Journal of Hand Surgery Global Online 6 (2024) 801–807

Contents lists available at ScienceDirect

Journal of Hand Surgery Global Online

journal homepage: www.JHSGO.org

Original Research

Case Series of Traumatic Peripheral Nerve Injuries in Pediatric Patients Treated with Allograft Repair

Jacqueline Van Gheem, MD, * Alexis Rounds, MD, * Taylor Blackwood, DO, * Cameron Cox, BA, * Evan J. Hernandez, MBA, * Desirae McKee, MD, * Brendan MacKay, MD *

* Department of Orthopedic Surgery, Texas Tech University of Health Sciences Center, Lubbock, TX

ARTICLE INFO

Article history:
Received for publication October 31, 2023
Accepted in revised form May 14, 2024
Available online September 21, 2024

Key words:
Allograft
Nerve injury
Nerve trauma pediatric
Peripheral nerve

Purpose: In the adult literature, allograft reconstruction of gapped peripheral nerve injuries has gained popularity over autologous nerve grafting. Allografts have demonstrated similar recovery while eliminating donor site morbidity. There is no well-defined incidence or treatment of such injuries in children. Our study explores the epidemiology and outcomes of traumatic pediatric peripheral nerve injuries treated with allograft.

Methods: This is a retrospective case series of a prospectively maintained database of all pediatric patients who underwent nerve allograft reconstruction at a Level I trauma center between September 2011 and July 2021.

Results: We identified 24 allograft nerve reconstructions in 18 patients, average age 12.9 years (range 1.5–17.0) and 78% male. Five patients (28%) were injured in a motor vehicle accident, and four were injured by sharp laceration, machinery, and blast injury (22%). The most injured nerve was digital (n = 10, 42%) followed by 8 (33%) ulnar, and 4 (17%) median. The average gap length was 30.3 ± 23.8 mm (range 4–87 mm). Fifteen nerves were repaired within 24 hours (63%). Average follow-up was 13.7 ± 14.5 months (range 1.6–46.8 months). At final follow-up, 9 (38%) had full sensory recovery, 6 (25%) protective sensation, 2 (8%) deep pressure, and 1 (4%) no sensation but a positive Tinel's sign.

Conclusions: Allograft reconstruction is a viable option for the treatment of traumatic pediatric peripheral nerve injuries with gaps not amenable to direct repair.

Type of study/level of evidence: Therapeutic IV.

Traumatic peripheral nerve injuries can result in sensory and motor deficits that cause lifelong functional impairment. These permanent disabilities can affect meaningful participation in important life activities.[1] The literature addressing traumatic peripheral nerve injuries in adults has rapidly evolved with regard to optimal treatment algorithms. When direct repair of a nerve injury is not feasible because of tension or gapping, options for treatment and reconstruction include nerve conduits, autologous nerve grafting, and processed or acellular human nerve allograft reconstruction.[2–4]

Although nerve conduits have been used for gaps up to 15 mm, they are generally used alone to repair gaps less than 10 mm in length; autografts have historically been used to address larger defects.[3,5,6] Given the inherent risk of donor site morbidity and increased operative time required for autograft harvest, novel alternatives have been developed to address shortcoming of autograft repair.[7,8] Several studies have shown allograft reconstruction can result in good recovery with outcomes comparable to that of autografts in adults.[2,7,9] Standards of nerve repair in pediatric populations have been extrapolated from the adult literature secondary to the lack of pediatric-specific research.[10–12]

The current body of evidence on allograft nerve reconstruction in pediatric patients focuses on brachial plexus injuries and repair of sensory nerves after maxillofacial intervention with promising results.[7,9,13–15] Other peripheral pediatric allograft literature is limited to case reports.[16] There is currently no well-defined incidence of traumatic peripheral nerve injuries or treatment in the

Corresponding author: Jacqueline Van-Gheem, MD, Department of Orthopedic Surgery, Texas Tech University of Health Sciences Center, 3601 4th Street, Lubbock, TX 79430.

E-mail address: Jacqueline.Van-Gheem@ttuhsc.edu (J. Van Gheem).

https://doi.org/10.1016/j.jhsg.2024.05.008

pediatric population despite its importance. The purpose of this study is to investigate the epidemiology, treatment, and outcomes of traumatic peripheral nerve injury treated with processed nerve allograft transplant.

Materials and Methods

This is a retrospective review of a prospectively maintained database that was approved by our center's Institutional Review Board and follows Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) guidelines. Consent for treatment, participation in the study, Health Insurance Portability and Accountability Act, and media was obtained from each patient's respective guardian(s) as all patients were less than 18 years old at the time of the index procedure. All patients 17 years of age and younger who underwent nerve allograft reconstruction at a single, Level I trauma center between September 2011 and July 2021 were identified as candidates for allograft during their index procedure and then enrolled after surgery. Given the uniqueness and capture of our center, gaps in clinical data are prevalent. We excluded two patients who sustained nerve injuries then later developed chronic, painful neuromas at 1 year and 5 years. These two patients underwent excision and allograft reconstruction. These presentations have considerably different clinical implications; therefore, it was decided to remove these patients from the study.

Patient demographics include age and male or female. We collected injury characteristics, including mechanism, time of injury to repair, and concomitant injuries.

All patients were taken to the operating room for either irrigation and debridement with exploration and repair of structures as indicated. In patients with a stable wound bed and defined zone of injury, acute reconstruction was performed. Those with highly contaminated wound beds were temporized with a plan to return to the operating room for repeat debridement until a clean wound bed was achieved and reconstruction could be performed. Nerves were sharply debrided at the surgeon's discretion. Repairs were performed by two fellowship-trained hand surgeons. The final resting gap length was recorded along with the name of the nerve and whether it was sensory, motor, or mixed based on location. In the majority of cases, coaptations were wrapped with porcine intestinal submucosa except in specific cases of digital repairs with soft tissue defects or small nerves that were not amenable to coaptation. Coaptation was used where amenable to bring the nerve and allograft ends together without overlap, providing tension relief on the repair and to improve outcomes as demonstrated by Ducic et al[17] and Zhukauskas et al.[18] They were secured to the nerve and allograft epineurium with appropriate sized 7-0 to 9-0 monofilament suture. Techniques included orientation sutures to bring the nerve and allograft ends together via epineural technique, with or without detensioning sutures and fibrin glue.

Functional outcomes were recorded based on physician evaluations at follow-up appointments and guardian reports. Evaluation techniques were based on physician standards of practice and were dependent on age of the patient and ability to cooperate. Patients have also been evaluated by independent observers since their operative intervention. The pandemic led to unforeseen changes in follow-up schedules and ultimately some losses to follow-up. We chose to only report final follow-up in our study. The basis of this study was to record objective and subjective findings at the patient's final follow-up. Functional outcomes were defined as normal use of the involved extremity as seen by the physician and/or reported by guardians, limitations as seen by the physician and/or reported by guardians, atrophy or clawing determined by the physician, Semmes-Weinstein (SW) monofilament grading scale, and visual analog scale to determine pain.

Descriptive statistics are used to report our data. Continuous variables are reported as mean ± standard deviation (SD) and range where appropriate, whereas categorical data are reported as n, %. Analysis was performed on all patients as well as a subgroup analysis of patients who had at least 6 months of follow-up.

Results

We identified 18 patients with 24 allograft nerve reconstructions (Table). The average age was 12.9 ± 5.7 years old (range 1.5–17.0). In total, 14 (78%) were male, and 4 (22%) were female. The most common mechanism of injury was motor vehicle accidents or all-terrain vehicles (Fig. 1). Five patients (28%) were injured in a motor vehicle accident, 4 (22%) by sharp laceration (glass, knife), 4 (22%) machinery (table saw, crush, auger, boat motor), 4 (22%) blast injury, and 1 (6%) fence avulsion. The most injured nerve was digital (n = 10, 42%) followed by 8 (33%) ulnar, 4 (17%) median, 1 (4%) radial, and 1 (4%) musculocutaneous. Common concomitant injuries included tendinous (n = 15, 63%), fracture (n = 11, 46%), and arterial injury (n = 4, 17%). Four (17%) patients had soft tissue loss with three requiring acellular dermal matrices and one requiring a rotational flap for coverage. The distribution of injured nerves can be seen in Figure 2. Twelve (50%) nerves were isolated sensory nerves, and 12 (50%) were mixed sensory and motor. No identified injuries were isolated.

Time to surgery was less than 24 hours in 15 nerves (63%). An additional six nerves (25%) were treated within 8 days (median = 5 days), 2 (8%) within 1 month, and 1 (4%) within 6 months with delay because of needing soft tissue coverage over the median nerve graft. The average gap length was 30.3 ± 23.8 mm (range 4–87 mm). Coaptation was achieved with isolated epineural repair for three nerves (12%) and connector assisted in 21 nerve reconstructions (88%).

Average follow-up was 13.7 ± 14.5 months (range, 1.6–46.8 months). At final follow-up, all patients reported a Wong-Baker FACES Pain Rating Scale (pediatric visual analog scale) of four or less. At most recent follow-up, SW monofilament sensory testing demonstrated, nine nerve injuries (38%) had normal sensation, 6 (25%) protective sensation, 2 (8%) to deep pressure, and 1 (4%) no sensation but a positive Tinel's sign. Three patients (five nerve injuries) were using their extremity normally without issue as reported by guardian but were too young (< 4 years) to participate in monofilament testing (Fig. 3). Of the 12 patients with mixed motor and sensory nerve injury, all had some improvement in motor function (Fig. 4). Nine (38%) patients and/or guardians reported no limitations with daily activity, whereas 4 (17%) patients demonstrated atrophy or clawing. Of the two patients who continue to demonstrate clawing, one had injury to their ulnar nerve, and one had injury to the median nerve.

In our subgroup analysis, we identified eight patients with 11 allograft nerve repairs. The average age was 12.8 ± 6.6 years old (range 1.5–17.0). Seven (87.5%) were male, and one (12.5%) was female. The most common mechanism of injury was motor vehicle accidents or all-terrain. In total, 3 (37.5%) patients were injured in a motor vehicle accident, 1 (12.5%) by sharp laceration, 2 (25%) machinery (table saw, crush, auger avulsion, fence avulsion), and 2 (25%) blast injury. Common concomitant injuries included tendinous (n = 6, 54.6%), fracture (n = 7, 62.6%), and arterial injury (n = 3, 27.3%). No identified injuries were isolated.

The most injured nerve was ulnar (n = 5, 45.5%) followed by 3 (27.3%) digital, 2 (18.2%) median, and 1 (9.1%) musculocutaneous. The average gap length was 29.1 ± 24.8 mm (range 16–87 mm). Four (36.4%) nerves were isolated sensory nerves, and 7 (63.6%) were mixed sensory and motor. Time to surgery was less than 24 hours in three patients (37.5%). An additional three patients (37.5%)

Table
Patient Demographics and Final Follow-up Outcomes

Patient No.	Age	Mechanism of Injury	Level of Injury	Nerve Injured	Days to Reconstruction	Length of Gap (mm)	Coaptation	Months After Surgery	Outcome
1	17	GSW		Median	171	68	Epineurial	13.8	Full extension of all digits except for index finger and can make a composite fist of all fingers except with the index finger
2	11	ATV	RDN3	Radial digital	3	12	Conduit	2.1	Patient claims full use of thumb Lacks 90° at PIP of index and long fingers
3	1.5	GSW	Mid forearm	Ulnar	0	20	Conduit	14.9	Full ROM
4	17	Crush	UDN2	Ulnar digital	1	10	Epineurial	1.6	Unable to make composite fist because of stiffness Normal sensation
5	3	MVC, laceration	Zone 5	Ulnar	0	20	Conduit	15.3	Full ROM Using hand without limitation Sensation grossly intact Intrinsic wasting and clawing Adductor and thenar wasting
5	3	MVC, laceration	Zone 5	Median	0	19	Conduit	15.3	Full ROM Using hand without limitation Sensation grossly intact
6	17	Laceration	UDN2	Ulnar digital	0	8	Epineurial	2.2	Loose composite fist with 1" p-p index Diminished protective sensation
6	17	Laceration	RDN2	Radial digital	0	5	Epineurial	2.2	Loose composite fist with 1" p-p index, Diminished protective sensation
7	17	Table saw	RDN3	Radial digital	0	16	Epineurial	10.8	Full composite fist Full extension of all digits Full ROM Normal sensation
7	17	Table saw	RDN2	Radial digital	0	22	Epineurial	10.8	Full composite fist Full extension of all digits Full ROM Normal sensation
8	17	GSW	Zone 5	Ulnar	4	40	Conduit	3.8	Full ROM Decreased sensation of the ulnar aspect of the small finger
9	17	ATV degloving	UDN1	Ulnar digital	6	25	Conduit	18.4	Decreased ROM of wrist and all digits given stiffness Unable to make a composite fist Thumb adduction contracture Wrist ulnarly deviated, lacking 30° of flexion and 20° extension No motion at thumb IP, 30° flexion to thumb passively Good motion at PIPs and DIPs of index, long, ring, and small fingers MCPs with decreased motion, most noticeably at the second MCP joint where flexion is lacking 30° Extensor tendons firing S3+
10	17	Fence caught	Palmar cutaneous nerve	Palmar cutaneous	1	20	Conduit	3.7	Mild atrophy noted to thenar eminence Composite fist Full ROM S4
10	17	Fence caught		Median	1	25	Conduit	3.7	Mild atrophy noted to thenar eminence Composite fist Full ROM S4
11	13	Glass laceration	UDN5	Ulnar digital	0	10	Conduit	2.5	FDS, FDP intact to small finger FPL/EPL/ intrinsics intact S3
11	13	Glass laceration	UDN5	Ulnar digital	5	8	Conduit	3.4	FDP, FDS firing Full ROM S3+
12	17	Stab laceration	At brachium	Ulnar	3	40	Conduit	17.7	Mild clawing of small finger Mild edema Mild swelling Absent nail to the fifth digit Intrinsic wasting Sensation to deep pressure
13	17	GSW	At cubital tunnel	Ulnar	0	50	Conduit	1.9	Clawing of ring and small fingers (passively able to extend digits) with minimal sensation to touch of these fingers
14	10	MVC, laceration	At cubital tunnel	Ulnar	1	40	Conduit	3.3	Full extension at PIP without lag at ring and small fingers S3
15	16	MVC, laceration		Musculocutaneous	37	40	Conduit	16.3	Composite fist Full ROM S4
15	16	MVC, laceration		Ulnar	37	68	Conduit	16.3	Composite fist Full ROM S4
16	14	Auger, avulsion		Ulnar	6	87	Conduit	13.3	Clawing in all five digits Sensation normal
17	6	ATV rollover		Radial	8	70	Conduit	3.8	No wrist extension against gravity Sensation returned Has extension of fourth and fifth digits
18	3	Laceration	UDN2	Ulnar digital	1	6	Epineurial	2.9	Full ROM Motor intact Sensation grossly intact Able to make composite fist
18	3	Laceration	UDN3	Ulnar digital	1	4	Epineurial	2.9	Full ROM Motor intact Sensation grossly intact Able to make composite fist

ATV, all-terrain vehicle; DIP, distal interphalangeal; EPL, extensor pollicis longus; FDP, flexor digitorum profundus; FDS, flexor digitorum superficialis; FPL, flexor pollicis longus; GSW, gunshot wound; IP, interphalangeal; MCP, metacarpophalangeal; MVC, motor vehicle crash; PIP, proximal interphalangeal; RDN, radial digital nerve; ROM, range of motion; UDN, ulnar digital nerve.

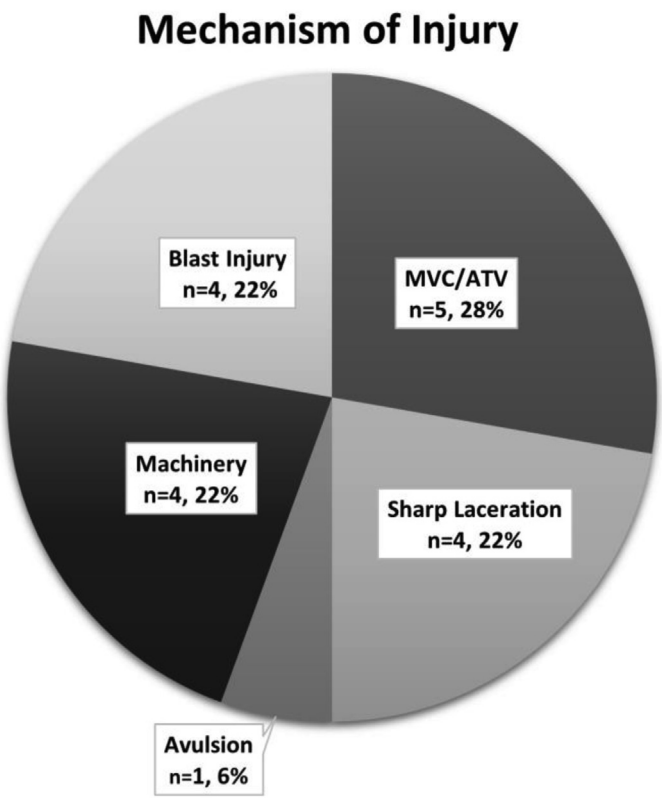

Figure 1. Distribution of the mechanisms of injuries. Sharp laceration included knife or glass injuries. Machinery included Auger or saw injuries. Blast included gunshot wounds and firework injuries. One neuroma was a result of a glass injury 1 year prior. ATV, all-terrain vehicle; MVC, motor vehicle accident.

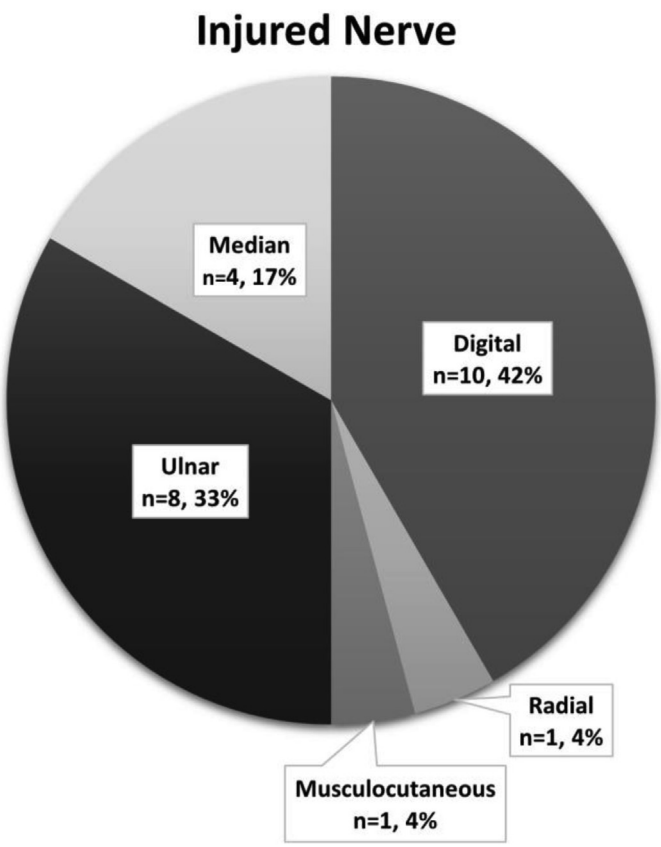

Figure 2. Distribution of nerves injured. The percentages of specific nerve injuries that were repaired are reported.

were treated within 1 week, 1 (12.5%) at 37 days, and 1 (12.5%) within 6 months. The average gap length was 32.3 ± 24.0 mm (range 4–87 mm). Coaptation was achieved with isolated epineural repair in eight patients (31%) and connector assisted repair in 18 patients (69%).

Average follow-up was 26 ± 13.1 months (range 10.7–42.8 months). At final follow-up, all patients reported a Wong-Baker FACES Pain Rating Scale of four or less (pediatric visual analog scale). We considered 82% (n = 9) of patients to have full recovery of sensation. Of the seven patients with mixed motor and sensory nerve injury, all had some improvement in motor function. At final follow-up, SW monofilament sensory testing demonstrated, six nerve injuries (54.5%) had normal sensation, one (9.1%) protective sensation, and one (9.1%) to deep touch. Semmes-Weinstein monofilament sensory testing was scored as demonstrated by Schreuders et al.[19] Two patients with three nerve injuries (27.3%) were using their extremity normally without issue as reported by their guardians but were too young to participate in monofilament testing (Fig. 5). There were eight patients (72.7%) who reported no limitations with daily activity, whereas two patients (18.2%) demonstrated atrophy or clawing. The two patients who continue to demonstrate clawing both had ulnar nerve injury. Ulnar nerve clawing was noted in all digits in one patient and the small and ring fingers in the other.

Over the time period of our study, no known complications occurred following the nerve allograft reconstruction. Further intervention was required in two patients for improvement in function. Interventions included abductor pollicis longus to first dorsal interosseous tendon transfer with ulnar shortening osteotomy and volar plate advancement in one patient. These procedures were performed to restore first finger abduction and alleviate clawing. Nerve transfer of the anterior interosseous nerve to the ulnar nerve was performed followed by cross nerve allografting between median and ulnar nerves in the wrist of one patient in attempt to improve sensory deficits. Cross nerve allografting was used as an alternative technique to that described in Felder et al.[20]

Discussion

There is no definitive treatment algorithm for traumatic pediatric peripheral nerve injuries. Our patients' successful recovery and lack of postoperative complications suggest that allograft is a safe option for treatment. We cannot directly compare our patient population with outcomes noted in the literature as those studies are based on brachial plexus, maxillofacial, or adult nerve reconstruction. Hamant et al[7] demonstrated no significant difference ($P > .05$) in outcomes between allograft and autograft treatment of brachial plexus injuries in children. There is currently no literature comparing autograft to allograft in the treatment of peripheral nerve injuries in the pediatric population. No prospective studies have been performed to compare autograft to allograft repair in peripheral nerve injuries in adults or children. These may be needed to determine whether autograft should remain the gold standard.

Historically, traumatic peripheral nerve injuries are challenging to treat in both adult and pediatric patients given the lack of standardized treatment algorithm. As our understanding of nerve injury and reconstruction options has evolved, there has been an increasing interest in improving treatment algorithms to produce more optimal outcomes.[3] Despite a rapid growth in nerve-related publications, the pediatric peripheral nerve injury population

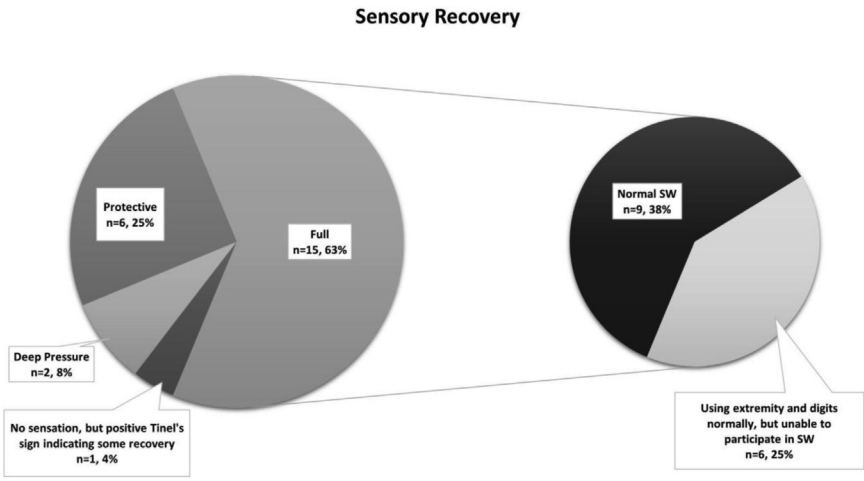

Figure 3. Sensory recovery. The amount of sensation recovered since time of repair is reported. Image to the right demonstrates patients who were too young to undergo Semmes-Weinstein testing (n = refers to number of nerves). SW, Semmes-Weinstein.

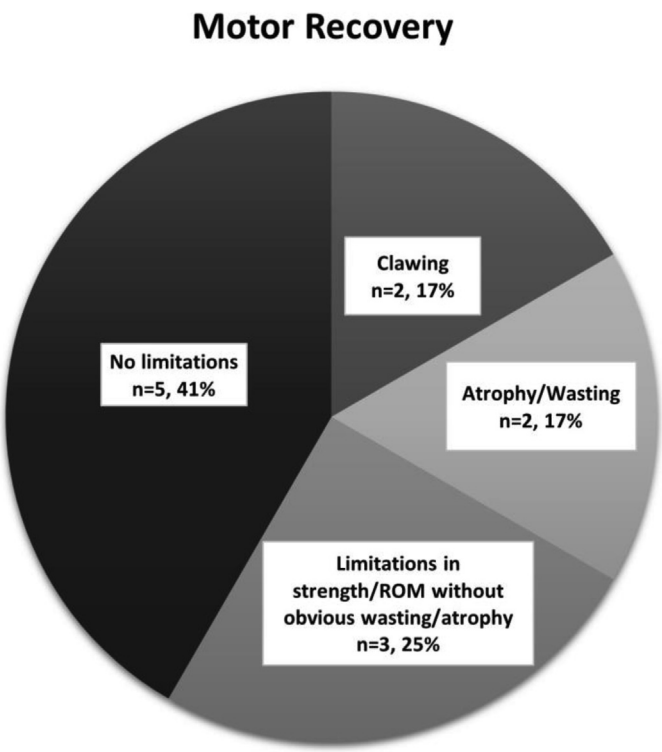

Figure 4. Motor recovery in those with mixed sensory and motor nerve injury. ROM, range of motion.

remains underrepresented in the literature. Based on our findings, the causes of pediatric peripheral nerve injuries are similar to those seen in the adult population as reported by Safa et al.[21] Our pediatric population was most commonly injured by involvement in motor vehicle accidents. Given that peripheral nerve injuries are often the result of high-energy or penetrating trauma, it may be common to see involvement of multiple organ systems. Concomitant injuries seen in our patient population included fracture, tendon, and arterial injuries. Males were more commonly affected in our study, which is expected as men are more commonly affected by trauma.

Timing is an important consideration when planning repair. It is recommended that when possible, open injuries with transected nerves be repaired immediately.[2,3,6,22,23] Over 60% of our patients were treated within this timeframe, and 74% in our subgroup analysis were treated within this timeframe. Our patients who experienced delayed repair were because of soft tissue coverage or wound contamination. Despite this, nearly 85% were treated within 1 week and 96% within 1 month, which is also true of our subgroup analysis. These patients, including our patient treated outside of 1 month, had outcomes demonstrating the viability of allografts including limited sensory or motor deficits, as seen in the Table.

Over the last decade, there have been many advances in treatments of nerve injuries as indicated in our introduction. Previous issues with allograft resulted from fresh transfer or transplant, which led to infections. Commercially available allografts are processed and considered acellular with the goal of mitigating such risks.[24] In our case series, no surgical site infections and no adverse outcomes related to the use of allograft were noted.[2,25]

Sensation recovery following nerve injury is important for response to stimuli. Our pediatric study yielded similar results with 71% sensory recovery of S3 or above, but with only 38% having full recovery of sensation by SW testing as compared to the study by Miloro and Zuniga[9] that demonstrated 100% recovery. Full sensation recovery may be lower in our study compared to Miloro and Zuniga[9] because of the variability between SW and Medical Research Council Scale measurement or the inherent differences in maxillofacial and extremity sensation. Semmes-Weinstein is more precise and clinically relevant than Medical Research Council Scale in the extremities than in the teeth; precise sensation in the fingers and toes is critical to respond appropriately to physical hazards. Like Hamant et al[7] who demonstrated motor and sensory improvement with autograft and allograft for brachial plexus injury, we also demonstrated improvement in both motor and sensation. Regardless of repair type, sensation generally demonstrates better recovery than motor.[26–28]

A multicenter registry study of acellular allograft reconstruction for peripheral nerve injuries in adults reported up to 73% of patients having motor recovery of M3 or above.[21] Our pediatric study yielded similar results with 83% (100% in subgroup analysis) demonstrating some motor recovery following allograft reconstruction. Given the descriptive nature of our motor recovery, direct comparison is difficult.

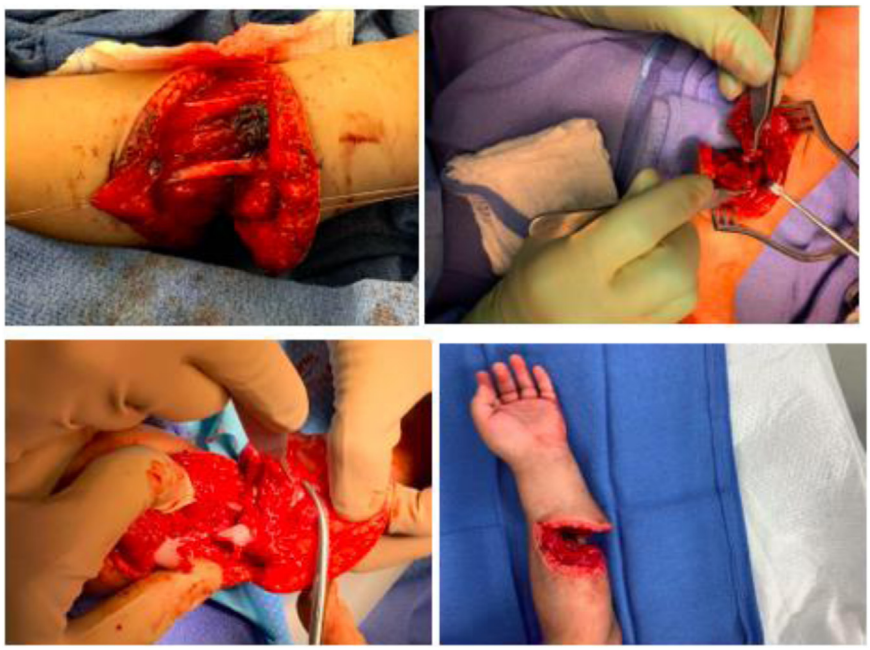

Figure 5. Injury and intraoperative photos. A 3-year-old from a motor vehicle accident with partial arm amputation.

This study has limitations. The external validity of our epidemiologic data are limited because of our large catchment radius, which includes a unique, mostly rural and suburban population. Given the relatively rare occurrence of traumatic peripheral nerve injuries in pediatric patients, this study has a small sample size. However, this is the largest known study of its kind, and the number of patients is on par with other similar nerve studies.[7,9,20] Treatment of patients with concomitant injuries is challenging, and we chose to proceed with only allograft reconstruction given the extent of injury and our desire to reduce the number of operative sites. This study is observational in nature without a comparison group. Additionally, our outcomes are largely subjective based on physician and guardian perception of function, which can be difficult to interpret based on differences in satisfaction of outcome. Our outcomes are subjective and do not include an objective evaluation of motor recovery or functional scores secondary to the young age of the patients and the study's retrospective nature. Given the difficulty of interpreting retrospectively collected data and the potential significance of this article, we are attempting to bring patients back to collect objective data, such as Jebsen's hand function, EMG, and two-point discrimination.

Conflicts of Interest

Dr MacKay is a primary investigator in the "A Multicenter Registry Study of Avance Nerve Graft Utilization, Evaluations and Outcomes in Peripheral Nerve Injury Repair" (RANGER) database, and we are a RANGER data collection site. Drs McKee and Mackay have been consultants for Axogen since 2019 and 2018, respectively. Mr Hernandez has been a consultant for Axogen since 2024. No benefits in any form have been received or will be received by the other authors related directly to this article.

Acknowledgments

The authors thank Gracie Baum, BS and Cody Perry, MSIV for help with manuscript editing.

References

1. Wang ML, Rivlin M, Graham JG, Beredjiklian PK. Peripheral nerve injury, scarring, and recovery. *Connect Tissue Res*. 2019;60(1):3–9.
2. Griffin JW, Hogan MV, Chhabra AB, Deal DN. Peripheral nerve repair and reconstruction. *J Bone Joint Surg Am*. 2013;95(23):2144–2151.
3. Pan D, Mackinnon SE, Wood MD. Advances in the repair of segmental nerve injuries and trends in reconstruction. *Muscle Nerve*. 2020;61(6):726–739.
4. Sachanandani NF, Pothula A, Tung TH. Nerve gaps. *Plast Reconstr Surg*. 2014;133(2):313–319.
5. Means KR Jr, Rinker BD, Higgins JP, Payne SH Jr, Merrell GA, Wilgis EF. A multicenter, prospective, randomized, pilot study of outcomes for digital nerve repair in the hand using hollow conduit compared with processed allograft nerve. *Hand (N Y)*. 2016;11(2):144–151.
6. MacKay BJ, Cox CT, Valerio IL, et al. Evidence-based approach to timing of nerve surgery: a review. *Ann Plast Surg*. 2021;87(3):e1–e21.
7. Hamant LG, Adelson PD, Kang P, Brown SD, Arango JI. Comparison of autograft versus allograft in the surgical repair of pediatric obstetrical brachial plexus injuries. *J Neurosurg Pediatr*. 2020;26(3):318–326.
8. Ducic I, Yoon J, Buncke G. Chronic postoperative complications and donor site morbidity after sural nerve autograft harvest or biopsy. *Microsurgery*. 2020;40(6):710–716.
9. Miloro M, Zuniga JR. Does immediate inferior alveolar nerve allograft reconstruction result in functional sensory recovery in pediatric patients? *J Oral Maxillofac Surg*. 2020;78(11):2073–2079.
10. Cho MS, Rinker BD, Weber RV, et al. Functional outcome following nerve repair in the upper extremity using processed nerve allograft. *J Hand Surg Am*. 2012;37(11):2340–2349.
11. Rinker BD, Ingari JV, Greenberg JA, Thayer WP, Safa B, Buncke GM. Outcomes of short-gap sensory nerve injuries reconstructed with processed nerve allografts from a multicenter registry study. *J Reconstr Microsurg*. 2015;31(5):384–390.
12. Rinker B, Zoldos J, Weber RV, et al. Use of processed nerve allografts to repair nerve injuries greater than 25 mm in the hand. *Ann Plast Surg*. 2017;78(6S suppl 5):S292–S295.
13. Callahan N, Miloro M, Markiewicz MR. Immediate reconstruction of the infraorbital nerve after maxillectomy: is it feasible? *J Oral Maxillofac Surg*. 2020;78(12):2300–2305.
14. Nietosvaara Y, Grahn P, Sommarhem A. Failed peripheral nerve reconstruction with processed nerve allografts in three patients. *J Hand Surg Eur Vol*. 2019;44(3):318–320.
15. Li L, Yang J, Qin B, et al. Analysis of human acellular nerve allograft combined with contralateral C7 nerve root transfer for restoration of shoulder abduction and elbow flexion in brachial plexus injury: a mean 4-year follow-up. *J Neurosurg*. 2019;132(6):1914–1924.
16. Kobraei EM, Dusch MN, Meisel EM, Stevanovic M. A novel method of treatment of macrodactyly with digital nerve resection and nerve allograft. *Plast Reconstr Surg Glob Open*. 2019;7(10):e2483.
17. Ducic I, Safa B, DeVinney E. Refinements of nerve repair with connector-assisted coaptation. *Microsurgery*. 2017;37(3):256–263.

18. Zhukauskas R, Fischer DN, Deister C, Alsmadi NZ, Mercer D. A comparative study of porcine small intestine submucosa and cross-linked bovine type I collagen as a nerve conduit. *J Hand Surg Glob Online*. 2021;3(5):282–288.
19. Schreuders TA, Selles RW, van Ginneken BT, Janssen WG, Stam HJ. Sensory evaluation of the hands in patients with Charcot-Marie-Tooth disease using Semmes-Weinstein monofilaments. *J Hand Ther*. 2008;21(1):28–35.
20. Felder JM, Hill EJR, Power HA, Hasak J, Mackinnon SE. Cross-palm nerve grafts to enhance sensory recovery in severe ulnar neuropathy. *Hand (N Y)*. 2020;15(4):526–533.
21. Safa B, Jain S, Desai MJ, et al. Peripheral nerve repair throughout the body with processed nerve allografts: results from a large multicenter study. *Microsurgery*. 2020;40(5):527–537.
22. Whitlock EL, Tuffaha SH, Luciano JP, et al. Processed allografts and type I collagen conduits for repair of peripheral nerve gaps. *Muscle Nerve*. Jun 2009;39(6):787–799. https://doi.org/10.1002/mus.21220
23. Giusti G, Willems WF, Kremer T, Friedrich PF, Bishop AT, Shin AY. Return of motor function after segmental nerve loss in a rat model: comparison of autogenous nerve graft, collagen conduit, and processed allograft (AxoGen). *J Bone Joint Surg Am*. 2012;94(5):410–417. https://doi.org/10.2106/jbjs.K.00253
24. Safa B, Buncke G. Autograft substitutes: conduits and processed nerve allografts. *Hand Clin*. 2016;32(2):127–140.
25. Brenner MJ, Lowe JB III, Fox IK, et al. Effects of Schwann cells and donor antigen on long-nerve allograft regeneration. *Microsurgery*. 2005;25(1):61–70.
26. He B, Zhu Z, Zhu Q, et al. Factors predicting sensory and motor recovery after the repair of upper limb peripheral nerve injuries. *Neural Regen Res*. 2014;9(6):661–672.
27. Lohmeyer JA, Kern Y, Schmauss D, et al. Prospective clinical study on digital nerve repair with collagen nerve conduits and review of literature. *Journal of reconstructive microsurgery*. 2014;30(04):227–234.
28. Grinsell D, Keating CP. Peripheral nerve reconstruction after injury: a review of clinical and experimental therapies. *Biomed Res Int*. 2014;2014:698256.