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Alternatives to sural nerve grafts in the upper extremity

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Abstract
Background The sural nerve is the most common nerve graft donor despite requiring a second operative limb and causing numbness of the lateral foot. The purposes of this study were to review our experience using nerve autografts in upper extremity nerve reconstruction and develop recommendations for donor selection.
Methods A retrospective case series study was performed of all consecutive patients undergoing nerve grafting procedures for upper extremity nerve injuries over an 11-year period (2001–2012).
Results Eighty-six patients received 109 nerve grafts over the study period. Mean patient age was 42.9±18.3 years; 57 % were male. There were 51 median (59 %), 26 ulnar (30 %), 14 digital (13 %), 13 radial (16 %), and 3 musculocutaneous (4 %) nerve injuries repaired with 99 nerve autografts (71 from upper extremity, 28 from lower extremity). Multiple upper extremity nerve autograft donors were utilized, including the medial antebrachial cutaneous nerve (MABC), third webspace branch of median, lateral antebrachial cutaneous nerve (LABC), palmar cutaneous, and dorsal cutaneous branch of ulnar nerve. By using an upper-extremity donor, a second operative limb was avoided in 58 patients (67 %), and a second incision was avoided in 26 patients (30 %). The frequency of sural graft use declined from 40 % (n=17/43) to 11 % (n=7/64).
Conclusions Our algorithm for selecting nerve graft material has evolved with our growing understanding of nerve internal topography and the drive to minimize additional incisions, maximize ease of harvest, and limit donor morbidity. This has led us away from using the sural nerve when possible and allowed us to avoid a second operative limb in two thirds of the cases.

Keywords Autograft · Donor · Nerve graft · Nerve transfer · Sural nerve

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Interposition grafting of upper-extremity nerve injuries is often required to perform a tension-free coaptation. Classically, the sural nerve has been the predominant source of nerve autograft, especially when a larger amount of graft material is required. Although sural donor site morbidity is minimal, it does result in diminished sensation at the lateral foot and a visible scar. For upper-extremity reconstruction, sural graft harvest involves a second operative extremity, awkward intra-operative positioning, and/or position changes that may lengthen operative time; the latter are especially true in obese patients [13].

Upper-extremity sources for nerve autograft have several potential advantages, which include confining donor morbidity to the affected limb, limiting additional incisions, and simplicity of harvest. Several upper-extremity nerve grafts have been described, including the medial antebrachial cutaneous nerve (MABC) [15, 31], lateral antebrachial cutaneous nerve (LABC) [15, 28–30, 45], median nerve fascicular branch to the third webspace (TWM) [5, 38, 41], palmar-cutaneous branch of median nerve (PCM) [1], dorsal-cutaneous branch of ulnar nerve (DCU) [3, 19], and posterior interosseous nerve (PIN) [22].

A summary of the literature on donor options for nerve autograft, including specific advantages and disadvantages, is shown in Table 1. Most studies have focused on specific graft options or reconstruction of specific nerve injuries. The results

Table 1 Characteristics of nerve autograft donors based on published data

Donor nerve	Harvestable length	Fascicle count	Cross-sectional area	Disadvantage	Advantage
MABC	Up to 28 cm (3)	7–10	2–3.15 mm^2	• Medial arm scar	• Long length and larger caliber nerve suitable for larger nerve gaps and/or multiple cables required • Can minimize donor morbidity with end-to-side repair of distal end MABC to median nerve
LABC	5–8 cm (14)	4–9 (46) 5–18 (6) 6–15 (5) 5–7 (14)	1.3–1.8 mm^2 (14)	• Visible forearm scar	• Good for short gaps • Good size match with digital nerve • Usually injured with SBR and therefore good nerve graft for SBR injuries • Dermatome overlap with SBR reduces donor morbidity (7)
TWM[a]	24.5 cm (8)	2–13	4.43 mm^2	• Sensory loss in hand (non-critical)	• Easy access through volar distal forearm incisions
PCM[a]	Mean length 5.24 cm (11)			• Sensory loss in palm	• Easy access through volar forearm incisions
DCU[a]	Up to 26 cm (12) •Dorsal-ulnar hand divisions, 5–6 cm		2.4 mm^2 at origin (13)	• Sensory loss to dorsal-ulnar hand and digits	• Useful if ulnar nerve already injured and working in same operative site
AIN[a]		3–5 (14)	0.6–0.7 mm^2	• Deep dissection into pronator quadratus • Short segment available	• No sensory loss • Good size match with digital nerves
PIN[b]	2.5 cm (47)	2 (14)	0.5–0.8 mm^2	• Visible dorsal incision • Small diameter graft	• No cutaneous sensory loss
SBR[a]				• Potential for hypersensitivity in donor territory	• Consider if radial nerve already injured
Sural	30–50 cm (48)	9–14 MSC 1–3 LSC 5–7	2.5–4 mm MSC 1.5 LSC 1.5	• Positioning difficult • Requires second extremity	• Long length
Obturator	9.9–13.6 cm 11.5 cm average (49)	2–4 (50)		• Loss of gracilis as possible future free functional flap	• No sensory loss • Expendable motor nerve graft

MABC medial antebrachial cutaneous nerve, *LABC* lateral antebrachial cutaneous nerve, *TWM* third webspace branch of median nerve, *PCM* palmar cutaneous branch of median nerve, *DCU* dorsal cutaneous branch of ulnar nerve, *AIN* anterior interosseous nerve, *PIN* posterior interosseous nerve, *SBR* radial sensory nerve, *MSC* medial sural cutaneous, *LSC* lateral sural cutaneous

[a] Used as non-critical portion of injured nerve

[b] Terminal branch

following nerve grafting are well described [9, 26, 27, 36, 40, 44, 51]. The purposes of this study were to review our experience using nerve autografts in upper-extremity nerve reconstruction and develop recommendations for donor site selection with an emphasis on alternatives to sural nerve.

Materials and Methods

A retrospective case series study was performed of all consecutive patients undergoing nerve grafting procedures for upper extremity nerve injuries over an 11-year period (2001–2012). Pediatric patients (<18 years) were excluded. Patient consent and study approval from the Institutional Review Board were obtained.

Eligible patients were identified from a prospectively maintained database of nerve surgeries performed by the senior author (SEM). Data on patient demographics, mechanism and timing of injury, nerve donor, nerve recipient, gap length, graft length, cable number, and operative site were collected. Descriptive statistics (means, standard deviations, frequencies, percentages) were performed for all variables, and an algorithm for upper-extremity nerve reconstruction was created.

Results

Patients and Nerve Injury

Eighty-six patients received 109 nerve grafts for upper extremity nerve reconstruction over the study period. Mean patient age at time of surgery was 42.9±18.3 years, and 57 % were male. Mechanism of nerve injury was documented in 80 patients and included sharp laceration (37 %), iatrogenic lacerations (24 %), traction (9 %), neoplasm (7 %), gunshot (6 %), fracture (3 %), crush (2 %), and other blunt trauma (1 %). Nerve repairs were performed at an average of 13.3± 17.2 months after primary injury, and 48 patients (56 %) had undergone one or more prior attempts at nerve repair. In 14 patients (16 %), multiple nerves were injured but only 6 patients (7 %) required repair of multiple nerves with a nerve graft.

There were 51 median (59 %), 26 ulnar (30 %), 14 digital (13 %), 13 radial (16 %), and 3 musculocutaneous (4 %) nerve injuries repaired with nerve graft. Pure sensory nerve injuries were most common (n=47, 53 %), followed by mixed (n=32, 36 %) and pure motor nerve injuries (n=10, 11 %).

Nerve Graft Donors

In total, 99 nerve autografts (71 from upper extremity, 28 from lower extremity) and 10 acellular nerve allografts (ANA) were used. The type and characteristics of nerve grafts utilized in this cohort are summarized in Table 2. Figure 1 demonstrates which nerve grafts were utilized by nerve injured.

Multiple upper-extremity nerve autograft donors were utilized, including the MABC, TWM, LABC, PCM, and DCU. By using an upper-extremity donor, a second operative limb was avoided in 58 patients (67 %) and a second incision was avoided in 26 patients (30 %). Lower-extremity autograft donors included the sural nerve and obturator nerve. Six patients (7 %) required bilateral sural nerve harvest. The frequency of sural nerve graft use declined from 40 % (n= 17/43) to 11 % (n=7/64) between the first and second half of the study period, with a corresponding increase in upper-extremity nerve donor utilization (Fig. 2). The sural was used primarily to repair complex injuries involving multiple nerves.

Where possible, the distal cut end of the donor nerve was repaired in an end-to-side fashion to an adjacent, normal sensory nerve. This was achieved in 25 of 99 autografts, specifically following MABC (n=13), TWM (n=7), and PCM (n=3) harvest. In two cases where a direct end-to-side repair was not possible, ANA was utilized to bridge the nerve gap.

An algorithm for nerve graft selection is proposed in Fig. 3.

Discussion

Nerve grafting remains an important reconstructive technique for acute management of upper-extremity nerve injuries. Our algorithm for selection of nerve graft material has evolved over the last decade owing to several factors. First, a growing understanding of upper-extremity nerve anatomy and internal topography now allows alternative reconstructions with nerve transfers and has expanded the available options and harvestable length of upper-extremity nerve donors. Second, the ongoing drive to minimize additional incisions, maximize ease of harvest, and limit donor morbidity has led us away from using the sural nerve when possible. Third, with the increasing prevalence of obesity in North America, the added difficulty and operative time required for sural nerve harvest is

Table 2 Type and characteristics of 109 nerve grafts utilized to reconstruct upper-extremity nerve injuries

Nerve	Number	Harvested length (cm) (mean±SD, range)	Cable length (cm) (mean±SD, range)	Number of cables (mean±SD, range)
Upper extremity				
MABC	29	17.6±10.7 (4.5–56[a])	6.3±2.9 (3–18)	3±2 (1–8)
TWM	14	8.5±5.3 (3–18)	4.8±1.8 (2–8)	2±1 (1–4)
LABC	12	8.4±4.6 (3.5–18)	4.4±3.3 (2–12)	1±1 (1–3)
PCM	8	6.5±3.8 (2–14)	5.6±2.3 (2–9)	1±0 (1–2)
DCU	6	9.6±5.9 (3–18)	5.8±3.0 (3–11)	2±1 (1–3)
AIN	1	2	2	1
SBR	1	12	12	1
Lower extremity				
Sural	24	28.0±11.5 (6–48)	10.0±5.2 (3–23)	3±2 (1–7)
Obturator nerve	4	6.8±3.7 (2–11)	4.5±2.2 (2–7)	2±1 (1–2)
Non-autograft				
ANA	10	2.5±0.6 (1.5–3)	2.5±0.6 (1.5–3)	1±0 (1–1)

MABC medial antebrachial cutaneous nerve, *LABC* lateral antebrachial cutaneous nerve, *TWM* third webspace branch of median nerve, *PCM* palmar cutaneous branch of median nerve, *DCU* dorsal cutaneous branch of ulnar nerve, *AIN* anterior interosseous nerve, *SBR* radial sensory nerve, *ANA* acellular nerve allograft

[a] Using both anterior and posterior branches of MABC

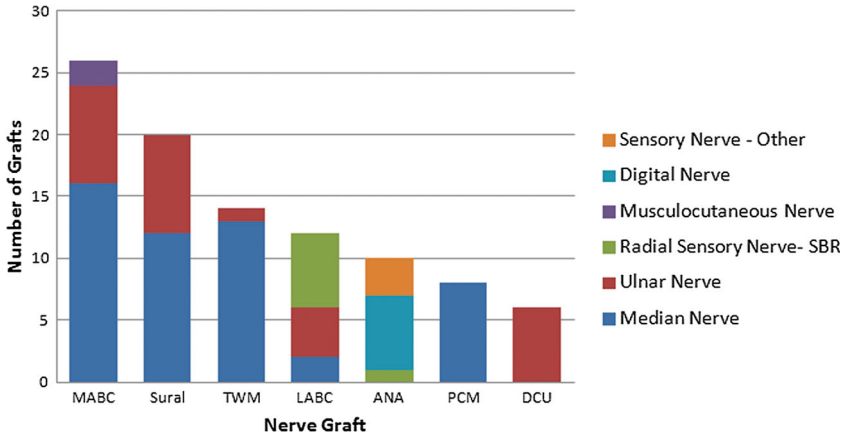

Fig. 1 Upper-extremity graft use by injured nerve. Histogram representing the frequency of use of each donor nerve and the nerve repaired with that donor. Includes ANAs used to facilitate and end-to-side repair of nerve graft donors and repair of other sensory nerves not specifically listed.

not insignificant. As a result, we now use the sural nerve only for situations requiring large amounts of graft material, such as multiple major nerve transection injuries.

For distal nerve injuries in the forearm, the MABC remains our first choice for repair of median and ulnar nerve injuries because of its caliber, available length, and proximity. Donor morbidity from harvesting the MABC can be minimized by performing an end-to-side anastamosis of the distal cut end of the MABC to the adjacent median nerve. Recent studies show that while motor axons require injury for end-to-side sprouting, sensory axons collaterally sprout spontaneously without need for additional axonal injury [35, 46]. Restoring some degree of innervation to the donor nerve territory may reduce forearm anesthesia or hypersensitivity caused by sprouting of adjacent sensory nerves after MABC harvest [11, 13]. This concept can also be applied to harvest of other nerves, such as the TWM.

Utilizing non-critical portions of the injured nerve also helps to minimize donor morbidity, avoid additional incisions, and minimize operative time. For example, the DCU becomes a useful donor in more proximal ulnar nerve injuries, as do the PCM and TWM in median nerve injuries. In this study, using DCU and TWM for graft material avoided a second incision in 3 of 6 patients and 10 of 14 patients, respectively. Owing to its small caliber and short length, we tend to reserve the PCM as a secondary source of graft material in distal median nerve injuries where the TWM alone was insufficient. Addition of the PCM in this review eliminated the need for a second incision in four of eight patients.

Along the same lines, our preference for radial sensory nerve reconstruction for short gap injuries in the forearm is the LABC because of its proximity, ease of harvest, and the likelihood that it is also injured in distal forearm injuries. Although the radial sensory nerve does not provide critical sensation to the hand, we prefer to reconstruct it because of the propensity for hyperalgesia in this region secondary to collateral sprouting [11]. Alternatively, in high radial nerve injuries, we will crush and proximally transpose the injured radial

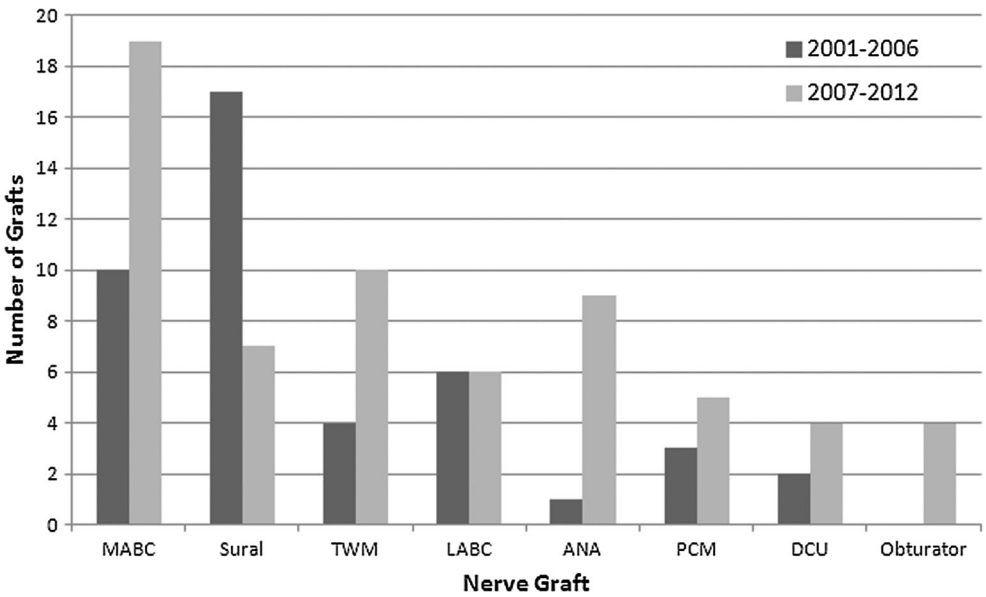

Fig. 2 Utilization of different nerve grafts over time. Histogram comparing the use of each donor nerve in the first half of the study period to the second half. Sural nerve use decreased as use of upper extremity donors increased

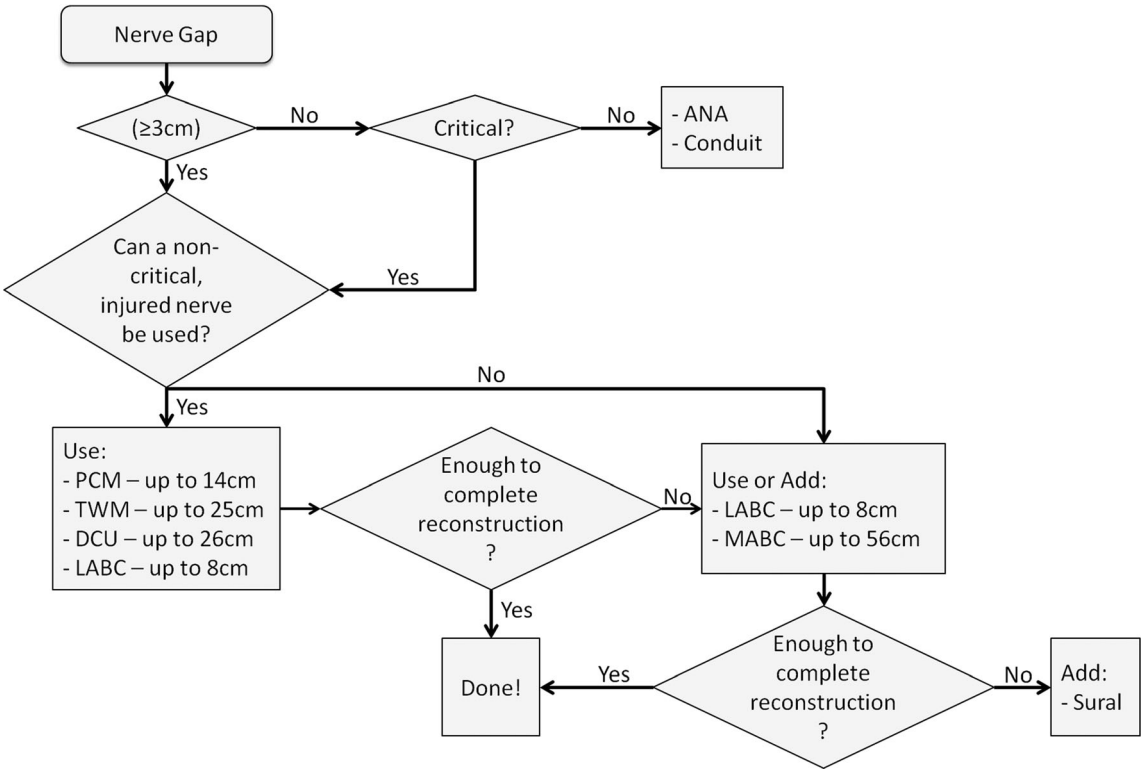

Fig. 3 Algorithm for sural alternatives. Flow diagram representing our algorithm for choosing donor nerves. *ANA* acellular nerve allograft, *DCU* dorsal cutaneous branch of ulnar nerve, *LABC* lateral antebrachial cutaneous nerve, *MABC* medial antebrachial cutaneous nerve, *PCM* palmar cutaneous branch of median nerve, *TWM* third webspace branch of median nerve

sensory nerve to avoid formation of a painful neuroma when reconstruction is not feasible. The distal radial sensory nerve can then be transferred end-to-side to the normal median nerve for recovery of sensation. We strongly advise against harvesting an uninjured radial sensory nerve as graft material.

Our preference for digital nerve reconstruction depends on the specific nerve injured. Critical sensory nerves supplying the ulnar and radial borders of the hand should be reconstructed with nerve autograft. Multiple donor options exist; however, we prefer the MABC and LABC owing to their size match and limited donor morbidity. The distal PIN is described as a graft source for digital nerve reconstruction [22] but it is small in diameter and leaves a visible scar on the dorsal forearm. Therefore, we tend not to use this graft.

We reserve the use of ANA for non-critical digital nerve injuries less than 3 cm in length. While a comprehensive discussion on the advantages and disadvantages of ANA is outside the scope of this manuscript, evidence supporting good outcomes following ANA reconstruction of proximal nerve injuries or large nerve gaps is lacking [4, 8]. In fact, we will utilize long ANA segments specifically when we wish to encourage incomplete nerve regeneration, as in the management of painful neuromas. As such, our personal practice is to use autogenous nerve for critical sensory or motor nerve repair.

The vast majority of autograft donors in this study were sensory nerves. In four cases, we utilized the obturator motor nerve for reconstruction of motor nerve injuries based on the hypothesis that motor and sensory Schwann cell specificity would markedly improve regeneration [21]. However, subsequent experimental work revealed that nerve architecture and endoneurial tube size are likely more important factors in facilitating nerve regeneration [23, 34]. Our current indications for harvesting a motor nerve as a graft source are therefore limited to critical motor nerve reconstruction not amenable to motor transfer, such as the deep ulnar motor branch in the hand and the spinal accessory nerve.

The advent of distal nerve transfers has limited our requirements for long nerve grafts. Our improved understanding of nerve injury and regeneration now cautions us against the use of long grafts (>6 cm) whenever possible [42]. A state of Schwann cell senescence following denervation was recently described and correlated with failures of axonal regeneration through long nerve grafts [42]. Irreversible arrest of proliferation, altered gene expression, and changes in the secretory profile characterize the senescent state [2, 6, 7, 10, 12, 14, 18, 24, 32, 33, 37, 39, 43, 47, 48]. Compared with short grafts, long and large diameter nerve grafts expose distal Schwann cells to prolonged ischemia-related oxidative stress and prolonged denervation, which may induce Schwann cell senescence [42, 49, 50]. This phenomenon may explain poor

Table 3 "Recipes" for high-level nerve injuries as alternatives to sural graft

Nerve injury	Priorities	Reconstruction technique
Median	AIN function	Motor nerve transfers[a]
	Thumb opposition	- ECRB to PT
	Pronation	- Brachialis or supinator to AIN
	Sensation	Sensory transfers
		- DCU to thumb and radial index sensory fascicles ETE
		- TWM and distal DCU to ulnar sensory fascicles ETS
		Tendon transfers
		- Opponensplasty
Radial	Wrist, finger, and thumb extension	Motor nerve transfers
	Sensation	- FDS to ECRB
		- FCR to PIN
		Sensory transfers
		- LABC to SBR ETE
		- SBR to median ETS
		Tendon transfers
		- PT to ECRB for early wrist extension (optional)
Ulnar	Intrinsic function	Motor nerve transfers
	Ring and small finger flexion	- AIN to ulnar motor
	Sensation	Sensory transfers
		- TWM to ulnar sensory fascicles ETE
		- PCM to DCU ETE or DCU to median ETS
		Tendon transfers
		- Tenodesis of FDP tendons

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AIN anterior interosseous nerve, *ETE* end-to-end, *ETS* end-to-side, *DCU* dorsal cutaneous branch of ulnar nerve, *PCM* palmar cutaneous branch of median, *SBR* radial sensory nerve, *TWM* third webspace branch of median nerve

[a] All motor transfers are end-to-end

regeneration across long grafts and grafts without immediate distal repair [17, 20, 25].

Based on this knowledge, we prefer to acutely manage single nerve injuries in the upper arm with distal nerve or tendon transfers rather than direct repair with nerve grafting (Table 3). Increased experience with nerve transfer and the use of MABC as graft material has reduced the need for sural nerve graft. We now only address a proximal single nerve injury if there is neuropathic pain. In these situations, rather than directly repair the nerve with a nerve graft, we address the injury with neuroma excision, and crushing the nerve proximal to the injury to create a neurotmetic injury and thus, "reset" the regenerative process. Finally, the nerve end is transposed into an adjacent muscle for pain control. As a result, even if nerve grafts are needed to complete a portion of reconstruction, donors from the upper extremity typically suffice. Sural nerve grafting is reserved for multiple major nerve transection injuries, where distal nerve or tendon transfers are not possible.

In summary, upper-extremity nerve reconstruction can be successfully accomplished using nerve donors from the ipsilateral limb in the majority of cases. Judicious selection of nerve donors can reduce patient morbidity and operative time but necessitates a thorough understanding of nerve anatomy and topography. While the sural nerve remains a useful donor for extensive, multiple nerve injury reconstruction, a growing body of scientific and clinical evidence suggests that in situations requiring large amounts of nerve autograft, alternative reconstructions such as nerve transfers may provide better results [16, 36]. In cases of distal injury requiring interposition grafting, we recommend use of alternative graft material including TWM and DCU for median and ulnar nerve injuries respectively, as well as MABC and LABC.

Conflict of Interest Louis H. Poppler declares that he has no conflict of interest.
Kristen Davidge declares that she has no conflict of interest.
Johnny C.Y. Lu declares that he has no conflict of interest.
Jim Armstrong declares that he has no conflict of interest.
Ida K. Fox declares that she has no conflict of interest.
Susan E. Mackinnon declares that she has no conflict of interest.

Statement of Human and Animal Rights The Institutional Review Board at Washington University approved this study and ensured that all data collection and analysis was performed with respect to human rights.

Statement of Informed Consent All data in this study had no personal identifiers and therefore informed consent was not necessary.

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