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REVIEW

Timing of nerve surgery in brachial plexus injuries, how much early and how much late is acceptable for nerve surgery: a scoping review

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Brachial plexus injuries are complex and debilitating conditions that can significantly impair upper limb function in both pediatric and adult patients. Timely surgical intervention plays a crucial role in optimizing functional outcomes and promoting nerve regeneration. This review provides a comprehensive analysis of relevant literature, encompassing clinical studies, retrospective analyses, and meta-analyses, to assess the impact of early versus delayed surgical intervention on functional recovery, nerve regeneration, and long-term outcomes. In pediatric patients, early surgical intervention within the optimal window of opportunity is crucial for harnessing the remarkable regenerative potential of nascent nerve fibers and preventing the development of secondary complications. The review discusses the current evidence supporting early nerve exploration and reconstruction techniques in pediatric cases while highlighting the challenges associated with accurate diagnosis and the need for close multidisciplinary collaboration. At the same time, we have analyzed the relevant literature for guidelines in late-presenting cases. Conversely, in adult patients, the timing of brachial plexus surgery is often influenced by a myriad of factors, including the potential for spontaneous recovery, the presence of associated injuries, and the need for preoperative optimization. The review assesses the available evidence on the timing of surgery in adult cases, focusing on the delicate balance between early intervention to maximize nerve regeneration and functional recovery and the potential benefits of delayed surgical strategies. In conclusion, this comprehensive review consolidates the existing knowledge on the timing of brachial plexus surgery in pediatric and adult patients. It emphasizes the importance of a tailored, patient-centerd approach that considers various clinical factors to optimize surgical outcomes and improve functional recovery. The findings presented in this review provide valuable insights for clinicians and researchers, serving as a foundation for further studies aimed at refining surgical strategies for managing brachial plexus injuries.

Keywords: brachial plexus surgery, adult brachial plexus injury, birth brachial plexus injury, brachial plexus surgery timing, delayed presentation of brachial plexus injury, late surgical intervention in brachial plexus injury

Introduction

Brachial plexus injuries are devastating in adults and in children and adults alike. They result in significant physical, psychological and financial burden on the affected individual and their family. However, brachial plexus surgery, if performed on time, can give reasonably acceptable results. But many times, due to mixed patterns of injury, unpredictable recovery or delayed presentation, it becomes difficult to choose between nerve surgery or muscle transfer in the form of a secondary procedure.

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This article aims to provide readers with an insight into the current guidelines regarding the timing of surgical intervention (nerve reconstruction or neurotization) for brachial plexus injuries.

A relevant literature review on the topic of timing of surgical intervention in brachial plexus injuries, including early versus late neurotization and delayed repair of brachial plexus injury, was conducted as a scoping review. The corresponding author also presents their own perspective and experience on this topic.

Timing of surgery

The timing of nerve surgery for brachial plexus injury depends on several factors, including the type and severity of the injury, the patient's age, and the presence of any associated injuries. It has been a controversial issue with a consensus in favor of early intervention (1). In general, brachial plexus injuries are classified into different types based on the extent of nerve damage.

However, patients may present at different times, and intervention is decided based on clinical examination, supported by radiological and electrophysiological assessment.

- **Early repair within 6 months**
  - Less than 3 months
  - 3–6 months
- **Late repair at more than 6 months**
  - 6 months–1 year
  - More than 1 year

How much early in adult

Early reconstruction focuses on the repair or reconstruction of the nerves of the brachial plexus. These procedures include direct repair, neurolysis for scar compression, nerve grafting, and nerve transfers.

Acute injury (open injury) (in the emergency department)

Although the incidence is lower, it is not uncommon to encounter an open wound over the supraclavicular area with an underlying injury to the brachial plexus when working in the trauma and emergency department (2). These injuries are usually seen when there is a penetrating injury or gunshot in the supraclavicular or axillary area.

An immediate brachial plexus exploration and possible repair should be attempted. If the two cut nerve ends are identified, the nerves are repaired primarily. However, if the ends are lacerated and crushed and the wound is contaminated, then they are tagged with polypropylene 3–0 sutures and fixed within tissue planes for easy identification during re-exploration 2–3 weeks later. At this stage, always document the position of cut nerve ends at an exact distance from a bony landmark so that if it needs to be re-explored by another surgeon, the location can be easily and accurately identified.

Many authors advocate for repair 2–3 weeks later, due to the peak metabolic response of cells that enhances regeneration and results in better recovery (intentionally early delayed repair) (3, 4). It is always a window of opportunity since the wound is open and the injured plexus can be repaired primarily.

High-velocity gunshot wounds with associated vascular injuries may warrant an emergency repair. In contrast, low-velocity gunshot wounds are usually treated 3–4 months after injury, as most of these lesions have a neurapraxic component (grades 1–3 degree of nerve injury), and they tend to recover over a period of a few months (5).

Closed injury (within 24 hours)

The most common clinical scenario involves patients with closed traction or rupture injuries. These patients are assessed clinically initially and then electrophysiologically using electromyography (EMG) and nerve conduction velocity (NCV) testing and radiologically after 3–4 weeks to correlate clinical findings. During this period, oedema settles, and patients understand the role of surgery, the postoperative outcome, and the course of physiotherapy and rehabilitation.

Closed injury (within 1–3 months of injury)

If there is unequivocal evidence of spinal nerve root avulsions (preganglionic injury), then there is no rationale for waiting, but surgery to perform in the form of exploration and nerve reconstruction/transfer should be undertaken as soon as possible. However, if there is a postganglionic injury, it is prudent to examine the patients at periodic serial intervals and proceed accordingly. The patient is followed up clinically and electrophysiologically every 3–4 weeks, and if the patient shows continued improvement, conservative physiotherapy is advocated. The patients carry the best chances of improvement in the first 3 months after injury, and the next best time window lies within the next 3 months.

Timing is the most important factor to determine the results after surgery, as muscle end plates tend to degenerate and may not accept reinnervation after 20–24 months.

The current indications for immediate/early repair (within 3–4 weeks post-injury) are

- Clinically or radiologically established diagnosis of root avulsion injury (pre-ganglionic injury).
- Established diagnosis of postganglionic injury (if the neck was explored for vascular repair and a diagnosis of brachial plexus injury was made, or intentionally delayed repair was advised due to unfavorable condition of the patient or the nerve ends).

Pondaag W et al. assessed the outcome of early nerve surgery (<2 weeks) and found M4 power in the biceps in all clinically and radiologically confirmed root avulsion cases (6). They also reported cerebrospinal fluid (CSF) leakage during surgery through the spinal foramen due to a fresh dural tear related to avulsion. However, intraoperatively, appraisal of the proximal stump (if any) becomes easier. As the number of patients undergoing ultra-early interventions was small and follow-up duration was short, the conclusions were convincing but not definitive regarding neurological recovery. The results related to shoulder or hand functions were also not reported. Additionally, Groen JL et al. also adopted the same protocol of operating within 2 weeks after trauma and reported a good outcome with patients achieving medical research council (MRC) grade 4 muscle strength following early surgical intervention (7). However, when analysing the fair outcome (MRC grade 3), there was less difference between the ultra-early group and those undergoing later surgery. These are small case reports that are encouraging, but they do not conclusively redefine the advantages over conventional timing, especially when dealing with patients with post-traumatic oedema, CSF leakage, and associated chest, abdomen, brain, and bony injury, which might be challenging. A few authors also argued that reimplantation of avulsed roots is possible in early surgery (8).

Within 3–6 months

Most of the surgeons agree to operate on the patients at this phase, as they are confident of the diagnosis within this time frame, and patients also understand that the recovery has not occurred as expected. Also, by this time, other associated injuries such as bony fractures and head injuries would have been stabilized and managed by the concerned department.

How much late in adults (between 6 months and 1 year or beyond 1 year of injury)

Late or secondary reconstruction is considered in two scenarios:

1. When patients present outside the optimal time window for nerve reconstruction or nerve transfer.
2. When patients have incomplete recovery after primary surgery.

The various causes of late presentations are

1. The patient is unwilling or not convinced to undergo surgery, resulting in delayed surgical intervention due to various reasons.
2. Inadequate repair or reconstruction by another surgeon
3. Surgical dilemma by the surgeon when the patient presents outside the window period of nerve surgery due to anticipated limited or no recovery
4. Patients consult various specialists or therapists and are misguided about the role of early surgery.

It is generally presumed that the outcomes of nerve surgery after 6 months decline, resulting in less or no recovery if it is performed after 1 year, due to degeneration of muscle end plates. However, nerve transfer, which utilizes healthy, normal fascicles taken adjacent to the nerve supplying the muscle end plate, can achieve reasonably good results, especially in upper brachial or extended upper brachial plexus injuries. The results of nerve transfer after 1 year in pan-brachial plexus injury are unpredictable and can be done in selective cases only.

Cho ÁB et al. reported the usefulness of the Oberlin procedure after 12 months of injuries and found that 9 patients out of 10 attained M3 or M4 recovery (9). Gopal Sedain et al. found that seven patients (77.8%) out of 9 achieved useful biceps function ≥3/5 MRC score by Oberlin transfer after an average of 12.2 months (range, 7–24 months) following injury (10).

H. Khalifa et al. found 67% good results in their series of 18 months who were operated on at more than 12 months (average delay of 18 months between injury and surgery, 12–36 months) post-injury; they had 10 patients with M4 power, and two had M3, whereas 6 patients had M2. However, most of their patients included C5, C6, and C7 injuries, and only 3 belonged to pan brachial plexus injury (BPI). They also observed that the results of nerve grafts were less constant in their series. Most of the literature concludes that nerve transfers remain feasible in delayed cases, although the number of reported cases in pan BPI remains limited (11).

Bhatia A also found that in his series, the failure rate of intercostal to musculocutaneous and spinal accessory to suprascapular nerve transfer is very high. However, the failure rate for Oberlin transfers did not change significantly, even up to 19.5 months from injury. Thus, he recommended anticipating a recovery in C5 and C6 injuries with a delay of 18–19 months (12). In another retrospective evaluation of 232 cases of post-traumatic total and near-total brachial plexus injury patients that were treated with nerve transfers, he found the difference in outcomes of patients operated on beyond 6 months was statistically significant after intercostal

nerve (ICN) to musculo cutenous nerve (MCN) transfers in total and near-total brachial plexus injuries (13). He achieved MRC grades 3 and 4 in 20 (46.5%) out of 43 of his patients who underwent nerve surgery beyond 6 months of injury. Alvin Wong et al. also noted similar findings where they analyzed data retrospectively, where nerve surgery was done after an average delay of 236 days. In their non-pan brachial plexus groups, they found 71.4% of patients demonstrated M3 elbow function and 48.8% M4 elbow flexion. In their Pan brachial plexus groups, only 38.1% could achieve M3 elbow flexion, and 28.3% attained M4 elbow flexion. A similar trend was demonstrated for shoulder abduction, where 53.5% achieved acceptable shoulder abduction in non-pan brachial plexus groups and only 23.5% achieved acceptable abduction of the shoulder in pan brachial plexus injury groups (14). The comparison of various studies of adult brachial plexus injuries and their outcome of various authors has been depicted in **Table 1** (15–18).

The author's practice of delayed nerve repair: We also have observed similar outcomes with delayed nerve repair in late-presenting cases. However, we recommend that in all partial or extended upper brachial plexus injury cases, one can go ahead with nerve surgery up to 12–15 months with acceptable shoulder abduction and elbow flexion, depending on the patient's compliance with physiotherapy. In total palsy, it's better to counsel the patients regarding the lesser chances of recovery and to consider the secondary procedures like muscle transfers.

Timing of surgical intervention in birth BPI (BBPI)

The timing of surgical intervention for BBPI remains a critical and debated topic, with recommendations ranging from early surgery within 3 months for severe cases, such as total palsy with Horner's syndrome, to extended observation periods up to 9 months for partial recoveries. Indicators like biceps recovery, Active Movement Scale (AMS) scores, and Horner's syndrome are frequently used as predictors for surgical need. However, the literature lacks a comprehensive mapping of the evidence regarding surgical timing, prognostic tools, and factors influencing decision-making, including parental and clinical considerations.

After an initial observation period, children with suspected brachial plexus palsy can be categorized as having either partial or total paralysis. Patients with total paralysis have a very low likelihood of spontaneous recovery. In contrast, those with partial paralysis have a higher chance of recovery, with complete recovery reported in as many as 92% of patients by the age of 3 months (19–21). However, complete recovery rates may not be as high as initially thought, with approximately 20%–30% of patients experiencing long-term deficits.

If the biceps do not recover by 3–6 months by antigravity M3 power, surgical intervention is warranted. However, it is always ideal to evaluate the motor functions at serial intervals to assess recovery. Motor examination in a child is difficult and requires multiple examinations before considering surgical intervention. Also, it is important to mentally prepare the parents for the possibility of surgery in case recovery does not occur.

Alternative assessment tools aim to reduce the margin of error associated with relying solely on biceps function.

Regarding surgical timing, it is typically performed between 3 and 8 months of age, with earlier surgery (at 3 months) indicated for children with pan-plexus palsies and Horner's syndrome. Also, Narakass grades 3 and 4 are less likely to achieve full functions without surgical intervention. Chuang DC et al. also reported the benefits of early surgery and concluded that early surgery within 3 months is highly indicated in total palsy (22). Hentz VR recommends sharing the Stanford experience that nerve surgery can be performed when the child attains 10 weeks of age, 10 pounds of weight, and 10 grams of hemoglobin, similar to Millard's rule of 10 for cleft lip repair (23). However, for the upper plexus with Erb's palsy, their current approach is to observe the biceps and deltoid reinnervation up to 6 months. They found that less than 20% of the babies in this category require surgery.

Gilbert A and Tassin JL also proposed an early indication of surgery by 3 months if the biceps do not recover. In case of a complete flail limb with Horner syndrome, there is less chance of recovery, and such children should be operated on by 12 weeks of age. He also proposed that in breach delivery with complete palsy of C5 and C6, there is a high chance that the above roots are avulsed. If the child does not show any recovery of the biceps, they should be explored early by the third month (24). Thatte and Mehta support the Gilbert principle. However, they further advised that if there is co-contraction of the triceps that is preventing biceps flexion, such children can be observed and managed further with or without a Botox injection. Studies have explored extending this observation period (25). Waters found that infants who failed to recover antigravity biceps strength by 5–6 months of life should undergo microsurgical reconstruction, arguing that successful surgery yields better outcomes than natural history alone (26). Furthermore, prospective studies suggest that infants who achieve antigravity biceps function by 4 or 5 months of age may have natural history outcomes comparable to those treated with microsurgery, especially when combined with secondary tendon transfers (26, 27).

How much late in birth BPI?

Because of the spontaneous recovery in birth brachial plexus palsy cases, many times surgeons and parents wait and often

TABLE 1 | Comprehensive summary of surgical timing, indications, results and recommendations of prominent research articles on traumatic brachial plexus injuries.

Sl. No.	Study/author group	Study methodology	Timing of surgery	Outcomes/reported results with respect to the timing of surgery	Conclusion
1.	Bhandari et al. (3)	Commentary No patients enrolled		In clean transections, if attempted, immediate direct repair is advised. In traction injuries, observation up to 3–5 months is advised to look for signs of recovery. Missile injuries are worked up and evaluated after 4 weeks of injury and investigations repeated every 2–3 weeks for signs of recovery. Early repair advised at 8–12 weeks.	Nerve repairs are generally not successful 1 year after injury and pedicled or free functional muscle transfer should be chosen for them.
2.	Birch (15)	Review article	The author has categorized early repair within 1 month, delayed within 1–3 months, up to 6 months and neglected for more than 6 months	The author advises early exploration and highlights 3 reasons for early exploration within a few days: better outcome if operated within 7 days, technical ease in repair if operated in the first 48 hours and improved pain scores if operated earlier.	The author proposes short delays in surgery since the injury, recommending that patients should undergo surgery within 2 weeks if they are fit.
3	Enrico Martin et al. (16)	Review article 43 studies were included, and data sets of 2,204 patients were analyzed.	Median surgical delay was 06 months (range 0–240 months). Patients were categorized into 5 delay groups: 0–3, 3–6, 6–9, 9–12, and >12 months.	Results indicate that best surgical outcomes for tractional injuries are achieved when operative delays are less than 6 months from injury. Although 7 studies showed earlier surgeries had better outcomes, only 3 studies showed statistically significant findings.	In stretch and blunt injury of the brachial plexus, the ideal operative time frame appears to be less than 6 months after the injury. Recovery is improved in those operated earlier, but while deciding the timing of surgery, the potential for spontaneous recovery should be borne in mind.
4.	Kline (17)	Author's personal experience, no statistical data in the study	Recommendation on the timing of surgery is given, as per the etiology of brachial plexus injury.	Sharp transection – Acute repair Blunt transection – extent of injury is unpredictable but becomes evident 2–3 weeks after injury, hence a delay of several weeks is recommended for surgery. Gunshot wounds – Baseline clinical and electrical examinations at 2–3 weeks, repeat monthly and look for signs of spontaneous recovery till 2–4 months. If recovery does not begin by then, exploration should be planned. Stretch/contusive injuries – Delay by 3–4 months once chances of spontaneous recovery have been ruled out.	In stretch/contusive injuries, delay by 3–4 months is advised, to ensure that chances of spontaneous recovery have been ruled out.
5.	Terzis et al. (18)	Retrospective observational analysis of 162 cases with BPI who underwent triceps nerve reconstruction. 139 patients who satisfied the inclusion criteria of a minimum 18 months follow-up were analyzed.	The denervation time (elapsed time since injury) was 16.90 ± 26.95 months. The patients were categorized into 2 categories: ≥8 months and <8 months	Slightly improved results noted in <8 months denervation time category. There was no statistically significant difference in recovery between the two-time categories ($p < 0.07$).	Early reconstruction of the injured nerve is recommended for a better outcome.

defer the surgery. Sometimes, it is a more difficult decision for parents to decide on surgical intervention, and such a dilemma delays the decision of surgery. Clark and Curtis recommend the indication of surgery for a child unable to perform the cookie test by 9 months of age (28). But the question is how much delay is not too late for infants, and if surgeons can still take a chance to operate on the child, expecting recovery?

Chuang et al. reported improved shoulder and elbow function after late primary nerve surgery after 1 year of age (29). Michal C. Daly enrolled 750 patients in a multicentric trial and included all patients after 9 months of age and a minimum follow-up of 12 months and found total AMS score improved significantly (30). However, they did not find any difference in outcome between nerve graft and nerve transfer (24). In another multicentric trial by Bauer et al., they found that surgery before 6 months of age (mean age of 4.2 months) in birth brachial plexus palsy does not have any definite advantages over surgeries performed later (mean age of 10.7 months) (31). The comparison of various studies of birth brachial plexus injuries and their outcome of various authors has been depicted in **Table 2** (32–37).

Corresponding author's approach: We strongly recommend early surgical intervention in all pan-brachial plexus palsy cases (Narakass grades 3 and 4), mostly around 3 months. 3 months is the time when parents also notice

TABLE 2 | Comprehensive summary of surgical timing, indications, results and recommendations for primary intervention in patients with BBPI in various studies.

Author(s)/study type	Indication(s) for surgery and methodology	Timing of surgery	Outcome/results reported	Conclusions
Nivetha Srinivasan et al. (32) Systematic review	Review article	Mean age of all patients was 11.4 + 10.7 months (range 2.5–65 months)	• Negative monotonic correlation ($p = 0.30$, $n = 89$, $p < 0.01$) between increasing age and mallet sub score for hand to mouth. • No significant correlation between age (6.31 ± 3.33 months) and mallet score for shoulder abduction (3.41 ± 0.82, $p = 0.09$, $n = 91$, $p = 41$). • And between age (7.92 ± 5.62 months) and MRC sub score for elbow flexion (3.65 ± 0.79, $p = 0.10$, $n = 119$, $p = 0.29$)	In upper trunk NBPP, microsurgeries performed before 6 months have significantly improved outcomes of the mallet sub-score for hand-to-mouth
Boome and Kaye (33)	If recovery in the upper roots had not started by 3 months of age. Delay beyond 3 months suggests root disruption is likely.	Operation should be considered from 3 months of age. The average age at exploration in their operated group was 5.3 months.	For operated cases (at 1-year follow-up): 80% achieved good recovery in the deltoid and 55% in the biceps. Infants who started recovery before 3 months gained full recovery (except external rotators).	If recovery of upper roots is delayed beyond 3 months, exploration and nerve grafting offer the best prospect of a useful arm.
Gilbert (34)/Maillet (35)	Complete palsy with a flail arm after 1 month, particularly with Horner's syndrome (indicating T1 avulsion/severe lesion). Hand palsy (C8–T1 affected) is an urgent condition.	Early operation at 12 weeks (3 months). 2–3 months of age for total palsy/Horner's syndrome.	Early surgical exploration demonstrates its value in complete palsies. Modified strategy focusing on distal roots (post-1995–1996) led to improved hand function results compared to proximal root focus.	Prioritize hand function (finger flexion and thumb movements) in severe lesions requiring early exploration.
Shah et al. (36)	Four factors present before 3 months independently predict need for microsurgery: Horner's syndrome, mean AMS score for finger/thumb/wrist flexion <4.5, AMS score for wrist extension <4.5, and AMS score for elbow flexion <4.5 (motion against gravity).	Median age at microsurgery was 5.4 months.	Microsurgery rates correlated stepwise with the number of predictors present (e.g., 0 factors = 0% surgery, 4 factors = 93% surgery). Antigravity elbow flexion before 3 months was the most predictive single factor.	Use early physical examination findings (AMS scores, Horner's syndrome) to counsel families regarding injury severity and plan for potential microsurgical intervention.
Ali et al. (37)	Critical review of a published article	The four groups were divided of no repair to repair at 3, 6, or 12 months of life	With respect to quality of life, improved outcomes were seen with delayed surgical repair at 12 months compared with no repair or early repair at 3 months or intermediate repair at 6 months	• Delayed approach of primary surgical reconstruction to optimize quality of life. • RCT (randomized controlled trial) would be required to optimize the point of surgical intervention

less recovery of motor and sensory functions of the affected limb, and at this time, the child is usually fit for surgery and anesthesia. However, in the Narkass grades 1 and 2, we wait for 5–6 months for the biceps to recover. If the biceps do not recover with antigravity power by this time, early surgical intervention is warranted. However, in severe late cases, over 1 year but less than 18 months, we still explore the plexus, and possible nerve surgery (mainly nerve transfer) is performed. We recommend evaluation and assessment of recovery at an interval of 2–3 months, and a minimum of 2 examinations and counseling should be done with patients and relatives to explain the course, stages of treatment, and expected outcome.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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