A

B

C

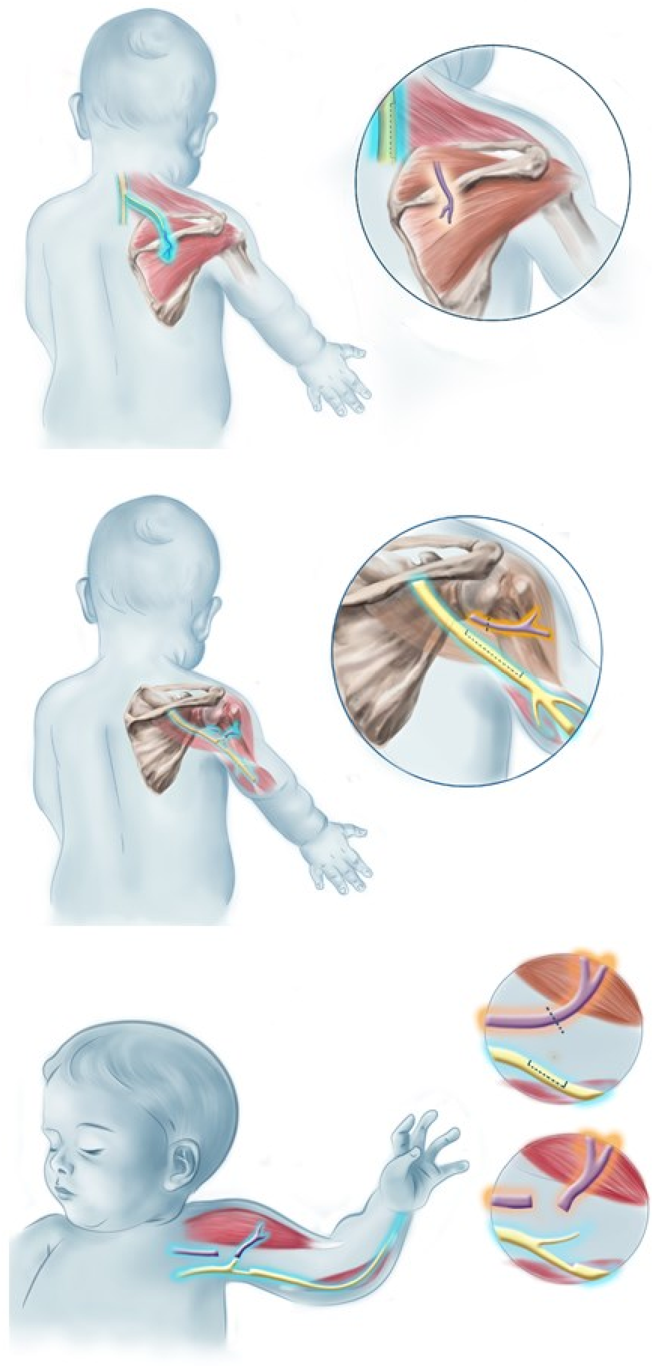


Figure 2.2

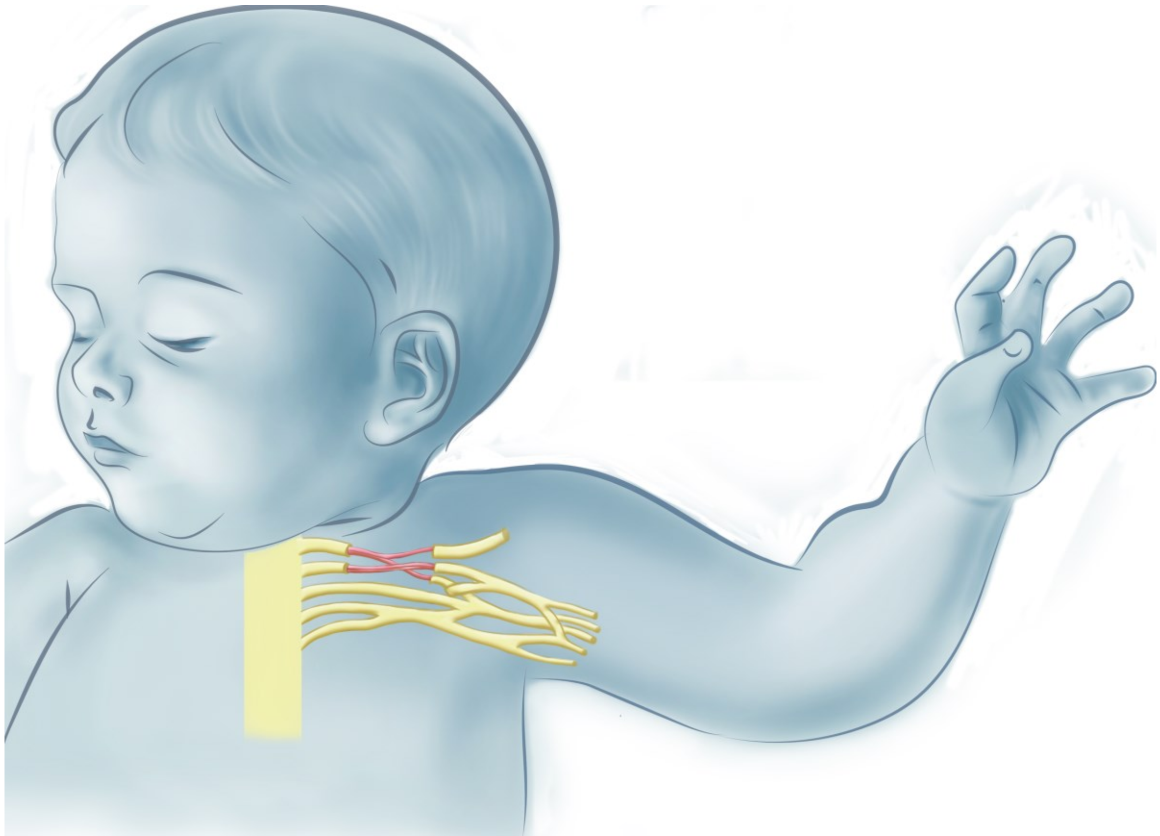


Figure 2.3

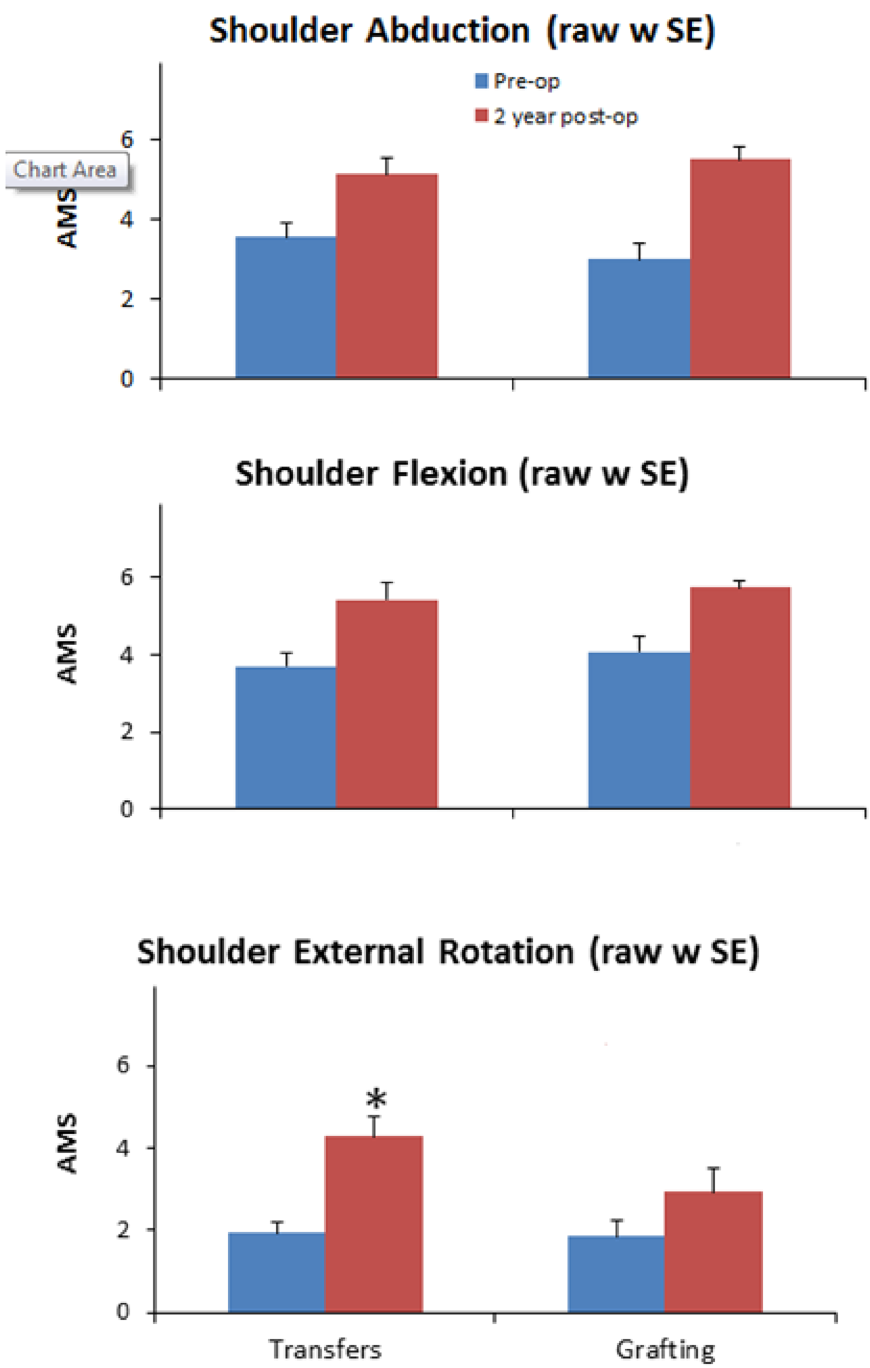
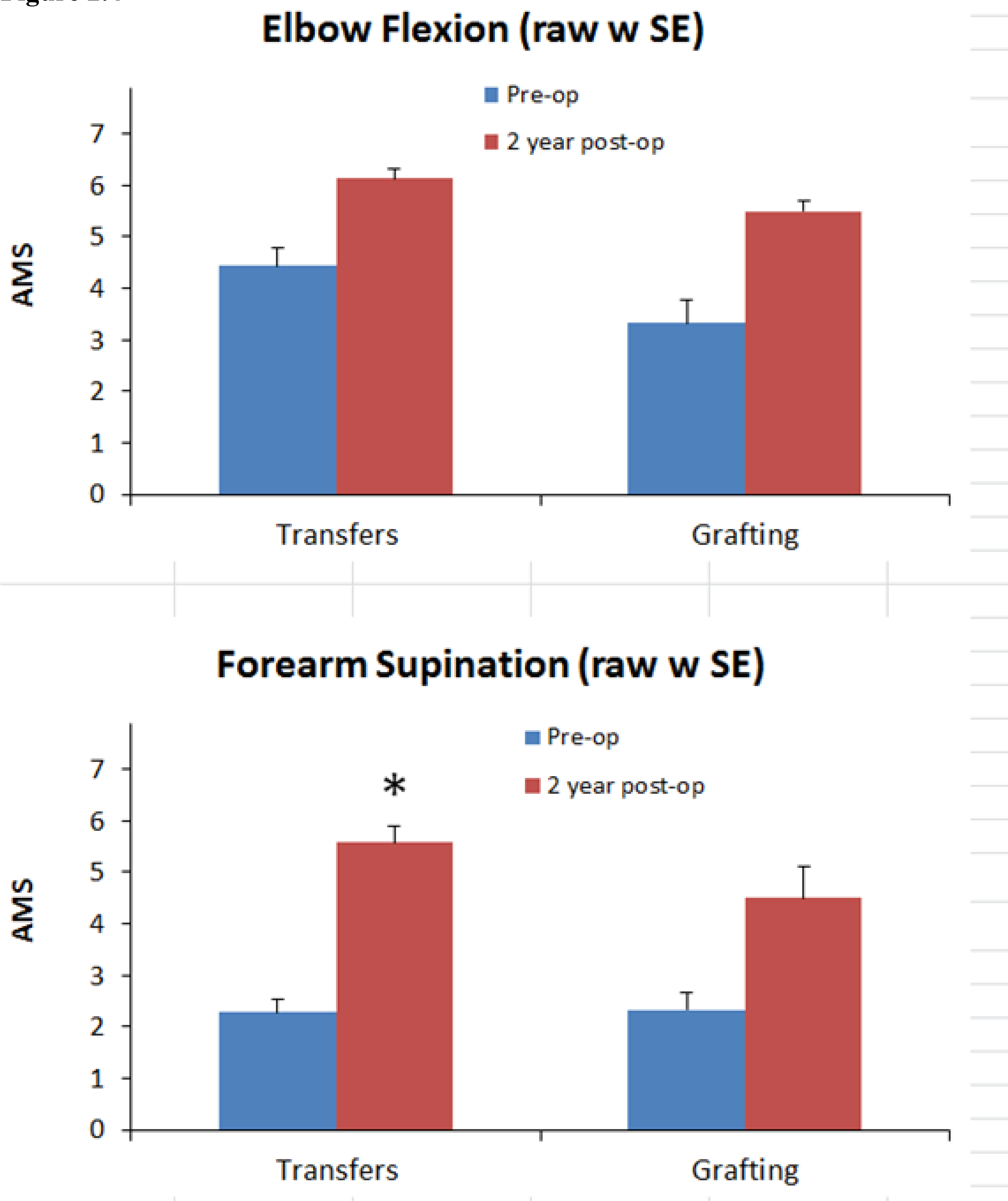

Shoulder Abduction (raw w SE)
Pre-op
2 year post-op
Chart Area
AMS
0
2
4
6
Shoulder Flexion (raw w SE)
AMS
0
2
4
6
Shoulder External Rotation (raw w SE)
AMS
0
2
4
6
*
Transfers
Grafting

Figure 2.4


Elbow Flexion (raw w SE)
Pre-op
2 year post-op
AMS
0
1
2
3
4
5
6
7
Transfers
Grafting
Forearm Supination (raw w SE)
Pre-op
2 year post-op
*
AMS
0
1
2
3
4
5
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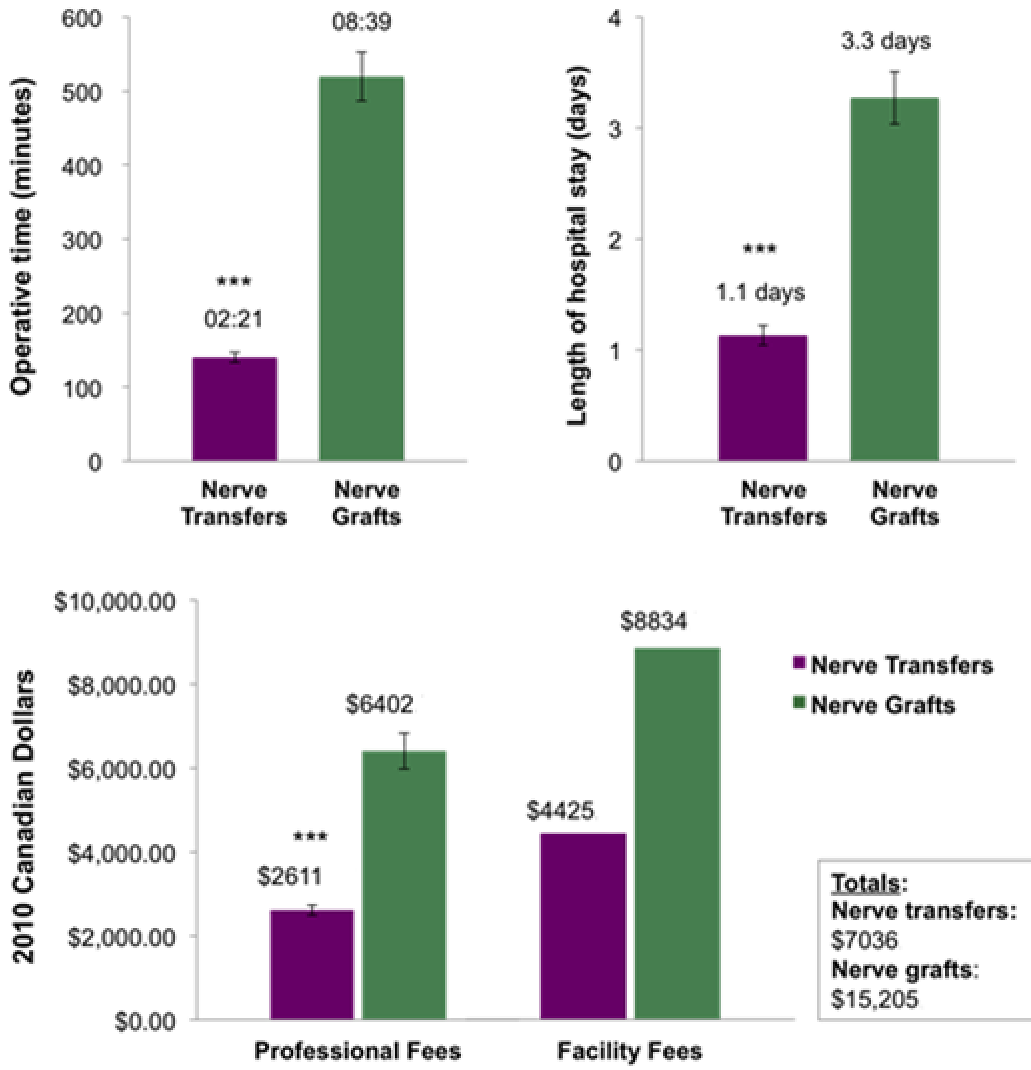
Transfers
Grafting

Figure 2.5



600
500
400
300
200
100
0
Operative time (minutes)
08:39
***
02:21
Nerve Transfers
Nerve Grafts
4
3
2
1
0
Length of hospital stay (days)
3.3 days
***
1.1 days
Nerve Transfers
Nerve Grafts
$10,000.00
$8,000.00
$6,000.00
$4,000.00
$2,000.00
$0.00
2010 Canadian Dollars
$8834
$6402
$4425
***
$2611
Professional Fees
Facility Fees
Nerve Transfers
Nerve Grafts
Totals:
Nerve transfers:
$7036
Nerve grafts:
$15,205

Chapter 3: Management of Upper Trunk Obstetrical Brachial Plexus Injury: Final Thoughts and Future Directions

In spite of more in-depth knowledge and better understanding of the mechanisms of brachial plexus injury during birth, the incidence of obstetrical brachial plexus injury remain stubbornly high, especially in North America. Based on population health data, obstetrical brachial plexus injury is up to 15 times more common in the United States compared to the United Kingdom (Iffy et al., 2015). Therefore, the needs for finding a better treatment to restore nerve function are becoming more urgent. This is one of the main motivating factors that spur us on to fully explore better alternatives than what is currently available. Apart from carrying a heavy cost to the baby and the family, the socioeconomic costs are very high.

Perhaps the most cost efficient measures are early detection and preventive measures. Macrosomia, labour dystocia, vacuum deliveries and vaginal breach deliveries are significant risk factors in obstetrical brachial plexus injuries (Okby & Sheiner, 2012). Screening policy for shoulder dystocia using ultrasound in late trimester can predict macrosomia (Souka et al., 2013). It has been closely evaluated and a cost-effectiveness analysis model has been built for offering the option of Caesarian Section to pregnant women.

For cases where severe injury has already occurred, apart from improvements in surgical options, there are other non-surgical possibilities on the horizon that may be worth considering. Strategies to enhance peripheral nerve regeneration have been an active area of investigation. With new mechanistic insights into key molecular pathways that can exert a major influence on nerve growth and guidance, there are attracting targets that may become feasible in the near future. This includes deploying adjunct treatment strategies that target molecular targets vital in expediting peripheral nerve regeneration into the distal stump. An example is brief post-surgical low frequency electrical stimulation to the proximal stump immediately after nerve repair or transfer. This treatment has been shown to accelerate nerve growth across the nerve suture site and enhance muscle reinnervation in patients with severe compressive neuropathy (Gordon et al., 2010). In addition, there are other pharmaceutical agents that work through complementary pathways for nerve growth and nerve guidance as well (Chan et al., 2014; Gordon et al., 2010). Together, these open the interesting specter of combining synergistic options with surgical interventions.

The potential issue of sensory restoration is an important one because hand sensibility plays a major function role in dexterous fine motor control. The question of where restoration of hand sensation actually requires nerve graft reconstruction in upper trunk brachial plexus injury remains unresolved. There are several lines of evidence suggesting that nerve graft reconstruction may not be necessary. First, infants possess highly dynamic cortical neuroplasticity that may allow them to circumvent areas of peripheral nerve injury (Taylor et al., 2009). Second, peripheral nerves in the young have been shown to have the capacity to sprout into the territories of injured nerves (Allodi et al., 2012). Third, from our clinical experience as well as observations by others, that few if any children sustain inadvertent trauma to their brachial plexus injury limb as a result of insensitivity. Indeed, they often show surprisingly good fine hand motor control.

An in depth review of the literature on nerve transfers in the upper trunk obstetrical brachial plexus population has revealed a major void that was addressed in this dissertation. Although several authors have examined isolated nerve transfers when suitable proximal stumps were not available for grafting or when children presented late to the surgeons thereby reducing the effectiveness of the nerve grafting procedure, only one preliminary study has examined the triple nerve transfer procedure in place of the nerve grafting procedure. The results of the triple nerve transfer procedure are shown to be similar to the nerve grafting procedure in shoulder abduction and flexion and yielded better results for shoulder external rotation, elbow flexion and forearm supination.

There continues to be a gap in the literature looking at how children with obstetrical brachial plexus injuries use their affected arm for everyday function. Many studies examine active range of motion and strength in isolation focusing exclusively on impairment of body function. Our results demonstrated that children who receive triple nerve transfers have good bimanual function and use their affected arm well to perform two handed tasks in real world tasks. The costs analysis also supports the argument that this surgical procedure represents reduced surgical time, reduced length of stay for the children, and as a result is significantly less expensive. Together, these findings suggest that triple distal nerve transfers could be a viable alternative to traditional nerve graft construction in appropriate cases of children with upper trunk obstetrical brachial plexus injuries.

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