Journal of Hand Surgery Global Online 6 (2024) 766–778

Contents lists available at ScienceDirect

Journal of Hand Surgery Global Online

journal homepage: www.JHSGO.org

Original Research

The Role of Vascularized Nerve Grafting in Upper Extremity Reconstruction: A Systematic Review

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ARTICLE INFO

Article history:
Received for publication October 16, 2023
Accepted in revised form January 20, 2024
Available online May 22, 2024

Key words:
Nerve grafting
Nerve regeneration
Nerve repair
Vascularized nerve graft

Purpose: Vascularized nerve grafts (VNGs) have been proposed as encouraging alternatives to conventional nerve grafting; however, there is ongoing debate regarding the clinical advantages of the approach compared with standard grafting. This review aims to gather and analyze reported cases of upper extremity nerve repair using VNGs documented in the published literature.

Methods: In accordance with Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines, PubMed/MEDLINE, Embase, and Cochrane were searched. Inclusion criteria for this review included the following: (1) human subjects or cadaveric studies, (2) describing a vascularized nerve grafting procedure or suggesting a nerve and vascular supply for a potential vascularized nerve graft, and (3) upper extremity nerve repair in clinical studies.

Results: Data were extracted from 45 clinical studies. Of 535 patients, the most common injury pattern was root avulsion and rupture (88.7%). The most utilized VNG was the ulnar nerve (72.8%), followed by nerve to long head of triceps (8.8%) and sural nerve (8.2%); most common recipients were median (57.6%), axillary (12.5%), and musculocutaneous nerves (11.9%). Between patients who had medical research council scale scores, 69% had functional (M3 and above) motor and 72.7% sensory (S3<) recovery.

Conclusions: Vascularized nerve grafts can increase the odds of functional gain in challenging conditions such as large nerve gaps, nerve avulsions, ruptures, and scarred and irradiated beds. With the exception of well-known VNG options, literature on alternative VNGs is largely confined to case reports and series, with additional published cases, outcomes, and basic science research needed to establish the role of VNGs in nerve repair.

Clinical relevance: Our findings support the promise of VNGs for complex cases of nerve reconstruction. Evidence from published cases also indicates that VNGs enhance motor and sensory function recovery compared with traditional nerve grafting.

Peripheral nerve injuries result in motor and sensory disability as well as chronic neuropathic pain, which detrimentally affect one's quality of life. Nerve grafting has emerged as a valuable therapeutic approach for bridging nerve gaps and bolstering functional recovery. Several strategies have been proposed to improve functional recovery after nerve injury, from end-to-end and end-to-side neurorraphy to nerve allografts, nerve conduits, nerve transfers, and vascularized nerve grafts.[1] Initially described by Taylor and Ham in 1976, vascularized nerve grafts (VNGs) represent a paradigm shift in the field of nerve regeneration by combining principles of neurobiology and vascularization.[2] Unlike conventional nerve grafts, which primarily rely on passive diffusion for nutrient supply and waste removal, VNGs integrate blood vessels directly into the graft tissue. This integration creates a dynamic

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https://doi.org/10.1016/j.jhsg.2024.01.028

Table 1
Database Search Terms

Database	Search Terms	Hits
PubMed/MEDLINE	((vasculariz* OR vascularis*) AND (“nerve transfer”[MeSH Terms] OR “peripheral nerves/transplantation” [MeSH Terms] OR “nerve coaptation*” OR “nerve reconstruct*” OR neurotization* OR “nerve graft*” OR “nerve transfer*” OR “nerve transplant*” OR “nerve crossover*”)) AND (“Humans”[MeSH Terms])	247
Embase	((“vasculariz*”.af. OR “vascularis*”.af.) AND (exp nerve transplantation/ OR “nerve coaptation*”.af. OR “nerve reconstruct*”.af. OR “neurotization*”.af. OR “nerve graft*”.af. OR “nerve transfer*”.af. OR “nerve transplant*”.af. OR “nerve crossover*”.af. OR “Transfer* nerve”.af. OR “Crossover* nerve”.af.)) NOT (exp animal/ not human/)	403
Cochrane	((vasculariz* OR vascularis*) AND (“nerve transfer”[MeSH Terms] OR “peripheral nerves/transplantation” [MeSH Terms] OR (nerve NEXT coaptation*) OR (nerve NEXT reconstruct*) OR neurotization* OR (nerve NEXT graft*) OR (nerve NEXT transfer*) OR (nerve NEXT transplant*) OR (nerve NEXT crossover*))) AND [mh “Humans”]	2

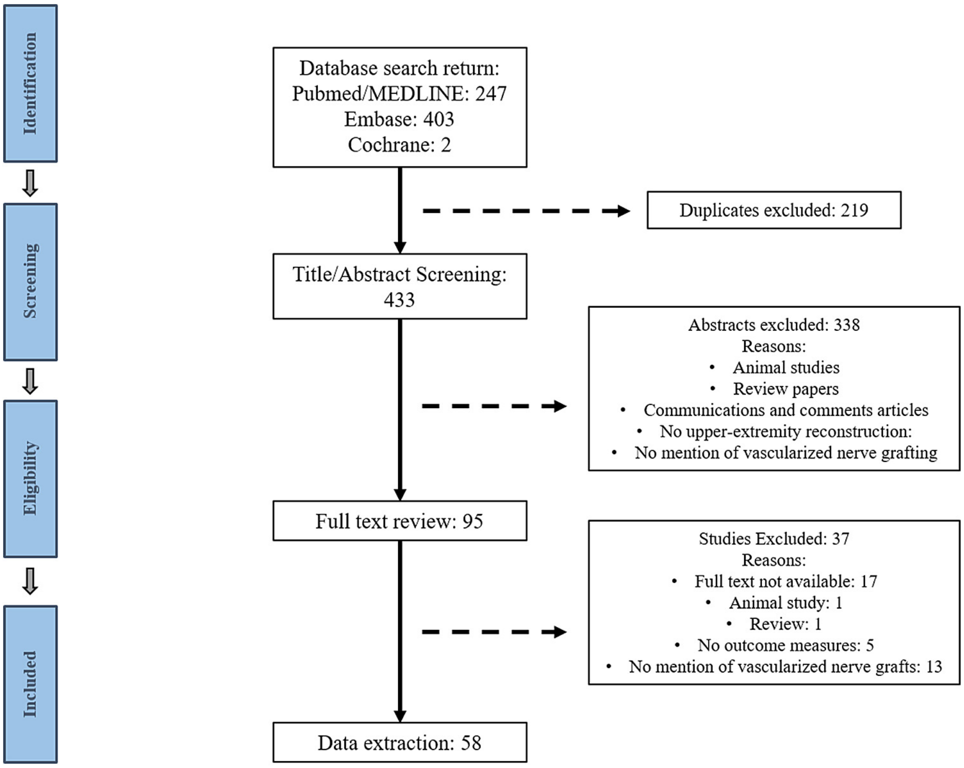

Figure 1. Preferred reporting items for systematic reviews and meta-analyses chart.

microenvironment that provides a continuous supply of oxygen, nutrients, and growth factors to support nerve regeneration.[3] This approach leverages the inherent regenerative potential of both the nervous and vascular systems, fostering an environment conducive to improved axonal sprouting, myelination, and ultimately functional recovery.[3]

In the clinical setting, VNGs are used for the reconstruction of large nerve trunks, long nerve gaps, and nerve reconstruction in ischemic or scarred environments.[4–7] This review aims to provide a comprehensive overview of the current state of research and clinical developments in the field of vascularized nerve grafts. We will delve into the various approaches for creating VNGs and their potential applications in the treatment of peripheral nerve injuries. By shedding light on the recent advancements and challenges in this innovative area, this review seeks to inspire further investigation and collaboration among researchers and clinicians with the ultimate goal of refining the indications and applications of VNGs.

Methods

In accordance with Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines,[8] Pubmed/MEDLINE, Embase, and Cochrane were searched with search terms provided in Table 1. All references were uploaded into Covidence systematic review software, and duplicates were removed.[9]

Title and abstract inclusion criteria were as follows: (1) human subjects or cadaveric studies, (2) original articles, (3) included description of at least one vascularized nerve grafting procedure (clinical studies) or recommendation of a reliable vascularized nerve graft (cadaveric studies), and 4) upper extremity nerve repair (for clinical studies). The exclusion criteria were the following: (1) animal studies, (2) review articles, (3) comments and communications, (4) containing no mention of nerve grafts’ vascularization, and (5) clinical studies solely discussing nerve defect reconstruction outside of the upper extremity. Full-text inclusion criteria were

Table 2
Nerve Grafting Components

Study Information		Nerve Grafting Information				
Authors	Year	Donor Nerve	Bridging Nerve Graft	Recipient Nerve	Nerve Graft Vascular Supply	(Average) Nerve Graft Length (cm)
Boorman and Sykes	1986[10]	Ulnar digital	Lateral antebrachial cutaneous	Ulnar digital	N/A	5
Mackinnon et al	1988[11]	Radial	Peroneal	Radial	Peroneal	5
Rivet et al	1988[12]	Ulnar collateral nerve of thumb	Posterior brachial cutaneous	Radial collateral nerve of thumb	Dorsalis pedis artery	N/A
Fukui et al	1989[13]	Median	Sural	Median	Posterior branch of profunda brachii	5
Krarup et al	1990[14]	Median	Superficial sensory portion of radial	Median	Dorsalis pedis venae comitant system used in lieu of artery	N/A
Tang and Chen	1990[15]	Common digital nerve to fourth and fifth digits	Deep peroneal	Common digital nerve to fourth and fifth digits	Pedicled on radial artery and its two venae commitantes	4
Koshima et al	1991[16]	Palmar digital	Deep peroneal	Palmar digital	N/A	5
Becker et al	1993[17]	Intercostal (second to fifth)	Ulnar	Thoracodorsal	N/A	N/A
Burge and Shewring	1995[18]	C7 nerve roots	Lower trunk brachial plexus	Middle trunk brachial plexus	Not Specified	5
Gailliot and Core	1995[19]	Ulnar	Intercostal	Ulnar	N/A	13
Koshima et al	2003[16]	Median	Femoral	Median	Not Specified	12
Hattori and Doi	2006[20]	Posterior cord	Radial	Ulnar nerve	N/A	19
Macionis	2008[5]	Median	Ulnar	Median	Medial plantar digital artery	14
Muramatsu et al	2013[21]	Ulnar	Sural	Ulnar	N/A	27 (folded to 9 cm)
Yamamoto et al	2014[22]	Median	Lateral femoral cutaneous	Median	Peroneal vessels	2
Campodonico et al	2019[23]	Median	Dorsal sensory branch of ulnar	Median	Superior ulnar collateral vessels (pedicled or free)	28 (folded to 14)
Foo et al	2019[24]	Ulnar digital	Dorsal sensory branch of ulnar	Ulnar digital	Not Specified	N/A
Kawamura et al	2022[25]	Median	Lateral antebrachial cutaneous	Median	First perforator of the profunda brachiae artery	N/A
Riordan et al	2002[26]	Median Nerve (Right Forearm); Median Nerve (Left Forearm)	Sural	Median (Right Forearm); Median (Left Forearm)	Superficial sural	40.5
Usami et al	2019[7]	Proper digital	Sural	Proper digital	Not Specified	4.6
		Proper digital	Posterior interosseus	Proper digital	Wrapped in cephalic vein	3
Taylor	1978[27]	Median	Radial	Median	Muscular branches of the radial vessels	24
		Median/Ulnar	Median/Ulnar (from contralateral amputated arm)	Median/Ulnar	Brachial vessels	26
		Median	Superficial radial	Median	Radial vessels	20
Tamaru et al	1986[28]	Radial	Sural	Median	Peroneal artery	26 (bisected and folded)
		Ulnar	Sural	Digital nerves of fifth digit	Peroneal artery	12 (bisected and folded)
		Median	Sural	Median	Muscular perforating branch of posterior tibial artery	30 (bisected and folded)
Reddy et al	1998[29]	Median	Ulnar	Median	Thoracodorsal	N/A
		Median	Ulnar	Median	Ulnar vascular pedicle	17
		Median	Ulnar	Median	Ulnar vascular pedicle	15
Hattori et al	2005[30]	Median	Ulnar	Median	N/A	16
		Radial	Ulnar	Radial	Superior ulnar collateral artery	16
		Median	Ulnar	Median	Superior ulnar collateral artery	25
Xu	2005[31]	Cervical Phrenic Nerve	N/A	Musculocutaneous	Pericardiophrenic vessels	10
						8
						8
						8
Rose and Kowalski	1985[32]	Radial	Deep peroneal	Radial digital	Dorsalis pedis artery	7
		Common digital nerve of thumb	Deep peroneal	Ulnar and radial digital	Dorsalis pedis artery	8
		Median	Peroneal	Radial digital	Dorsalis pedis artery	8
		Common digital nerve of thumb	Peroneal	Radial digital nerve	Dorsalis pedis artery	5
		Radial	not specified	Radial	N/A	5

Doi et al	1987[33]	Brachial plexus (posterior cord)	Sural	Axillary and radial nerves	Muscular perforating branches of the posterior tibial	25 (quadrisected)
		Median	Sural	Median	Muscular perforating branch of the posterior tibial	24
		Median	Sural	Median	N/A	30 (bisected)
		Ulnar	Sural	Ulnar	Muscular perforating branch of the posterior tibial	6
		Digital	Sural	Digital	N/A	12 (bisected)
Okinaga and Nagano	1999[34]	Intercostal	N/A	Musculocutaneous	Ulnar vascular pedicle	N/A
Hasegawa et al	2004[35]	Median	Sural	Median	Descending branch of the lateral circumflex femoral artery	25
		Median		Median	N/A	30
		Median		Median	N/A	25
		Ulnar		Ulnar	N/A	20
		Median		Median	N/A	20
		Median		Median	N/A	20
Hierner et al	2007[36]	C7	Ulnar	Musculocutaneous	Superior ulnar collateral artery	N/A
Del Pinal et al	2007[37]	Radial digital	Tibial digital	Radial digital	N/A	2.5
		Ulnar digital	Tibial digital	Ulnar digital	First digital metatarsal artery	6
		Radial digital	Tibial digital	Radial digital	First digital metatarsal artery	3.5
		Ulnar digital	Tibial digital	Ulnar digital	First digital metatarsal artery	5.2
		Ulnar digital	Tibial digital	Ulnar digital	First digital metetarsal artery	3.8
		Ulnar digital	Tibial digital	Ulnar digital	Medial plantar digital artery	4
Doi et al	2003[33]	Ipsilateral C5 root, ipsilateral C6 root, ipsilateral C4 root, and contralateral C7 root	Ulnar	Suprascapular	Superficial Sural artery	N/A
Bertelli et al	2009[38]	C5 Nerve Root	Ulnar	Musculocutaneous Nerve	Posterior branch of the ulnar recurrent artery, basilic vein (pedicled)	30
Potter and Ferris	2017[39]	C5 root	Ulnar	Musculocutaneous or common branch to biceps and brachialis	Lateral circumflex femoral artery	30
Rose et al	1989[40]	Radial or Ulnar digital	Deep peroneal	Radial or Ulnar digital	N/A	4.4
Lin et al	2011[41]	Contralateral C7	Ulnar	Medial median and musculocutaneous	Superior ulnar collateral artery	Not Specified
Chen et al	2023[42]	Contralateral C7, lateral/ posterior cord, C6 root	Ulnar	Median and/or musculocutaneous and/or radial	Proximal ulnar artery and vein	35.8
Chuang et al	1993[43]	Trunk or root of the brachial plexus	Ulnar	Musculocutaneous nerve or lateral cord	Brachial artery (Pedicled)	N/A
Chen et al	2012[44]	Proper digital	Dorsal digital	Proper digital	Superior ulnar collateral vessels	2.7
Oberlin	1989[45]	C5 and/or C6, anterior division of upper trunk, musculocutaneous, median among other donors	Ulnar	Median, Musculocutaneous, radial, anterior, and/or posterior division of upper trunk, lateral cord, and suprascapular	Peroneal artery	13.5
Doi et al	1992[46]	Posterior cord	Sural	Axillary	Cutaneous branchof the peroneal artery or muscular perforatingbranch of the posterior tibia1Posterior interosseous artery	6
		(Proximal or Distal) Ulnar		(Proximal or Distal) Ulnar		5.7
		(Proximal or Distal) Radial		(Proximal or Distal) Radial		8
		Digital		Digital		5.6
		Median		Median		5.3
Dympep et al	2021[47]	Radial	Nerve to long head of triceps	Anterior division of axillary	Posterior interosseous artery	N/A
Terzis and Kostopoulos	2009[48]	Ipsilateral C4, C5, C6, C7, lower roots, or lateral pectoral cord	Ulnar	Median, Musculocutaneous, nerve to triceps, axillary, thoracodorsal, suprascapular, lateral pectoral, or free muscles	Inferior collateral ulnar artery Superior ulnar collateral artery (pedicled)	17
		Contralateral C7		Median	Superior ulnar collateral artery	51
				Single motor targets (axillary, musculocutaneous, triceps)	Superior ulnar collateral artery	

(*continued on next page*)

Table 2 *(continued)*

Study Information		Nerve Grafting Information				
Authors	Year	Donor Nerve	Bridging Nerve Graft	Recipient Nerve	Nerve Graft Vascular Supply	(Average) Nerve Graft Length (cm)
Chuang and Hernon	2012[49]	Contralateral C7	Ulnar	Median	Dorsal metacarpal artery (pedicled)	N/A
		Contralateral C7	Ulnar	Median and musculocutaneous	N/A	N/A
		Contralateral C7	Ulnar	Median or median and musculocutaneous	N/A	N/A
Lin et al	2023[50]	Ipsilateral C5 or Contralateral C7	Ulnar	Median and/or Musculocutaneous	Ulnar artery	N/A

all the criteria mentioned in the title and abstract stage with the addition of at least one outcome measure following vascularized nerve grafting (eg, motor outcomes, sensory outcomes, electromyography reinnervation, or Tinel's sign progression) for clinical studies. In the title and abstract screening stage, after the exclusion of 219 duplicates, 339 studies were excluded because they were animal studies, review articles, communications, and comments articles, not discussing vascularized nerve grafting and finally solely describing vascularized nerve grafting in body parts other than the upper extremity. In the full-text review stage, 17 studies were excluded because of the unavailability of full text, which was verified by utilizing access from multiple institutions; these studies were either published prior to 1990 or in international journals. The 20 other studies that were excluded in the full-text review stage were reviews ($n = 1$), animal studies ($n = 1$), did not have outcome measures ($n = 5$), or included no mention of vascularized nerve grafting ($n = 13$). Descriptive statistics were computed for patient age, sex, denervation time, nerve grafting information, and outcomes; standard deviations were not computed for variables where we had pooled cohort data instead of data for individual patients. Details of the screening and extraction process are displayed in Figure 1.

Results

Overall, 535 patients received VNGs in 45 clinical studies. Patient sex was available for 240 patients; 82.9% were men. Age or cohort age average was available for 506 patients, with a mean of 28.5 years. Follow-up time was reported for 303 patients, with a mean of 24.9 months. Denervation time was available for 424 patients, averaging 8.5 months, ranging from immediate reconstruction to 5.8 years. Mechanism of injury was specified for 416 patients. The most common injury pattern by far was root avulsions and ruptures (88.7%), followed by laceration (4.8%), crush injury (1.7%), and other injury patterns (4.88%).

Specific data on graft recipient nerves were available for 472 procedures (Table 2). The most common recipients were median (57.6%), followed by axillary (12.5%), musculocutaneous (11.9%), digital (10.6%), and other nerves (7.4%). For 265 cases, the sites of proximal coaptation were identified; these included 22 cervical spinal roots, various brachial plexus cords and trunks, and 154 peripheral nerves.

Data on bridging VNGs were available for 525 procedures. The most common was ulnar (72.8%), followed by nerve to long head of triceps (8.8%), sural (8.2%), dorsal digital (3.0%), deep peroneal (2.7%), and other nerves (4.6%). Nerve graft length was available for 221 cases, with a mean length of 14.7 cm.

Motor outcomes were assessed in 486 patients with a high level of heterogeneity in grading motor outcomes. The Medical Research Council (MRC) grading was used for 364 patients. Pooled mean values were reported for 164 patients, and breakdown of muscle scores was unavailable. Of the remaining 206 patients, 69% had scores of M3 and above, indicating functional recovery. Data were available for 99 patients regarding the attainment of M4 strength (for 107 patients,[10,11] it was reported if strength levels were M3 or above, without detailing the exact score), and 36 (36.4%) gained M4 or above strength.

Sensory outcomes were assessed in 178 cases. The MRC sensory scale, 2-point discrimination, or Semmes-Weinstein (S-W) test results were available for 81 unique cases; 16 of these were reported in the form of pooled mean values. In 33 cases, MRC sensory score breakdown was available, and 72.7% had scores of S3 and above. Twenty-six cases had 2-point discrimination data available, and 92.3% had good and excellent 2-point discrimination per the

Table 3
Motor Outcomes[*]

Study Information		Injury Pattern	Recipient Nerve	Final Motor Outcomes	(Average) Follow-Up Time (Mo)
Authors	Year				
Fukui et al	1989[13]	Traumatic avulsion	Median	Poor recovery of palmar abduction of thumb.	24
Tang and Chen	1990[15]	Avulsion	Common digital nerve to fourth and fifth digits	Satisfactory flexion and extension.	N/A
Becker et al	1993[17]	N/A	Thoracodorsal	Four minimal functions of the transferred muscle; two minimal grip functions restored; two training the transferred muscle.	18
Burge and Shewring	1995[18]	Nerve root rupture and avulsion	Middle trunk brachial plexus	M4 power in deltoid, latissimus dorsi and pectoralis major, triceps and biceps, wrist flexors, grade 2	27
Gailliot and Core	1995[19]	Electrical burn injury	Ulnar	55 kg grip strength	4
Hattori and Doi	2006[20]	Laceration	Ulnar nerve	60° angle of extension of the wrist joint against the gravity and the full extension of metacarpophalangeal joints of fingers.	36
Macionis	2008[5]	Electrical burn injury	Median	Claw deformity and weak grip.	17
Muramatsu et al	2013[21]	Defect due to tumor resection	Ulnar	Power of interosseus muscle: M3, Wrist flexion-extension 120°, pronation-supination 170°, Grip strength 15 kg.	24
Yamamoto et al	2014[22]	Neurolysis following neuroma	Median	ROM of wrist, middle finger's MP joint, PIP joint, and distal interphalangeal DIP joint improved from 30/0, 45/0, 60/0, and 30/0° to 45/−45, 90/0, 100/0, and 75/0°, respectively.	5
Campodonico et al	2019[23]	Laceration	Median	M5	60
Kawamura et al	2022[25]	Neurolysis for neuroma	Median	3.5 kg of key-pinch strength (improved from 1.8 kg)	24
Riordan et al	2002[26]	Crush Injury	Median (Right Forearm); Median (Left Forearm)	Good return of both intrinsic and extrinsic function (Right Forearm); Good return of extrinsic and intrinsic function with reasonable thumb abduction (left forearm).	18
Usami et al	2019[7]	Crush Injury	Proper digital	Not applicable.	6
			Proper digital	Not applicable.	9
Taylor	1978[27]	Laceration	Median	Noticeable hypertrophy of the flexor pollicis brevis but no evidence of any muscle activity due to reinnervation.	24
		Electrical burn injury	Median/ulnar	Early protective sensation to the distal palm and proximal segments of the thumb, index, and middle fingers.	9
		Volkmann's ischemia	Median	At 3 mo, early contraction of brachioradialis was observed.	6
Reddy et al	1998[29]	Electrical burn injury	Median	Authors stated need for additional procedures to restore motor function.	6
			Median	Authors stated need for additional procedures to restore motor function.	6
			Median	Span and hook grasp, could bring glass to mouth.	6
Hattori et al	2005[30]	Laceration	Median	FDP and FPL Strength M4, 150° index, 140° in the middle, 120° in the ring, and 110° in the small finger.	24
		Avulsion	Radial	60° extension of the wrist joint against gravity and full extension of the metacarpophalangeal joints of the fingers.	36
		Avulsion	Median	M3 strength of FDP and FPL.	36
Xu	2005[31]	Avulsion	Musculocutaneous	M4 M3 M4 M0	28 <
Rose and Kowalski	1985[32]	Laceration	Radial digital	Key pinch, pulp pinch, and grip strength were 100% of normal.	41
		Avulsion	Ulnar and radial digital	Pinch strength between the thumb and long finger was 70%.	36
		Traction avulsion	Radial digital	Pinch strength was 30% of normal.	37
		Amputation	Radial digital nerve	Pinch strength was 21.6% of normal. Grip strength was 33.6% of normal.	13
		Crush	Radial	Pulp pinch was 50%. Grip strength was 75%.	12
Doi et al	1987[33]	Avulsion	axillary and radial nerves	Deltoid and triceps strength: M4, Extensor carpi radialis: M2.	20

(*continued on next page*)

Table 3 (*continued*)

Study Information		Injury Pattern	Recipient Nerve	Final Motor Outcomes	(Average) Follow-Up Time (Mo)
Authors	Year				
Okinaga and Nagano	1999[34]	Crush Injury Avulsion	Ulnar Musculocutaneous	Intrinsic muscle strength: M4. All patients gained M3 or above motor strength, 3/5 of patients gained M4 strength. *Nonvascularized control: All patients gained M3 strength, 4/6 gained M4 strength.*	19 44.2
Hierner et al	2007[36]	N/A	Musculocutaneous	5/6 (Elbow flexion > 90 1.5 kg at wrist)—Functional Result; Autonomization—3/6, 6/6 achieved M3 and above. *Nonvascularized grafting outcomes: 1/4 achieved M3 and above*	60
Doi et al	2003[51]	N/A	Suprascapular	Shoulder Flexion Angles: 28 ± 16°, Shoulder Abduction: 36 ± 15°, Shoulder Abduction: 64 ± 46°, Internal Rotation 63 ± 13, Rotational Arc 64 ± 46, Scapulothoracic Abdominal Arc 18 ± 9.0, 5/13 muscles neurotized by vascularized nerves in 3/6 patients achieved strength of M3. *Nonvascularized control outcomes: 2/10 patients with MRC scores reached M3 and above*	24 <
Bertelli et al	2009[38]	N/A	Musculocutaneous nerve	None of the patients recovered useful function mediated by the vascularized ulnar nerve. None scored higher than M2 for either elbow flexion or wrist extension.	26.7
Potter and Ferris	2017[39]	Ruptures and Avulsions	Musculocutaneous or common branch to biceps and brachialis	4/8 patients achieved M3 < elbow flexion, 3/8 patients achieved M4 *Functional free muscle transfer recipient comparison: all 13 patients achieved M3 and above*	45
Lin et al	2011[41]	Avulsion	Medial median and musculocutaneous	Biceps: M3 in 4 patients, M4 in 2 patients, M2 in 2 patients, No notable recovery in 2 patients/Wrist and Finger Flexors: M3 in 5 Patients, M2 in 2 Patients, No notable recovery in 3 Patients.	39.4
Chen et al	2023[42]	Ruptures, Avulsions, Amputation, or not specified	Median and/or musculocutaneous and/or radial	4 Patients had M3 or above elbow flexion, none of the patients had M3 or above finger flexion	15
Chuang et al	1993[43]	Avulsion	Musculocutaneous nerve or lateral cord	Pedicled vascularized ulnar nerve graft: 8/9 above M3, Free vascularized ulnar nerve graft: 4/6 above M3 *Nonvascularized nerve graft outcomes: 80/113 achieved M3<*	24
Oberlin	1989[45]	N/A	Median, musculocutaneous, radial, anterior, and/or posterior division of upper trunk, lateral cord, and suprascapular	In the 18 cases that biceps flexion restoration was attempted (recipient nerve being musculocutaneous, anterior or posterior division of upper trunk), 15 cases (83.3%) achieved M3 and higher strength.	24<
Doi et al	1992[46]	N/A	Axillary	100% M3 and above (60° shoulder abduction), 80% M4 and above. *Nonvascularized grafting outcomes: 100% M4 and above*	26
			(Proximal or Distal) Ulnar	80% M3 and above, 20% M4 *Nonvascularized nerve grafting outcomes: 0% M3 and above*	
			(Proximal or Distal) Radial	100% M3 and above, 75% M4 *Nonvascularized nerve grafting outcomes: 40% M3*	
			Median	50% M3 and above, 0% M4 *Nonvascularized nerve grafting outcomes: 0% M3 and above*	
Dympep et al	2021[47]	Avulsions and Ruptures	Anterior division of axillary	100% achieved M3<, Average of 10.4 mo to M4 recovery, average of 99.8° of shoulder abduction.	24.7
Terzis and Kostopoulos	2009[48]	Avulsions and ruptures	Median, musculocutaneous, nerve to triceps, axillary, thoracodorsal, suprascapular, lateral pectoral, or free muscles	Average strength of Biceps: M2.95, Deltoid: M2.9, Triceps: 2.7 Average strength of Biceps: M2.95, Deltoid: M2.5, Triceps: 1.6	69.6

Table 3 (*continued*)

Study Information		Injury Pattern	Recipient Nerve	Final Motor Outcomes	(Average) Follow-Up Time (Mo)
Authors	Year				
Chuang and Hernon	2012[49]	Avulsion	Median	30 of 55 patients achieved M3 or greater (success rate, 55%)	48<
		Avulsion	Median and musculocutaneous	82.6% achieved elbow flexion strength M3 or greater. 39% patients achieved M3 or greater finger flexion.	
		Avulsion	Median or median and musculocutaneous	74% achieved M3 or greater finger flexion.	
Lin et al	2023[50]	Avulsion and/or rupture	Median and/or Musculocutaneous	Mean elbow flexion: M3.0 Mean finger flexion: M1.8.	60<

DIP, distal interphalangeal; FDP, flexor digitorum profundus; FPL, flexor pollicis longus; MP, metacarpophalangeal; PIP, proximal interphalangeal.

[*] Nonvascularized nerve grafting outcomes in italics where applicable.

Mackinnon-Dellon scale. Individual case data on S-W test results were available for 18 patients; 11 (61.1%) had grades of 4 and above, indicating protective sensation. Another method of reporting sensory outcomes was reporting return of protective sensation, assessed in 132 patients, with solely 2 (1.5%) explicitly reporting not having protective sensation. For studies contrasting VNG and conventional grafting, outcomes of conventional grafting can be found in italics in Tables 3 and 4.

A subset of parameters was less consistently reported throughout the studies and can be found in Supplementary Table S1, available online on the Journal's website at https://www.jhsgo.org.

From 13 purely cadaveric studies, 15 unique potential dependable nerve grafts and vascular supplies that had not been previously used in upper extremity reconstruction (marked with an asterisk*) were proposed (Table 5).

Discussion

The present study offers a compilation of clinical applications of VNGs in the context of upper extremity reconstructions, providing details of patient populations, utilized grafts, and outcomes. To our knowledge, there has not been such compilation of clinical applications of vascularized nerve grafts in the form of a review. However, reviews of the literature on animal models of vascularized nerve grafting have been conducted.[66,67] Although one of the two systematic reviews on this topic states that no conclusive evidence can be drawn from the literature on the superiority of vascularized nerve grafts from animal studies,[66] the other concludes that VNGs result in superior outcomes compared with conventional grafts, but advises caution on extending this conclusion to human application and suggests conducting future studies in settings more closely mimicking human conditions.[67]

As for the studies fitting our inclusion criteria, the authors' consensus across nearly all investigations affirmed the superiority of vascularized nerve grafts. Pooled data from systematically reviewing studies on nonvascularized nerve autografts indicate that 71.8% of recipients reached S3 and above and 36.3% achieved M4. As for VNGs, 72.7% attained S3 and above, and 36.1% reached M4.[68] It is noteworthy that nerve gaps bridged by the mentioned nonvascularized autografts did not exceed 7 cm, and those bridged by VNGs ranged from 2 to 51 cm, with a mean length of 14.7 cm. Overall, published literature recommends VNGs in conditions where conventional nerve grafting proves difficult.[14,15,69] The particular indications discussed in studies include scarred and poorly vascularized beds,[16,17] larger nerve gaps,[14,18–22] scarcity of donor nerves in total paralysis,[23] preganglionic injuries, and avulsions (utilizing contralateral nerve roots).[10,24,25] Younger age,[14,26] smaller nerve gaps,[26,27] shorter denervation times,[26] and pedicled grafts[5,28,29] are associated with more favorable outcomes. Terzis et al[26] found denervation time vital for muscle restoration in both vascularized and standard nerve grafts, with later surgeries corresponding with reduced muscle strength. Patients younger than 20 years old had a high-quality muscle recovery rate of 72.7%, compared with 61.5% for those older than 20 years old. Additionally, cases with graft lengths of less than 5 cm showed significantly better motor and sensory recovery compared with graft lengths longer than 11 cm and between 6 and 10 cm. Chen et al[29] also showed the superiority of the pedicled nerve graft over the nonvascularized nerve grafts in reconstructing proper digital nerve defects of the thumb, with superior sensory recovery seen with vascularized grafts.

Most studies that contrasted vascularized and nonvascularized nerve grafting concluded that vascularized nerve grafting has superior outcomes (these studies included 88 cases of VNGs and 217 conventional nerve grafts), potentially due to improved nerve regeneration.[30,31] In a cohort study by Doi et al, although only 13.3% of conventional graft recipients achieved M3 and above recovery, 78.5% of VNG recipients gained this functional level of recovery. The rate of functional sensory recovery, indicated by a score of S3 and above, was 70.5% compared with 23.1% in the standard grafting group.[19] Chuang et al found that vascularized ulnar nerve grafts (VUNG) were an alternative to conventional nerve grafting after C8 and T1 root avulsion, as the vascularized grafts yielded 80% M3 and above strength, when compared with conventional nerve grafts that had a rate of 66%. Initially, Chuang et al stated that superior results were achieved with pedicled VNGs compared with free VNGs and attributed this difference to shorter surgical time and decreased ischemia period.[28] However, this group now argues that free VUNG is superior to pedicled VUNG because of more consistent perfusion of both ends of the ulnar nerve after anastomosis, more robust caliber of the donor vessel in ulnar artery compared with SUCA, and increased comfort in performing anastomosis reliably, given the advance of microsurgery techniques.[50]

Two studies reported unsatisfactory results, in which the authors proposed modifications to the technique of nerve grafting such as dividing the graft into multiple segments[32] or using multiple nerve grafts.[33] Two other studies by Okinaga and Nagano, as well as Tang and Chen, stated that utilization of VNGs does not offer clinical benefit over conventional grafts.[29,34] More specifically, these two studies indicated that in adequately vascularized beds and for nerve grafts with a diameter of less than 2 mm, VNGs did not offer any advantage over common clinical practice, potentially due to rapid revascularization and lower demand of blood supply of smaller grafts. A contradicting conclusion was drawn by Mackinnon et al[35] from a case of median nerve repair; in this study, the radial portion was neurotized using the radial sensory

Table 4
Sensory Outcomes[*]

Study Information		Injury Pattern	Recipient Nerve	Final Sensory Outcomes	(Average) Follow-Up Time (Mo)
Authors	Year				
Boorman and Sykes	1986[10]	Tumor resection	Ulnar digital	m2PD is 6 mm, compared with opposite (no intervention) thumb being 4 mm *Nonvascularized nerve grafting outcomes: absent 2-point discrimination*	9
Mackinnon et al	1988[11]	Avulsion	Radial	Improved sensibility in the thumb and index fingers than in the long and radial side of the ring finger, 2-point discrimination in the thumb and index finger. The m2PD and s2PD were 6/11 and 8/14 in the thumb and index respectively. *Non vascularized nerve grafting outcomes: no 2-point discrimination in the long or ring finger.*	24
Rivet et al	1988[12]	Pressurized oil injection	Radial collateral nerve of thumb	Protective sensation, Weber 2-point discrimination of 15 mm, m2PD of 8 mm	9
Fukui et al	1989[13]	Traumatic avulsion	Median	s2PD of the pulps of the thumb and index finger was 20 mm and of the pulp of the middle finger was 15 mm.	24
Krarup et al	1990[14]	Combined section-avulsion injury	Median	Partially recovered sensation to pin-prick and touch	53
Tang and Chen	1990[15]	Avulsion	Common digital nerve to fourth and fifth digits	2-point discrimination of 10 mm in fourth digit at 8 wk	N/A
Koshima et al	1991[16]	Crush Injury	Palmar digital	Nine months after operation, moving 2-point discrimination test was 13 mm and S-W test was 3.14 gm at the finger tip	12
Burge and Shewring	1995[18]	Nerve root rupture and avulsion	Middle trunk brachial plexus	Faint sensibility in the C5 and C6 dermatomes.	27
Gailliot and Core	1995[19]	Electrical burn injury	Ulnar	Return of protective sensation	4
Koshima et al	2003[52]	Defect due to tumor resection	Median	m2PD on the fingers controlled by the median nerve is 10 mm	30
Macionis	2008[5]	Electrical burn injury	Median	Patient could localize the palm, thumb, and index finger	17
Muramatsu et al	2013[21]	Defect due to tumor resection	Ulnar	S-W monofilament number: 3.61	24
Yamamoto et al	2014[22]	Neurolysis following neuroma	Median	Result of S-W improved from monofilament number 5.08 to 4.31 in median nerve innervated area	5
Campodonico et al	2019[23]	Laceration	Median	S3+	60
Foo et al	2019[24]	Neurolysis (Primary injury was laceration with neuroma after primary nerve repair)	Ulnar digital	S-W monofilament number improved from > 6.65 to 3.61 within 1 y of surgery	N/A
Kawamura et al	2022[25]	Neurolysis for neuroma	Median	Improved S-W and static 2-point discrimination from 5.12 and 15 mm to 3.61 and 6 mm, respectively, in the thumb	24
Riordan et al	2002[26]	Crush Injury	Median (Right Forearm); Median (Left Forearm)	Good protective sensation (Right Forearm); At a 2-y follow-up visit, there was excellent light touch and protective sensation in the median nerve distribution to all fingers except the index finger (Left Forearm).	18
Usami et al	2019[7]	Crush Injury	Proper digital	s2PD and m2PD 8 and 6 mm at final follow-up	6
			Proper digital	s2PD and m2PD 5 and 3 mm at final follow-up	9
Taylor	1978[27]	Laceration	Median	Contact sensation, pin-prick detection and light touch intact but no 2-point discrimination	24
		Volkmann's ischemia	Median	Patchy sensation in palmar distribution of median nerve	6
		Laceration	Digital nerves of fifth digit	Paresthesia on little finger tip, no 2-point discrimination	10
Reddy et al	1998[29]	Electrical burn injury	Median	Protective Sensation	6
			Median	8–10 mm 2-point discrimination	6
			Median	6–8 mm 2-point discrimination	6
Hattori et al	2005[30]	Laceration	Median	protective sensation	24
Rose and Kowalski	1985[32]	Laceration	Radial digital	s2PD was 5.5 mm 41 mo after operation.	41

Table 4 (*continued*)

Study Information		Injury Pattern	Recipient Nerve	Final Sensory Outcomes	(Average) Follow-Up Time (Mo)
Authors	Year				
		Avulsion	Ulnar and radial digital	s2PD of the long finger was 7 mm 36 mo after the operation.	36
		Traction avulsion	Radial digital	Heat, cold, pressure, vibratory, and touch localization were present	37
		Amputation	Radial digital nerve	s2PD of the long finger was 13 mm.	13
		Crush	Radial	s2PD was 6 mm	12
Doi et al	1987[33]	Avulsion	axillary and radial nerves	Paresthesia, S2	20
		Avulsion	Median	S2+	28
		Avusion	Median	S2+	25
		Crush Injury	Ulnar	S3–S4, 2-point discrimination 12–15 mm	19
		Crush Injury	Digital	S3–S4, 2-point discrimination 12–15 mm	31
Hasegawa et al	2004[35]	Amputation	Median	s2PD of 15 m, S-W monofilament number: 3.84	68
		Traumatic avulsion	Median	s2PD of 20 mm, S-W monofilament number: 4.56	29
		Amputation	Median	s2PD of 15 mm, S-W monofilament number: 4.56	64
		Amputation	Ulnar	s2PD of 10 mm, S-W monofilament number: 3.84	28
		Fracture	Median	s2PD of 11 mm, S-W monofilament number: 4.56	24
		Amputation	Median	s2PD of 25< mm, S-W monofilament number: 6.65	15
Hierner et al	2007[36]	N/A	Musculocutaneous	All patients were complaining of temporary paresthesia in the dorsal part of the thumb, index, and middle finger. There was complete sensory recovery at the 3-mo postoperative examination.	60
Del Pinal et al	2007[37]	Laceration	Radial digital	Pulp moving 2-point discrimination 5 mm, static 2 point discrimination 6 mm, S-W monofilament number: 2.83	120
		Dupuytren's contracture	Ulnar digital	Pulp m2PD 5 mm, s2PD 7 mm, S-W monofilament number: 3.61	60
		Laceration	Radial digital	Pulp m2PD4 mm, s2PD 6 mm, S-W monofilament number: 2.83	60
		Dupuytren's contracture	Ulnar digital	Pulp m2PD 7 mm, s2PD 10 mm, S-W monofilament number: 4.31	36
		Laceration	Ulnar digital	Pulp m2PD 5 mm, s2PD 7 mm, S-W monofilament number: 2.83	24
		Laceration	Ulnar digital	Pulp m2PD 7 mm, s2PD 9 mm, S-W monofilament number: 3.61	12
Rose et al	1989[40]	Laceration	Radial or Ulnar digital	Mean m2PD: 5.8 mm, Mean s2PD: 8.3 mm, Median S-W test: 2.83 *non vascularized nerve grafting outcomes: Average of 10.3 mm and 14.3 mm for moving and static 2-point discrimination.*	28.3
Lin et al	2011[41](p201)	Avulsion	Medial median and musculocutaneous	S3 in 7 Patients, No notable recovery in 3 Patients	39.4
Chen et al	2012[44]	Avulsion and Crush	Proper digital	Average scores of s2PD : 6.7 mm Average S-W test: 3.62, 7/16 reported mild cold intolerance	22
Doi et al	1992[46]	N/A	(Proximal or Distal) Ulnar	S2.75	
		N/A	(Proximal or Distal) Radial	S3	
		N/A	Digital	S3, mean S-W monofilament number: 3.35	
		N/A	Median	S3	
Terzis and Kostopoulos	2009[48]	Avulsions and Ruptures	Median	91.6% of patients with median nerve neurotization achieved protective sensation in the hand.	69.6
			Single motor targets (axillary, musculocutaneous, triceps)	91.6% of patients with median nerve neurotization achieved protective sensation in the hand.	
			Median	Almost all reconstructed patients (101 patients) achieved finger sensation with protective sensory recovery	

(*continued on next page*)

Table 4 (*continued*)

Study Information		Injury Pattern	Recipient Nerve	Final Sensory Outcomes	(Average) Follow-Up Time (Mo)
Authors	Year				
Chuang and Hernon	2012[49]	Avulsion	Median and musculocutaneous	Almost all reconstructed patients (101 patients) achieved finger sensation with protective sensory recovery	48<
		Avulsion	Median or median and musculocutaneous		
		Avulsion			

m2PD, moving 2-point discrimination; s2PD, static 2-point discrimination; S-W test, Semmes-Weinstein test.

* Nonvascularized nerve grafting outcomes in italics where applicable.

Table 5

Anatomical Studies: Suggested Vascularized Nerve Grafts and Their Respective Vascular Supplies

Year of Study	Suggested Nerve Graft	Arterial Supply
1983[53]	Ulnar	Mostly from proximal ulnar collateral, in some cases from distal ulnar collateral
1986[54]	Ulnar (axillary section)*	Lateral thoracic or branch from axillary
	Ulnar (medial intermuscular section)	Superior ulnar collateral
	Ulnar (supracondylar section)	Posterior branch of recurrent ulnar or inferior ulnar collateral
	Ulnar (Forearm section)	Ulnar
1992[55]	Palmar digital*	Palmar digital
1998[56]	Ulnar	Superior Ulnar Collateral
	Superficial branch of Radial	Direct branches from radial
	Saphenous*	Saphenous
	Deep Peroneal	Anterior tibial
1999[57]	Long thoracic*	Thoracodorsal
2003[58]	Terminal cutaneous portion of saphenous*	Descending genicular
	Vastus lateralis branch of femoral*	Lateral circumflex femoral
	Deep peroneal distal to the extensor hallucis longus branch	Anterior tibial
	Posterior femoral cutaneous*	Branch of inferior gluteal
	Tibial*	Posterior tibial and peroneal
	Lateral plantar*	Lateral plantar
	Medial plantar*	Medial plantar
2006[59]	Ulnar (in upper arm and forearm)	Superior ulnar collateral
	Median (in upper arm and forearm)	Direct branches of brachial/branches to brachialis
	Anterior interosseous distal to flexor pollicis longus*	Anterior interosseous
	Upper lateral brachial*	Dedicated cutaneous vessels
	Lower lateral brachial*	Dedicated cutaneous vessels
	Superficial radial	Direct branches from radial
	Terminal branch of posterior interosseous	Branches of anterior interosseous perforating through interosseous membrane
2010[60]	Superficial radial	Direct branches from radial
2013[61]	Sural	Superficial Sural
2015[62]	Vastus lateralis branch of femoral	Descending branch of lateral circumflex femoral
	Femoral cutaneous	
2021[63]	Lateral antebrachial cutaneous	Radial perforators
	Medial antebrachial cutaneous*	Ulnar perforators or brachial perforators
2022[64]	Posterior interosseous	Dorsal branch of the anterior interosseous artery or fourth extensor compartment artery
2023[65]	Sural communicating*	Branch from lateral sural or peroneal

* Asterisks indicate nerve grafts that have not yet been clinically used.

nerve and ulnar portion by a conventional sural nerve graft, resulting in only the radial side recovering 2-point discrimination, which was supportive of using VNGs even for satisfactory beds and small caliber graft.

Anatomical studies suggest numerous nerve choices that demonstrate the potential for reliable vascular supply.[53–65] The decision on the reliability of a nerve's vascular supply can be made using the Taylor classification, which divides nerves into five categories with type A being the most favorable and type E being the least favorable,[2,58,59] definitions and examples are provided in Table 6. Although type A is the ideal nerve graft, types B and C have also been indicated as suitable donor nerves.

Aside from more popular nerve grafts (ulnar and sural nerves), the body of literature on the clinical application of VNGs remains almost entirely in the format of case reports and series.[15,58,59] Finally, a practical section detailing the harvest of the two most frequently utilized VNGs alongside intraoperative photographs is included in Supplementary Table S2 and Figure S1, available online on the Journal's website at https://www.jhsgo.org, respectively.

One of the strengths of our study is its inclusivity, as we did not exclude any research based on its publication year or language, ensuring a thorough overview of existing literature. Additionally, we considered potential nerve grafts highlighted in cadaveric studies. Aggregate analysis of outcomes was limited by heterogeneous methods of reporting levels of motor and sensory function. In the future, supplementary outcomes research and clinical trials comparing VNGs and conventional nerve grafts, coupled with additional animal and basic science research can further establish the role and applications for vascularized ulnar nerve grafting in the nerve-injured patient.

Table 6
Anatomical Studies: Taylor Classification and Examples

Category	Nerve and Vascular Supply Structure	Examples*
A	A long unbranched nerve that receives a segmental blood supply from a single parallel arteriovenous system.	**Upper extremity:** Median (upper arm), ulnar (forearm), superficial radial (forearm), anterior interosseous, posterior interosseous (terminal portion) **Lower Extremity:** Anterior tibial (distal leg), posterior tibial (distal leg), peroneal
B	Similar to A, but the nerve branches early	**Upper extremity:** Radial and profunda brachii, intercostal **Lower extremity:** Superior gluteal, inferior gluteal, anterior tibial (proximal leg), posterior tibial (proximal leg)
C	A long unbranched nerve supplied by a single large nutrient vessel	**Upper extremity:** Median nerve (forearm, with well-developed median artery segmentally supplying the nerve), distal ulnar, radial (descending to elbow) **Lower extremity:** Sciatic (when supplied by arteria comitantes)
D	A long unbranched nerve receiving supplying branches from different parent vessels of varying diameters	**Upper extremity:** Medial antebrachial cutaneous **Lower extremity:** Sciatic (thigh), sural
E	A branching nerve with a fragmented blood supply.	**Upper extremity:** Musculocutaneous, median (cubital region and proximal forearm), radial (around elbow), ulnar (around elbow and hand), posterior antebrachial cutaneous (except distal region) **Lower extremity:** Cutaneous nerves of thigh, saphenous (calf)

* Certain nerves have varying classification throughout their course, noted in parentheses.

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