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Review

Brachial Plexus Birth Injury: Current Concepts in Its Assessment and Management

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Abstract

Brachial plexus birth injury is an uncommon but serious obstetric complication. It follows a highly variable course, with outcomes ranging from mild transient impairment to significant lifelong disability. Infants with brachial plexus birth injuries require careful, regular monitoring to guide decision-making about the treatment and management of the condition. A variety of techniques may be implemented in the conservative management of brachial plexus birth injury. These aim to ensure a full range of motion and to prevent muscle imbalances. Surgical management varies but predominantly involves microsurgical nerve grafting and nerve transfers. This may be followed later by further orthopedic procedures depending on the needs of the patient. Despite the long history of this condition in the medical literature, there continues to be broad variations between the management pathways favored by different treatment centers. International research groups are now working to establish a minimum standard of patient outcome data to facilitate more effective future research on this topic. This article summarizes the current strategies used in the assessment and management of patients with brachial plexus birth injury.

Keywords: birth injury; brachial plexus; obstetrical paralysis

1. Introduction

Brachial plexus birth injury (BPBI), also known as obstetric brachial plexus paralysis, is a neurological injury of varying severity caused by forceful traction on the brachial plexus during childbirth. This most commonly occurs due to movement of the head away from the shoulder during shoulder dystocia, stretching the brachial plexus on the ipsilateral side [1]. Infants with BPBI present with immobility in the affected upper limb. In severe cases, this can persist for the rest of their life, even with optimal care [2]. While many infants recover spontaneously, a substantial proportion requires multidisciplinary care. This requires complex decisions about interventions and surgical timing, and the optimal approach can be a contentious issue. All patients with BPBI require therapeutic management to mitigate the risks of glenohumeral dysplasia, muscle imbalance and contracture. This should be accompanied by close monitoring of the infant's progress [3]. Those who do not demonstrate sufficient spontaneous improvement or show early signs of severe injury may require surgical intervention. Yet, there is considerable variation between regions in the criteria for surgical referral [4]. This may change in the near future with improvements in the consistency of outcome data reporting, which will improve the quality of the available evidence.

Surgical nerve reconstruction utilizes nerve grafts and nerve transfers to reinnervate the muscles of the upper limb and improve function. Historically, nerve grafts have been favored, but recent advances in nerve transfer techniques have increased the popularity of this option [5]. Further research is required to better understand the long-term costs and benefits of each procedure. Surgical intervention may also include orthopedic procedures, such as contracture release and tendon transfer. These interventions can significantly improve shoulder function, and, with further research, it is possible that targeted surgeries could reduce the need for nerve reconstruction [6,7].

This focused review provides an overview of the available literature on BPBI, highlighting the epidemiological data, prognostic indicators and evolving treatment options. BPBI education for clinicians working with this patient population in hospital settings is essential to ensure the early diagnosis and referral of children with BPBI, optimizing care and outcomes.

2. Pathophysiology

The brachial plexus is comprised of the five nerve roots that emerge from the spinal cord at the C5, C6, C7, C8 and T1 levels. These roots combine into three trunks, with C5 and C6 forming the upper trunk, C7 forming the middle trunk, and C8 and T1 forming the lower trunk. The brachial plexus then redivides further along its path into divisions and cords. Ultimately, it forms into five terminal branches, with contributions from the five nerve roots (C5 to T1) [8] (Fig. 1). The nerves of the brachial plexus provide motor and sensory innervation to the upper limb, includ-

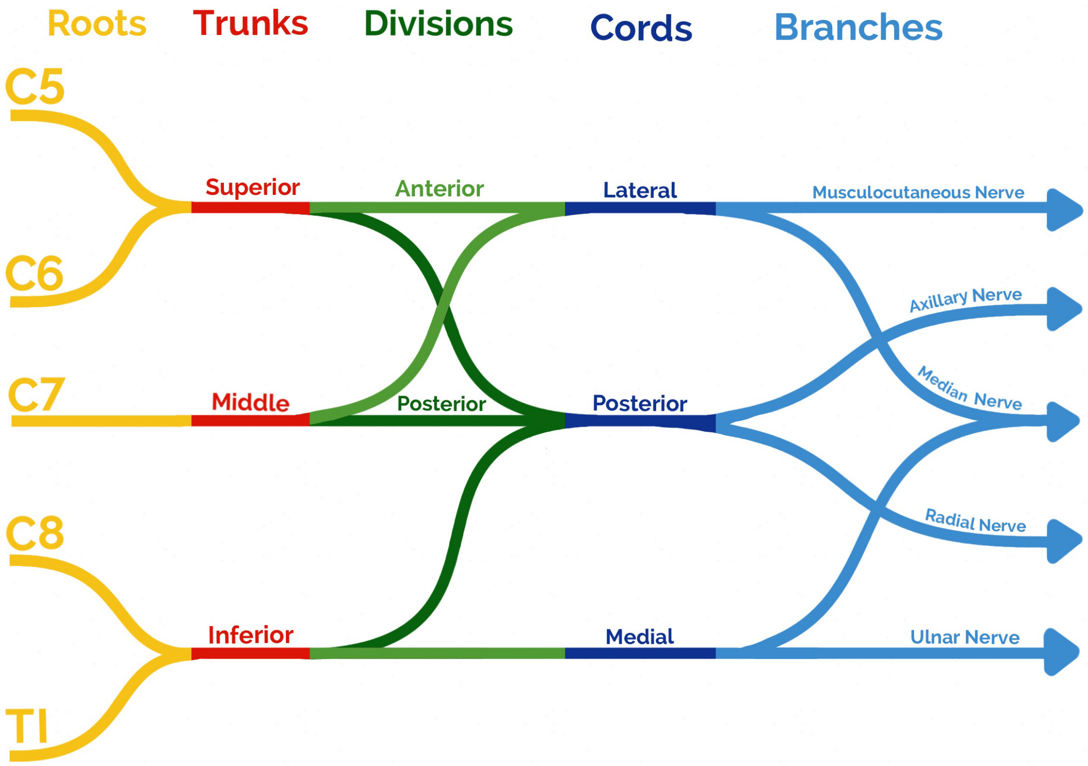

Fig. 1. Diagrammatic representation of the brachial plexus, excluding preterminal branches. Illustration created by the author using the Tayasui Sketches app for iPad v36.2 (SKETCHES SRL, Piacenza, Italy).

ing the scapula region [9]. In addition to the five terminal branches, there are numerous preterminal branches, otherwise known as collateral branches. The complex divisions and connections along the course of the brachial plexus contribute to the complexity and variability of BPBI presentation in infants [10].

Although there is some overlap, each trunk of the brachial plexus is broadly responsible for a particular area of function. The upper trunk is primarily responsible for shoulder and elbow movement. The middle trunk innervates the muscles involved in the straightening of the arm (elbow, wrist and finger extension). The lower trunk contributes to wrist movement and innervates the muscles of the fingers, enabling fine motor control [11].

BPBI can be classified according to the level of the brachial plexus injury and the clinical outcome, although these classifications have evolved over the years. The most common type of BPBI is upper brachial plexus palsy (Erb's palsy). This involves the upper trunk (C5, C6) [12]. Extended Erb's palsy is classical Erb's palsy with the additional involvement of C7. Lower brachial plexus palsy (Klumpke's palsy) involves the lower trunk (C8, T1) [13]. Total brachial plexus palsy, which can co-occur with Horner's syndrome, is the most severe form of BPBI, with damage to the upper, middle and lower trunks (C5–T1). In 1987, Narakas devised a similar classification system that stratifies BPBI into four groups by level and severity [14]. Group 1 is upper brachial plexus palsy involving C5 and C6. Group 2 is the same as group 1, but with the additional involvement of C7. Groups 3 and 4 are both total brachial plexus palsy, with group 4 having comorbid Horner's syndrome. Since then, an additional, intermediate palsy group has been described, in which there is partial palsy of the plexus involving C7, with varying degrees of involvement of the upper and lower trunks [15]. Al-Qattan *et al.* [16] proposed a further division of Narakas group 2 into two subgroups according to whether the infant had the capacity for active wrist extension against gravity by 2 months of age. Infants who demonstrated this early recovery of wrist extension movement have been found to have a significantly higher chance of spontaneous recovery than those who do not. Finally, damage to the four nerve roots C5–C8, named "T1-hand", has been described by Bertelli and Ghizoni [17].

Further classification of nerve injuries to the brachial plexus divides the injury types into preganglionic and postganglionic lesions, depending on whether the lesion is proximal (preganglionic) or distal (postganglionic) to the dorsal nerve root ganglion. This distinction is important for surgical planning as preganglionic lesions involve avulsion of the nerve root, and the patient is much less likely to show spontaneous recovery of function. Seddon classified postganglionic nerve injuries by severity [18]. The first and most severe type is neurotmesis, in which there is a complete physiological interruption of the communication pathway along the nerve. This degree of damage precludes spontaneous recovery. Axonotmesis is damage to the nerve fibers that, untreated, would lead to peripheral degeneration and loss of function. Patients with this postganglionic severity classification retain the capacity for spontaneous recovery, with varying degrees of functional improvement, provided the nerve's supporting structures are preserved. The third type of postganglionic brachial plexus nerve injury is neuropraxia, in which there is loss of nerve function but no peripheral degeneration. In these cases, there is invariably full recovery.

3. Causes

BPBI is one of the most common forms of birth trauma with an incidence of around 0.8–1.5 cases per 1000 live births [19–22]. Shoulder dystocia is the most significant risk factor for BPBI, with an odds ratio of 116, indicating an approximate 10% risk of BPBI in infants who suffer shoulder dystocia [19,23]. This is concordant with the mechanism by which BPBI is thought to occur, as shoulder dystocia would cause lateral traction to pull the delivered head away from the obstructed shoulder. Other risk factors for BPBI include forceps or vacuum-assisted delivery and macrosomia. However, they carry a much smaller degree of risk than shoulder dystocia [19,23]. Conversely, delivery by cesarean section and multiple pregnancies are protective factors that reduce the risk of BPBI [22]. When the mother has previously given birth to infants with shoulder dystocia or BPBI, the odds ratios for BPBI are 5 and 17, respectively. With such women, the physician should discuss delivery plans for future pregnancies, with these risk factors in mind [24].

Over the past decade, several studies have identified a decrease in the incidence of BPBI. This is thought to be associated with corresponding increases in cesarean delivery rates and multiple pregnancies, along with decreasing rates of exceptionally large babies (>4500 g) and forceps deliveries [19,21–24]. Yet, paradoxically, the reported rates of shoulder dystocia are increasing, even among populations with stable or decreasing rates of BPBI [25,26]. This change is likely driven by improved awareness and training in the management of shoulder dystocia among medical professionals. Increased recognition of shoulder dystocia when it occurs increases reported occurrences, while also reducing the chance of BPBI [27]. Previous underreporting of shoulder dystocia could also explain the prevalence of cases of BPBI in which there were no apparent risk factors [28].

4. Assessment

Brachial plexus injury is often apparent very shortly after birth due to significantly reduced movement in the affected upper limb. Clinical examination and a detailed history from the mother should then be performed to identify any risk factors for BPBI and better characterize the symptoms.

Observation alone can sometimes be sufficient for BPBI classification, as particular lesions are associated with particular presentations. For example, the "waiter's tip position" indicates upper brachial plexus palsy. This involves internal rotation and adduction of the shoulder, and extension and pronation of the radioulnar joint due to insult at the C5 and C6 levels. If there is concurrent wrist flexion, then the injury is more severe, involving C7 and sometimes C8 [29]. Lower brachial plexus palsy (Klumpke's palsy) can be inferred from a clawed hand deformity, which involves wrist extension, metacarpophalangeal hyperextension and interphalangeal flexion. If the child has total brachial plexus palsy, they will typically present with a flaccid, paralyzed arm [30].

Fig. 2 illustrates clawed-hand deformity and waiter's tip deformity of the hand with wrist flexion. T1-hand is associated with palsies affecting shoulder abduction and external rotation (ER); elbow flexion and extension; and wrist, finger and thumb extension [17]. The affected arm is largely paralyzed, but wrist and finger flexion are preserved.

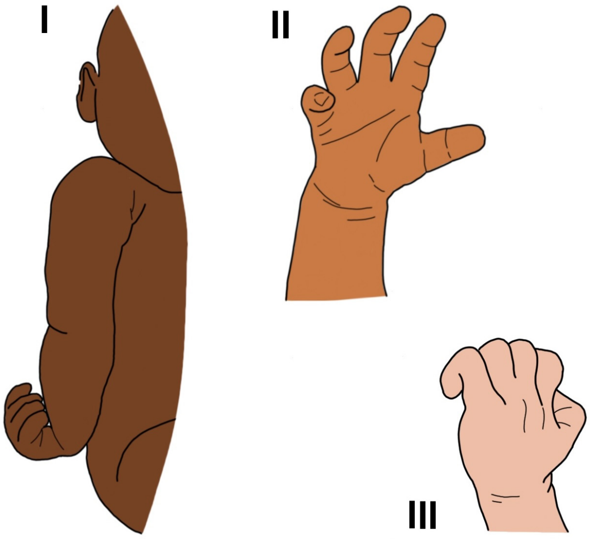

Fig. 2. Presentation of brachial plexus birth palsy. (I) The "waiter's tip" position is characteristic of upper brachial plexus palsy. (II,III) Clawed hand deformity is characteristic of lower brachial plexus palsy. Illustration created by the author using the Tayasui Sketches app for iPad v36.2 (SKETCHES SRL, Piacenza, Italy).

Passive range of motion (ROM) should be assessed at all consultations with a BPBI infant. This should be normal [11]. If passive ROM is restricted in a BPBI infant, then differential diagnoses should be considered. Namely, arthrogryposis is likely if bilateral restriction is present; and tumor, infection or trauma if there is unilateral restriction [29,31].

Table 1. Primitive reflexes and their use in the assessment of brachial plexus birth injury [32].

Reflex name	Stimulus	Description	Relevance to brachial plexus palsy
Grasp	Stimulation of the palm	Finger flexion and a clenched fist	Lower trunk pathology can be identified by claw hand deformity with an inability to flex the fingers
Moro	Allowing the head to suddenly drop back a short distance, mimicking the sensation of falling	Sudden abduction and extension of arms and fingers, followed by flexion and adduction	Upper trunk pathology leads to asymmetrical upper limb movements, while lower trunk pathology leads to asymmetrical finger movements
Asymmetric tonic neck reflex	Turning the infant's head to the side	Extension of the upper limb on the side the infant is facing, flexion of the upper limb on the contralateral side	Upper trunk pathology can be identified by weak shoulder abduction on the chin side or weak elbow flexion on the contralateral side

Active movement of the limb can be assessed in infants through observation and play, and by testing the primitive reflexes. These reflexes provide a consistent assessment of motor response in the affected limb. For example, an abnormal Moro reflex may reveal a deficit in shoulder abduction in the affected limb. When this is present alongside a normal grasp reflex, it can indicate an upper brachial plexus injury [30]. Table 1 (Ref. [32]) describes the primitive reflexes and their relevance to BPBI.

The Active Movement Scale (AMS) and the Toronto Test Score (TTS) are common tools used by clinicians to assess patients with BPBI through the quantification of upper extremity function. Both scales have good intra-operator reliability and effectively predict the need for referral for surgical management [33–35]. The AMS assesses 15 different active movements of the upper limb and grades the range of motion on a scale of 0 to 7. Scores of 0 to 4 represent movement without gravitational resistance, and 5 to 7, movement against gravity. The TTS assesses five movements on a seven-point scale. The combined scores for each item are converted to an overall score between 0 and 2.

In the initial assessment of an infant with BPBI, it is important to look for signs of Horner's syndrome (unilateral ptosis, miosis and anhidrosis) as its presence is likely to reflect more severe neuronal injury. It has been suggested that the presence of Horner's syndrome combined with disruption of the cephalic sympathetic chain at T1 indicates that an avulsion-type injury is responsible for the brachial plexus palsy. Classically, the co-occurrence of BPBI and Horner's syndrome has been associated with a lower chance of spontaneous recovery than that in BPBI without Horner's syndrome. However, this has been disputed [14,36–38]. Murine studies have demonstrated potential communication between the C7 nerve root and the superior cervical ganglion during infancy. If correct, this would indicate an additional mechanism through which Horner's syndrome could co-occur with BPBI that differs from that responsible for adult brachial plexopathy [39]. Further work on the association between Horner's syndrome and avulsion-type injuries is required. A similar mechanism, leading to an association between BPBI and phrenic nerve palsy, has also been proposed. In infants with total brachial plexus palsy, it is important to screen for phrenic nerve palsy as it can lead to diaphragmatic paralysis or dysfunction. If the child presents with respiratory distress and asymmetrical thorax elevation, a high index of suspicion is required. With abnormal hemidiaphragm elevation suggestive of phrenic nerve palsy, chest X-ray should be the first line of investigation. Bedside ultrasound is also a useful means of visualizing diaphragmatic movements [40]. As with Horner's syndrome, there is conflicting evidence relating to the effect concurrent phrenic nerve palsy has on the likelihood of spontaneous recovery in infants with BPBI [41,42].

Clavicle and humeral shaft fractures can occur in BPBI, so all affected infants should be examined for signs of concurrent fracture during their initial assessment [20,43,44]. If a fracture is suspected, then X-ray imaging is indicated to confirm the diagnosis. Neonatal clavicular and humeral fractures can be conservatively managed with excellent long-term outcomes. Parents should be advised to avoid infant movement and minimize the time they spend lying on the affected side. However, there is no expectation of cosmetic or functional deficits associated with these fractures [45].

When assessing a newborn with suspected BPBI, it is crucial to assess for differential diagnoses. Ipsilateral lower limb weakness with hyperreflexia can be more suggestive of hemiplegia secondary to a central nervous system pathology such as cerebral palsy, stroke or brain tumor. Widespread generalized weakness can indicate a neuromuscular pathology such as spinal muscular atrophy or muscular dystrophy. If both upper limbs are affected, then imaging may be necessary to rule out a spinal cord lesion, especially if there is also respiratory distress [46].

Radiological assessment can be used for earlier identification of the need for surgery than can be achieved by clinical examination alone. While surgical exploration is the standard for identifying nerve root avulsions, it is the most invasive option. Computed tomography (CT) myelography is considered the gold standard for radiological

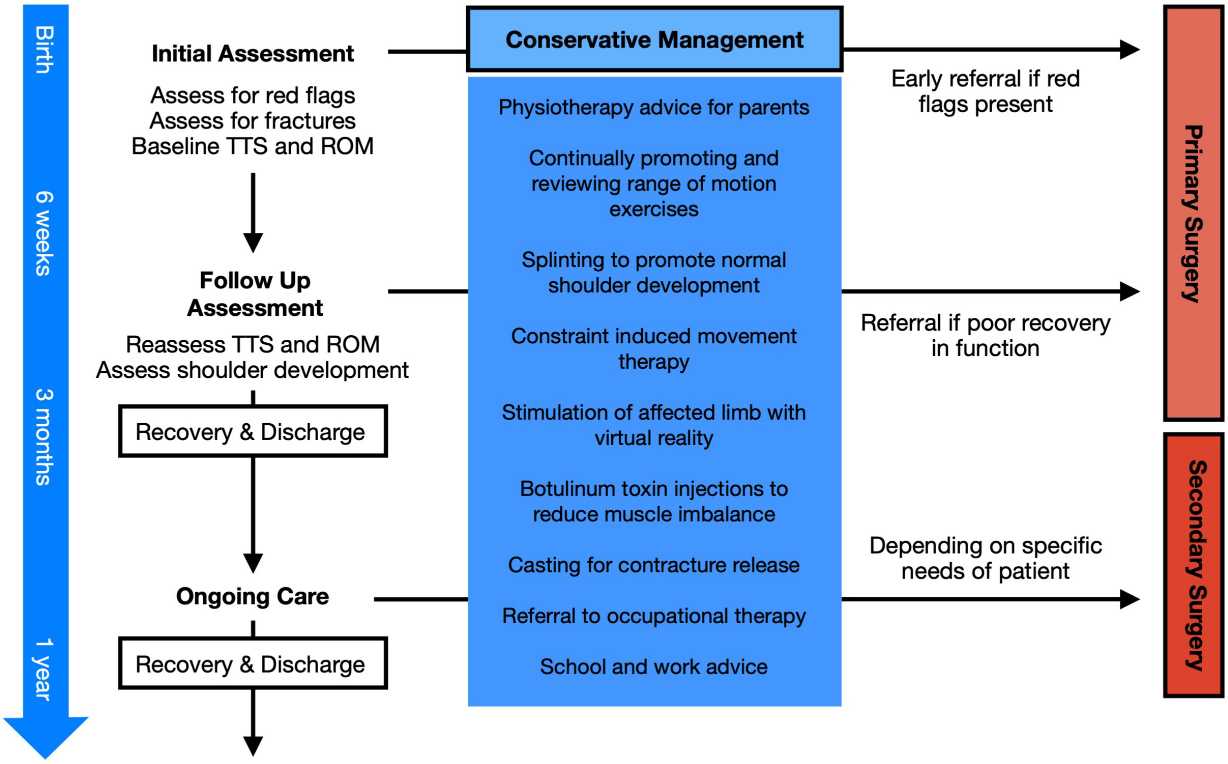

Fig. 3. Flowchart illustrating a proposed assessment and management strategy for use with patients with brachial plexus birth injury [53,57]. Illustration created by the author using the Tayasui Sketches app for iPad v36.2 (SKETCHES SRL, Piacenza, Italy). TTS, Toronto Test Score; ROM, range of motion.

assessment of nerve root integrity. It has demonstrated a sensitivity of 72.2% for preganglionic nerve root avulsions [47]. Magnetic resonance imaging is a promising alternative. It has a similar sensitivity for the detection of nerve root avulsions to CT but does not require sedation, lumbar puncture or radiation exposure [48–50]. Electromyography (EMG) and nerve conduction studies can be used to identify severe forms of BPBI. This facilitates earlier surgical management in cases that require it [51]. Nonetheless, the utility of electrodiagnostic studies in this patient population is controversial due to concerns that studies of EMG use have been overly optimistic in their interpretations of the value of this approach [52]. As a result, some centers do not use the technique during pre-operative assessments [53]. When EMG is used, the evidence suggests that the infant's age at the time of testing is crucial to the accuracy of the results, with 1 month being the optimum age. It has also been shown to most usefully guide surgical planning when used in conjunction with clinical assessments and imaging [54,55].

In the UK, there is no centralized National Health Service (NHS) guidance on the timelines for brachial plexus injury assessment and management. Therefore, this is determined by individual centers based on the resources available. However, organizations such as Plexus Nexus have been working to establish international consensus on best practices with BPBI. An example of the kind of timeline-related regulations needed is the importance of patient referral to specialist brachial plexus services in the first 2 months of life if there are persistent deficits in upper limb function [56]. Fig. 3 (Ref. [53,57]) presents a flowchart illustrating a potential assessment and management strategy for BPBI. It is based on information from the Hospital for Sick Children in Toronto and published guidance from the Association of Chartered Physiotherapists. The figure highlights the flexibility required among healthcare professionals, based on the progression of the patient and the importance of continual therapeutic input.

The current lack of standardization of outcome measures between centers is an obstacle to the production of high-level evidence for or against specific practices in BPBI management. iPluto (the International Plexus Outcome Study Group) have connected BPBI centers across the world to establish a minimum standard for outcome measures. The ultimate goal of this is to ensure the quality of future research. Thus far, consensus has been reached between the centers on four key assessment points during patient follow-up [58].

(1) Evaluations should take place when the child is aged 1, 3, 5, and 7 years;

(2) The patient's passive range of motion should be measured in degrees;

(3) The patient's active range of motion should be measured in degrees;

(4) The Mallet score of every patient should be calculated at each assessment.

More recently, consensus has also been reached on the value of patient-reported outcome measures, but there is no consensus as yet on the specific measures that should be used [59].

5. Management

5.1 Conservative Management

There is no consensus on the optimal management of BPBI as centers around the world follow different treatment pathways, adopt different management techniques and use different outcome measures [58]. However, there are common practices that can be discussed, and evidence for individual interventions in the management of BPBI is available. During the patient's journey to recovery, they may receive care from hand surgeons, orthopedic surgeons, physiotherapists, occupational therapists, nurses, psychologists and social workers. Therefore, it is important for each center to have an established pathway from assessment to treatment and follow-up. There must also be good interdisciplinary communication and effective service evaluations [53].

To accurately predict prognosis and guide surgical planning, it is essential to perform serial assessments alongside therapeutic interventions. However, the point at which surgical intervention is indicated is determined differently between centers [4]. In patients with upper brachial plexus palsy, spontaneous recovery is likely, so these patients may be managed conservatively. The need for surgery depends on whether or not the infant is showing signs of upper limb function recovery. A typical treatment course includes regular assessment of the presence and degree of ongoing impairment of the upper limb over the first 6 months. This is a good indicator of the likelihood of spontaneous recovery. Findings suggestive of severe injury, such as total brachial plexus palsy or Horner's syndrome, will usually prompt consideration of earlier surgical treatment (before 3 months) [53]. Due to the rarity of BPBI and the heterogeneity of outcome measures, the quality of current evidence for best practices is low, and differences persist between regions in the age at which surgery is performed in these patients [4].

During the initial rehabilitation of the affected limb in infants with BPBI, the primary goals are the prevention of muscle contracture and deformity, and maximization of strength and development. In the first 2 weeks of life, therapy is limited to allow tenderness from the injury to subside. Instead, caregivers are encouraged to focus on promoting sensory awareness in the affected arm by playing with the child's hand and placing it in their line of sight. In the next therapeutic stage, the focus is on passive range of motion exercises. These are to be completed frequently at home, with the support and supervision of a hospital therapy team.

Given the risk of glenohumeral dysplasia, particular care needs to be taken to promote normal growth of the shoulder. Abnormalities in glenohumeral development have been noted in infants as young as 3 months old and have been associated with greater degrees of muscle imbalance [60]. Splinting can be used to mitigate the risk of glenohumeral dysplasia. The supination-external rotation (Sup-ER) splint is a novel orthotic device designed to comfortably hold the affected upper limb in a position that maintains glenohumeral congruity, while lengthening the muscles most susceptible to contracture [61]. The name is derived from the supination (Sup) of the radioulnar joint and the external rotation (ER) of the shoulder when the orthosis is applied (Sup-ER). This splint holds the limb in the normal anatomical position of the shoulder during growth, reducing the risk of complications developing during the natural recovery of neurological function. The Sup-ER splint has been shown to improve shoulder rotation functional outcomes in patients with severe BPBI [62]. Alternatively, some centers utilize a 'teapot' brace [63,64]. It has been argued that the teapot results in better control of external rotation as the elbow is not extended. However, further research comparing the two techniques is required. The Sup-ER splint is illustrated in Fig. 4 and the teapot splint in Fig. 5.

Posterior shoulder subluxation is more common in all patients with BPBI [65]. An important aspect of the ongoing monitoring of patients with BPBI is regular assessment of the glenohumeral joint. Ultrasound screening can be used to effectively screen for patients with early shoulder complications. Examination findings, such as reduced passive external rotation, can be used adjunctively to determine which infants are most at risk of shoulder complications. Bauer *et al.* [65] have proposed a cut-off of $\leq 60°$ of external rotation. They found this to yield a sensitivity of 94% and specificity of 69% for posterior dislocation detection.

Botulinum neurotoxin type A (BoNT-A) injections can be used as an adjunct to therapy and may delay or avoid the need for secondary musculoskeletal surgery entirely. BoNT-A appears to facilitate more effective rehabilitation through the correction of muscle imbalances. This is achieved through the inhibition of neuromuscular transmission in the stronger, unaffected, antagonist muscles of the upper limb, which leads to strengthening of the weaker, agonist muscles [66]. Additionally, BoNT-A injections have been found to facilitate motor learning in infants and to increase plasticity in sensorimotor circuits [67]. There is ongoing research into the long-term efficacy of BoNT-A injections; however, several studies have found that their beneficial effects are not sustained over time [68,69]. Long-term positive outcomes are more likely in younger patients, who have a greater degree of neuroplasticity [70].

Serial casting and splinting as components of constraint-induced movement therapy are effective treat-

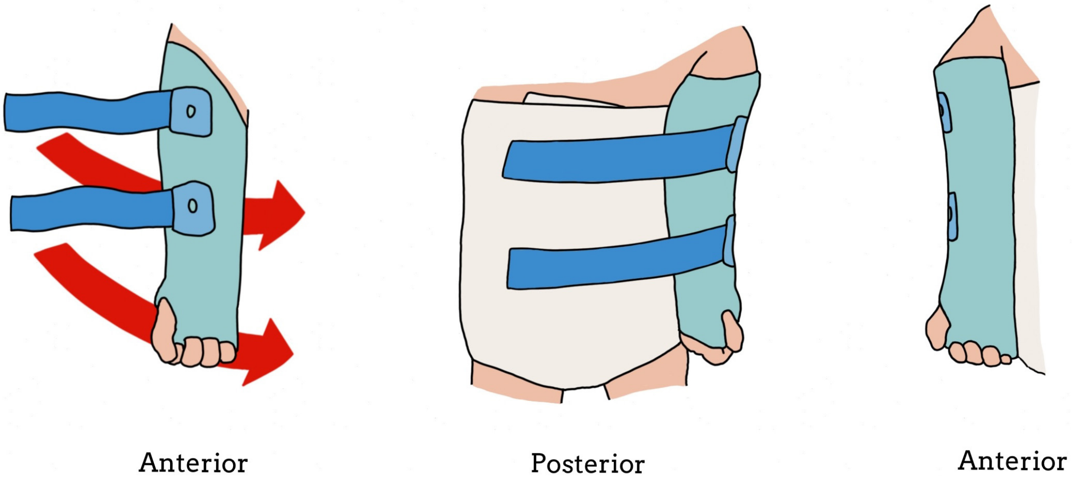

Fig. 4. Diagram of the application of a Sup-ER splint. The splint is applied to the forearm and extends to the axilla. A harness is applied to hold it to the trunk. Straps on the splint are attached to the posterior trunk, holding the affected upper limb in external rotation and pronation. Illustration created by the author using the Tayasui Sketches app for iPad v36.2 (SKETCHES SRL, Piacenza, Italy). Sup-ER, supination-external rotation.

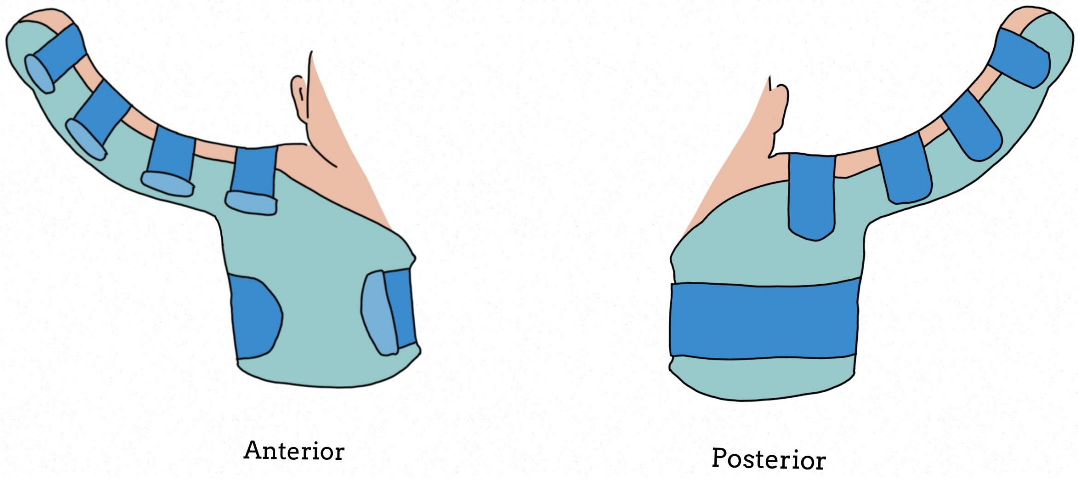

Fig. 5. Diagram of a "teapot" splint in situ. As with the Sup-ER splint, the affected limb is in external rotation, but with abduction of the shoulder and no elbow extension. Illustration created by the author using the Tayasui Sketches app for iPad v36.2 (SKETCHES SRL, Piacenza, Italy).

ments for BPBI [71]. Muscle weakness in the affected arm can cause the child to preferentially use the unaffected limb in their daily activities. This can limit neurodevelopment in the affected limb, even after recovery from the brachial plexus palsy. The constraint of movement in the unaffected limb with a dynamic splint or cast is a technique originally developed to treat hemiparesis secondary to stroke. However, it has been shown to increase use of the affected limb and improve BPBI outcomes [72–74].

The use of virtual reality technology with robotic assistance devices can assist in stimulating an affected limb. This has been shown to improve infant engagement with rehabilitation tasks, ultimately leading to an improved range of movement in the upper limb [75]. A combination of early range of motion exercises, screening for glenohumeral dysplasia, BoNT-A injections and splinting have been shown to have a significant impact on the eventual shoulder function of infants with BPBI [76].

5.2 Surgical Management

As with therapeutic management, there is no strict consensus on which patients should undergo surgery and which procedures are most appropriate. This is an exciting area of research, and studies comparing treatment strategies are regularly published. This is aided by projects such as iPluto, which aim to establish a minimum standard for follow-up assessments [58,77,78].

The key principle in effective surgical decision-making is to identify those patients with better chances of postoperative recovery than recovery following a conserva-

Table 2. Advantages and disadvantages of nerve grafts and nerve transfers [5,84,86,89].

Nerve graft	Nerve transfer
Advantages	
• Preserves original nerve root to motor endplate connection; • Multiple distal branches can be reinnervated from one proximal source.	• More appropriate in late presentations due to quicker reinnervation of the motor endplate; • Able to target isolated deficits; • Does not require a proximal root and can be performed following root avulsion; • Preserves functional nerve fibers within the neuroma.
Disadvantages	
• Requires viable proximal roots and is not possible with root avulsion; • Recovery time is prolonged as axonal regrowth must span the length of the graft; • There is a greater risk of misdirected axonal regrowth, leading to poorer functional outcomes than in nerve transfer.	• Risk of morbidity at the donor site; • Cannot repair as many functions simultaneously as nerve grafts; • May limit the motors available for future secondary musculoskeletal reconstruction.

tive approach. For this reason, early surgical referral is indicated in patients with total brachial plexus palsy, as meaningful spontaneous recovery is highly unlikely [79]. Unfortunately, difficulties can arise when assessing the need for surgical intervention in patients with upper brachial plexus palsy, as the clinical signs are less distinctive. It is well established that a lack of recovery of biceps function (i.e., active movement against gravity) by 3 months predicts poor spontaneous recovery and indicates the need for surgical referral [80–82]. More recently, researchers at a surgical center developed an algorithm that uses maternal and neonatal factors (such as birth weight and delivery method) to predict the risk of persistent BPBI before surgical intervention [83]. The exact criteria for surgical referral vary between sites. However, they often involve the use of assessment tools such as the AMS or TTS as well as serial examination of upper limb function. With improved communication between sites and the standardization of outcome measures, high-quality evidence of best practices may emerge.

Once the decision to perform surgery has been made, it is then necessary to determine the most appropriate procedure. As with many aspects of BPBI, this is a dynamic area of discussion, but the two main modalities of treatment are nerve grafts and nerve transfers. Historically, nerve grafts have been the gold standard and the primary surgical treatment for BPBI. However, recent advances in nerve transfer techniques have led more centers to adopt this treatment modality. Evidence for its efficacy continues to accumulate [5,84]. It is worth noting that previous research has found no useful role for neurolysis alone in the treatment of BPBI [85].

Nerve grafts require excision of the neuroma until viable fascicles become accessible. Then, a donor nerve, usually the sural nerve, is used to provide a scaffold upon which to reinnervation between the proximal and distal nerve stumps [86,87]. During nerve transfer, a donor nerve is divided distally, keeping the nerve root intact. The donor nerve is then coapted to the denervated brachial plexus nerve and, where possible, primary repair is performed [88]. The pros and cons of nerve grafts and transfers are summarized in Table 2 (Ref. [5,84,86,89]).

Early studies suggest that nerve transfer results in a greater degree of external rotation in the shoulder. However, direct comparisons between surgical techniques have been hindered by differing outcome measures and low-quality evidence [89]. Some authors have expressed concern that donor site morbidity in the growing patient, specifically in nerve transfers, may currently be underreported [90]. Therefore, definitive conclusions about the superiority of either technique are not yet possible. It may be that maximal innervation is best achieved using both nerve grafts and nerve transfers [5].

In addition to primary microsurgery, secondary surgery can be used to treat specific sequelae of BPBI. The requirements for these procedures are tailored to the needs of the patient, and take account of their hobbies, school or work requirements and personal care needs. Tendon transfer is one such surgical method, whereby a functional muscle is transferred to the site of a paralyzed muscle to improve the joint functionality. This procedure can be performed independently or with the concomitant release of an impaired muscle. For example, if there is an internal rotation contracture, release of the subscapularis could be performed concurrently with the transfer of the latissimus dorsi and teres major. The procedure performed will depend on the extent of the neurological injury and the potential for bone remodeling [91]. Functional improvement in the shoulder is largely due to reorientation of the arc of rotation, with diminished internal rotation in exchange for greatly improved external rotation [92]. Despite this, contracture release and muscle tendon transfer have the potential to significantly improve global shoulder function and quality of life [7]. Although traditionally, secondary orthopedic procedures take place after primary nerve reconstruction, a recent study explored the possibility that targeted surgical treatment of the shoulder could remove the need for nerve surgery. While this idea was just presented in a proof-of-concept study of a highly selected group of infants, it suggests a possible direction in the future evolution of shoulder surgery for BPBI [6].

6. Conclusion

BPBI is a significant burden on healthcare systems, the affected patients and their parents. It requires close monitoring and thorough assessment to ensure optimal treatment and management decisions. Numerous innovative treatments and strategies have been developed for the therapeutic and surgical management of this condition. Therefore, it is incumbent upon healthcare services involved with this patient population to stay abreast of new approaches to ensure their patients have the best chance of recovery. There remains a great deal of variability in management pathways between centers, and studies comparing the efficacy of treatment strategies have been hindered by their adoption of inconsistent assessment parameters. However, resolution of this issue is expected in the near future due to current efforts to introduce minimum standardized outcome assessment methods for widespread application. Also, despite the lack of standardized guidelines, individual centers have contributed some promising treatment innovations, and the evidence for their efficacy is accumulating.

Key Points

- The significant variability in prognosis and difficulty predicting the course of brachial plexus birth injury necessitates close monitoring of affected infants and personalized treatment plans.
- Therapeutic interventions are necessary for optimal care of infants with brachial plexus birth injury to reduce the risk of muscle imbalances and improve long-term functioning.
- In severe cases of brachial plexus birth injury, surgical intervention can significantly improve functional outcomes, but there is no consensus on which surgical interventions are most efficacious.
- High-quality research comparing treatment strategies for brachial plexus birth injury has been hindered by the heterogeneity of assessment tools and timelines between studies.
- Efforts are currently being made to establish minimum standards for outcome reporting in studies of brachial plexus birth injury, to improve the quality of future research.

Availability of Data and Materials

Not applicable.

Author Contributions

WRA and EKM both made significant contributions to the acquisition and interpretation of information for the article. WRA wrote the manuscript. WRA produced the images for the article. Both authors contributed to the important editorial changes in the manuscript. Both authors read and approved the final manuscript. Both authors have participated sufficiently in the work and agreed to be accountable for all aspects of the work.

Ethics Approval and Consent to Participate

Not applicable

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Conflict of Interest

The authors declare no conflict of interest.

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