The brachial plexus is a complex system of nerves exiting the spinal cord at the C5-T1 levels. These nerve roots then branch out to support motor and sensory function for the upper extremities (see The brachial plexus). William Smellie was the first to record a brachial plexus injury associated with birth, and his findings were published in 1768. In 1872, Guillaume Duchenne, a French physician, coined the term, ‘obstetrical brachial plexus palsy’ and clearly stated the etiology of the injury. He was then followed in 1874 by Wilhelm Erb, a German neurologist, who outlined the anatomy associated with brachial plexus injuries.1

**Incidence**

Brachial plexus birth palsy occurs in 1.5 per thousand live births and is thought to be related to the birthing process.2 Known risk factors for brachial
Birth palsy

Birth palsy include large birth weight, maternal diabetes, shoulder dystocia, prolonged labor, instrumented delivery, and breech presentation. Despite these, less than half of infants with brachial plexus palsy have known risk factors. The injury is identified immediately after birth, and the degree of injury for each nerve found in the brachial plexus can range from neurapraxia to avulsion (see Types of injuries).

Evaluation
Referral to a specialty center is recommended, as serial physical exams are the best method for evaluation. During the assessment, a number of methods may be used to document a patient’s level of function, including the Toronto Score, Mallet Classification, Active Movement Scale (AMS), and the Narakas Classification. The Toronto Score is used to quantify upper extremity function using a 0 to 10 scoring method and was designed to predict outcomes in patients with brachial plexus birth palsy at 3 months of age. The AMS is comprehensively used to document muscle group function controlled by the entire brachial plexus, the reliability of these instruments has been documented.
Narakas developed his classification in an attempt to categorize brachial plexus injuries by level of involvement. Group I refers to C5 to C6 involvement, Group II designates C5 to C7 involvement, Group III indicates a total plexus injury, Group IV signifies the most severe form, characterized by a flail extremity with a Horner syndrome (see Child with a total brachial plexus birth palsy). Horner syndrome results from avulsion of T1 and is signified by ptosis, miosis, and anhidrosis on the affected side. Spontaneous recovery of function in the upper extremity has been reported in 64% of Narakas I and II patients. These patients demonstrated biceps muscle recovery at 3 months of age, while only 9% of patients in the Narakas III and IV group had the same result. Nerves regenerate at a rate of 1 mm/day or 1 in. (2.54 cm)/month. It’s common for the shoulder to begin functioning before the elbow. Through observation, the best indication of a good outcome is how quickly the biceps muscle begins to function against gravity. The assessment of biceps function is best isolated when the patient is placed on the involved side with the arm straight out at shoulder height. Clear biceps function against gravity and can be palpated and seen when the elbow bends during the hand-to-mouth motion.

### Preoperative diagnostic testing

Diagnostic testing is recommended preoperatively to identify concurrent injuries. Humerus or clavicle fractures may be identified with X-rays. Shoulder dislocation, which results from altered muscle function and growth, may be ruled out with a shoulder ultrasound. An electromyogram (EMG) and/or magnetic resonance imaging (MRI) of the brachial plexus may be recommended to gain further information regarding the actual lesions and muscle function impacted.

### Nonsurgical intervention

Individualized treatment plans are developed following the initial assessment and often include occupational or physical therapy to optimize each patient’s function. Therapy may begin as early as 1 to 2 weeks of age and usually occurs once a week, so family education and home exercise programs are important aspects of treatment. Therapy may include aquatics, constraint-induced movement therapy, orthoses, therapeutic taping, and neuromuscular electrical stimulation. Appropriate intervention is important to maximize motor function, promote increased signals to the brain, and minimize development of deformity. In addition to therapy, a nonsurgical option may include the use of onabotulinumtoxinA to improve muscle balance around the shoulder and/or elbow.

### Types of injuries

- **Avulsion:** The nerve is pulled away from the spinal cord
- **Rupture (Neurotmesis):** The nerve is torn but still attached to the spinal cord
- **Neuroma:** The nerve is surrounded by scar tissue
- **Neurapraxia:** The nerve has been stretched

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**The brachial plexus**

- **C5:** Moves the shoulder
- **C6:** Flexes the elbow and wrist
- **C7:** Sensory trunk, which straightens the elbow and allows wrist movement
- **C8:** Flexes wrist and fingers, extends the fingers, and provides hand movement
- **T1:** Controls hand muscles

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**Image provided as a courtesy of the authors and Cincinnati Children’s Hospital Medical Center.**

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**Image provided as a courtesy of the authors and Cincinnati Children’s Hospital Medical Center.**
**Surgical intervention**

Children who don’t have a spontaneous recovery within the first few months of life are typically recommended for microsurgery to restore function to the affected upper extremity. Each case is individualized based on the location and extent of the injury. The severity of the injury is determined preoperatively by the degree of functional return in the shoulder, biceps, and hand. The timing of surgery is debatable amongst multiple authors. Some authors recommend intervening as early as 3 months of age, while others recommend intervening beyond 3 to 6 months of age. The general consensus is that those infants who clinically appear to have global lesions (Narakas III and IV) and the presence of Horner syndrome are considered for surgery by 3 months of age.5,8-10 Early intervention in global lesions is important to minimize the loss of motor function and maximize the recovery time.8

The actual procedure entails exploring the brachial plexus and then restoring function with nerve grafts and/or nerve transfers. During the exploration, the plexus is examined for the presence of a neuroma, injury severity, number of nerve roots involved, and motor response distal to the injury. The information gathered from the exploration determines whether nerve grafting, nerve transfers, or a combination of both are necessary.9,12

**Preoperative assessment**

In addition to determining the rate and degree of return of function in the affected extremity, the infant needs to be evaluated for potential anesthesia and surgery risks. The infant is screened for a history of cardiac and respiratory disorders, family history of blood disorders, malignant hyperthermia, and pseudocholinesterase deficiency. Parents are questioned about the family’s previous exposure to anesthesia and any related complications. A preoperative head-to-toe assessment performed by the primary care provider is reviewed for any risk factors, such as underlying respiratory disorder, upper airway congestion, fever, and skin rashes. A complete listing of known allergies and medications, in addition to N.P.O. status for solids and liquids, is collected preoperatively.

A few important aspects to consider when performing a preoperative assessment are the symmetry of the chest during respirations and the baseline functional evaluations utilizing the Toronto Score and AMS. Chest ultrasounds are performed preoperatively to evaluate the function of the diaphragm and to determine if the phrenic nerve was injured. The phrenic nerve arises from C3 to C5, and a weakening in the diaphragm reflects a possible upper trunk or global injury.8,12 The preoperative evaluation of the diaphragm is used to determine if intercostal nerves could be transferred (if necessary) and is later compared with the postoperative evaluation. The serial evaluations of function can determine if there have been improvements in the overall function. The clinical picture determines if the child is a surgical candidate and predicts which nerve roots are affected.

**Preparing for surgery**

Patient education is an important aspect of preoperative care. Many families may have some mistrust in the healthcare system because of the belief that the injury could have been avoided. Listening to the family’s story and providing patient education about the injury and treatment is crucial in instilling trust. The family should be informed of the different severities of injury, clinical findings, and treatment options. In addition, detailed information about the surgical
procedure and the recovery time should be discussed with the families.

The OR and same-day surgery nurse should be knowledgeable of the policies concerning the presence of a parent/guardian during induction of the child. The induction procedures are explained by the anesthesia staff to the parents in the preoperative phase. The families are provided with frequent updates throughout the case, since most brachial plexus nerve repairs are 4 to 8 hours in length.

A preoperative briefing with the surgeons, anesthesia staff, and OR nurses should take place prior to the case, so the entire team is aware of the plan of care. The infant’s medical history, proper positioning, administration of neuromuscular blocking agents, prepping of the extremities, and the necessary equipment should be discussed. Many times during brachial plexus repairs that involve nerve grafting, three of the four extremities need to be prepped, so determining which extremity to place the BP cuff and insert the I.V. line is important to maintain sterility. Also, discussing which side of the mouth to secure the endotracheal tube based on which side of the neck the surgeon will be making the incision is important to prevent accidental extubation of the patient during the case. Neuromuscular blocking agents are not administered during brachial plexus repairs—so the surgeons can internally stimulate the nerves of the plexus—and evaluate the response. Discussing these plans prior to the case starting will reduce errors, and clarify what is needed and expected from the surgeons.

**Intraoperative set-up**

Set-up of a brachial plexus repair case entails proper patient positioning, verifying that the microscope is available, a nerve and muscle stimulator is present, and that the fibrin sealant is thawed and in the room. A fibrin sealant (which consists of human fibrinogen and human thrombin) is utilized as an off-label adjunct to suturing the nerve fascicles together. The fibrin sealant takes approximately 60 to 110 minutes to thaw at room temperature, and unopened pouches can be stored at this temperature for 48 hours. The nerve and muscle stimulator is utilized to determine the quality of the motor response of the nerve and can identify nerves, such as the phrenic, spinal accessory, and others that may be transferred. The microscope should be prepped, draped, and tested for proper functioning, and the lamp should be set at the lowest feasible levels to prevent burns.

Proper positioning of the patient prior to applying the sterile drapes is very important and should be discussed with the surgeon prior to the case. Most surgeons prefer to have the patient situated in a supine position if an exploration is going to take place. The infant is placed on the operating table, and the neck is extended with the head turned to the opposite side of where the incision will be made. Sterile towels or a shoulder roll is placed between the shoulder blades to promote extension of the neck and to open the supraclavicular region. All pressure points should be meticulously padded, including the head. If the surgeon is confident that nerve grafting will take place, the patient may be placed in a prone position to harvest the sural nerve from the back of the legs and then turned to a supine position. If nerve transfers are indicated, the patient is placed on a bean bag and positioned in a lateral decubitus position to allow exposure of the posterior aspect of the affected shoulder. The affected upper extremity and bilateral lower extremities are prepped and draped free. A urinary drainage catheter is placed to monitor urine output and maintain sterility of the lower extremities. Once the infant is positioned and secured to the OR table, a forced-air warming device is placed over the patient to control body temperature.

**Brachial plexus exploration**

Brachial plexus exploration involves exposing the actual plexus through an incision in the crease of the neck to localize the extent of the lesions. A distinction is made between nerve root avulsion, neurotmesis or rupture of nerve roots, or axonotmesis based on inspection of the nerves and electrical
stimulation with a nerve stimulator. The most common finding in brachial plexus injuries is a neuroma-in-continuity of the upper trunk located at the C5 and C6 nerve roots. A neuroma-in-continuity is a lesion where the intraneural architecture of a nerve is severely damaged, but the nerve is not severed into two separate parts. A nerve root is considered to be avulsed if a dorsal root ganglion is visible, neuroma formation is absent, and there is an absence of muscle contractions in response to stimulation. Neurotmetic nerves are normal in appearance at the intraforaminal level, have an increase in diameter of the nerve, abundant fibrosis, and provide weak muscle contractions when stimulated. Axonotmetic nerves have no increase in diameter, limited fibrosis, and provide a muscle contraction that induces limb movement. These findings determine which type of repair is required to restore function to the affected upper extremity.

The phrenic nerve is identified and stimulated to assess diaphragmatic function and involvement. Careful neurolysis of the phrenic nerve typically occurs if it is involved in the neuroma and may result in a weakening in the diaphragm function on the affected side postoperatively. If a phrenic nerve injury occurs, most resolve within 1 year (postoperatively) without intervention.

Nerve grafting
Nerve reconstruction is recommended for neurotmetic nerves, which involves dissecting the neuroma and stimulating the proximal stumps to determine if a muscle contraction occurs. The quality of the muscle contraction distal to the stimulus determines if the nerve root is suitable for grafting. Some surgeons send the dissected nerves to pathology for histologic evaluation to determine if the proximal and distal stumps are viable targets for grafting and reinnervation.

Schematic of a brachial plexus repair

The sural nerve is a sensory nerve used for grafting that runs down the posterior calf. It is dissected free from surrounding attachments through 2 to 3 cm transverse incisions starting at the lateral malleolus to the popliteal crease. Additionally, 13 to 15 cm of sural nerve can be harvested from each leg of a 10 kg infant. Typically, the distance between the distal and proximal stumps is 2.5 to 4.5 cm in length, and segments of the grafts are placed as cables in a tension-free manner. Several nerve graft segments are utilized to bridge the gap between the stumps. The fibrin sealant is used to coapt the grafts to the nerves (see Schematic of a brachial plexus repair).

Nerve transfers
Nerve transfers are becoming more common in the treatment of brachial plexus injuries. Transfers are either used in conjunction with nerve grafting where there are nerve root avulsions, neurotmetic nerves in certain portions of the plexus, or in lieu of the reconstruction. Nerve transfers are a direct motor-to-motor neural connection and are utilized to target particular muscle groups to restore a function. For instance, one common nerve transfer that is performed to restore function of the infraspinatus muscle transferring the terminal motor branch of the spinal accessory nerve to the suprascapular nerve (see Nerve transfer: Spinal accessory to suprascapular nerve transfer). This transfer

Nerve transfer: Spinal accessory to suprascapular nerve transfer

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Key: SSN = suprascapular nerve, UT = upper trunk, LT = lower trunk, C5 = cervical level 5 nerve root, C6 = cervical level 6 nerve root, C7 = cervical level 7 nerve root.

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targets the child’s ability to externally rotate the shoulder. In the case where four to five nerve roots of the plexus are avulsed, a contralateral C7 transfer may be performed to restore hand function. This transfer involves “borrowing” C7 from the nonaffected side to tunnel it through the retropharyngeal space, and connect it with sural nerve grafts to the distal stump of the lower trunk. Other transfers may include the utilization of intercostal nerves or fascicles of the ulnar nerve to motor branches of the biceps. This restores elbow flexion and/or the long head of the triceps branch of the radial nerve to the axillary nerve to improve shoulder abduction.8

**Postoperative care and concerns**

At the conclusion of the case, all incisions are irrigated with 0.9% sodium chloride and closed with absorbable sutures in the deep dermis and the subcuticular. A topical skin adhesive is also applied to all of the incisions, and neck incisions are covered with gauze and transparent film dressing. The legs are often placed in soft casts to protect the integrity of the incisions. The upper extremity is placed in a stockinette sling and elastic wrap with an abdominal pad placed over the shoulder and between the arm and torso for padding. The arm is adducted and flexed against the anterior chest (see **Infant after surgery**). The arm is maintained in this position for 2 to 3 weeks. Typically, the infant spends 1 to 2 days in the hospital after surgery. The infant is transported home in a car bed to prevent restraining straps from disrupting the neck incision and repair of the plexus.

Concerns to consider following a brachial plexus repair are diaphragm function, signs of infection, and pain. A repeat chest ultrasound is performed during the first postoperative day and compared with the preoperative evaluation to determine if there are any differences. If the phrenic nerve was stunned during the neurolysis, the diaphragm on the affected side will show a weakening or paralysis on ultrasound. The infant’s respiratory state should be monitored in addition to the ability to feed appropriately. Infants who have a phrenic nerve injury sometimes have difficulty coordinating the suck, breathe, and swallow pattern.

Infection and pain are common considerations following any surgical intervention. Parents should be educated regarding how to identify signs and symptoms of infection, determining and treating pain, and caring for the incisions. Treating the child with acetaminophen may be sufficient in treating the pain.

The return of function in the affected extremity is variable. The rate of recovery is determined by the distance from the proximal stump to the neuromuscular junction.12 The first evidence of return consists of improvements in shoulder movement and is seen within 6 months (postoperatively) followed by a flicker of biceps.16 The degree of return is monitored by clinical exam at 3- to 6-month intervals. Further recovery may be seen up until 3 to 4 years postoperatively when improvements in function plateau.12 During the recovery period, therapy and home exercise programs are an important part of care so that all joints remain supple and loose until the child is able to move the joint independently.

**Outcomes**

The surgical outcomes for patients undergoing primary nerve repair by 6 months of age at the authors’ center have indicated that 54% don’t require additional surgical intervention, and 64% don’t require treatment with onabotulinumtoxinA to correct muscle imbalances. Significantly, fewer Narakas I patients require additional intervention as opposed to Narakas IV patients, as expected, based on the severity of initial injury. Nerve transfers showed a higher increase in function pertaining to the Toronto Score during 1-year follow-up as opposed to nerve grafting alone in all Narakas levels.

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**Infant after surgery**

Soft casts are applied to lower extremities to protect leg incisions. Elastic wrap and stockinette dressing are applied to upper extremity postoperatively.

*Photo provided as a courtesy of the authors. Permission to use was obtained at the time the photo was taken.*
While there isn’t one appropriate treatment plan for all patients with brachial plexus injuries, there are many options available to treat each individual child. The controversy regarding timing and appropriate treatment continues, as physicians performing nerve repair surgeries continue to study and share outcomes across the globe.

REFERENCES

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