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GENERAL REVIEW • UPPER LIMB - LOWER LIMB

Current concepts in peripheral nerve surgery

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Abstract
The injuries of the peripheral nerves are relatively frequent. Some of them may lead to defects which cannot be repaired with direct end-to-end repair without tension. These injuries may cause function loss to the patient, and they consist a challenge for the treating microsurgeon. Autologous nerve grafts remain the gold standard for bridging the peripheral nerve defects. Nevertheless, there are selected cases where alternative types of nerve reconstruction can be performed in order to cover the peripheral nerve defects. In all these types of reconstruction, the basic principles of microsurgery are necessary and the surgeon should be aware of them in order to achieve a successful reconstruction. The purpose of the present review was to present the most current data concerning the surgical options available for bridging such defects.

Keywords Peripheral nerve defect · Nerve autograft · Nerve conduit · Nerve allograft · Nerve transfer · End-to-side neurorrhaphy

Introduction

Peripheral nerve injuries are common in all forms of extremity trauma, including lacerations, fractures, dislocations, ligamentous tears, and crush or amputation injuries. Some common causes resulting in peripheral nerve trauma are falls and collisions, motor vehicle accidents, penetrating war trauma, and industrial accidents [1]. Even in simple injuries such as ankle sprains and hamstrings injury, there may be peripheral nerve lesion [2, 3]. Ferara was the first one who performed reconstruction of a transected nerve in the first years of the 17th century. The use of operative microscope in nerve surgery in 1964 by Curtze and the evolution of microsurgery signal the birth of modern peripheral nerve surgery [4].

After a peripheral nerve injury, there may be tissue loss, and the continuity of the nerve between its two ends must be bridged without tension in order to encourage nerve regeneration and restore possible sensory and/or motor deficits [5–7]. There are several factors which affect the result after the repair of a peripheral nerve deficit. The perfect microsurgical technique as well as the young age of the patient advocates for better result. The level of the lesion plays also a significant role since the differentiation of the nerves in pure motor or sensory is made distally. Other factors include possible associate diseases, the mechanism of the injury, the extent of the damage of the surrounding tissues, and the length of the deficit since the shorter gaps have more possibilities for successful results [8].

The purpose of this review paper is to present the most updated data concerning several techniques focusing on the repair of peripheral nerve deficits.

Demographics

The vast majority of peripheral nerve injuries are due to traumatic etiology. It is estimated that approximately 5% of all trauma patients suffer from peripheral nerve or brachial plexus injury [9]. More explicitly, 350,000 nerve injuries per year take place in the USA [10]. In a large case series published by Kouyourmdjian [11], the vast majority of the patients were male under the age of 40. Moreover, the upper limb was affected in more than 70% of the cases, and more than 80% of the injuries were affecting only one nerve. The radial nerve is the most common nerve of the upper limb which is affected. The second one is the ulnar

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nerve followed by the median nerve. As far as the nerves of the lower limb are concerned, the most injured nerve is the sciatic followed by the peroneal nerve [12].

Classification

The two most popular nerve injury classifications are those of Seddon [13] and Sunderland [14]. According to Seddon [13], the nerve injury can be classified into three grades of severity. The first grade is neurapraxia which is the mildest injury to a nerve, caused by transient compression or stretch. The loss of nerve function results from a conduction block where the nerve anatomy is intact. The prognosis of neurapraxia is excellent with almost full recovery. The second stage is the axonotmesis where the nerve axons are divided. The prognosis is very good because the intact endoneurial sheath permits perfect guidance foe the regeneration of the neuraxons. The third stage of Seddon classification is the neurotmesis. In this situation, the nerve is completely divided and surgical intervention is needed in order to provide the highest possibility for the regeneration of the nerve and the return of the limb function (Table 1).

In the Sunderland classification system, there are five stages of nerve injury [14]. This classification is based on increasing anatomical disruption of the nerve trunk and distinguishes injuries where the nerve trunk is in continuity, but there is damage to the epineurium or the perineurium or the endoneurium of the nerve. The first stage of Sunderland classification equals to neurapraxia, whereas the second one to axonotmesis. In grade 3 injuries, there is disruption of the endoneurium. In grade 4, injuries perineurial disruption is present, and as a result, there is structural damage of the nerve fascicles, whereas in stage 5, there is epineurial disruption, and the nerve may be severed [15]. In 1988, Mackinnon and Dellon [16] proposed a sixth grade of this classification with nerve injuries in continuity with a mixed degree of nerve damage that necessitates specialized microsurgical techniques (Table 2).

Table 1 Seddon classification

Grade	Name	Prognosis
1	Neurapraxia	Excellent
2	Axonotmesis	Very good
3	Neurotmesis	Microsurgical intervention needed

Table 2 Sunderland classification

Type	Name
1	Conduction block (neurapraxia)
2	Axonal injury (axonotmesis)
3	Type 2 + Disruption of the endoneurium
4	Type 3 + injury of the perineurium
5	Type 4 + injury of the epineurium (neurotmesis)
6	Nerve injury in continuity

Methods of nerve suturing (Table 3)

Several techniques focusing on peripheral nerve suturing have been described over the years. In general, sutures should be as few as possible, but as many as necessary to ensure a persistently correct orientation [17]. The quality of suture material is of high importance due to the fact that poor quality of suture threads generates greater foreign body reaction. In addition, the use of magnifying loops and/or surgical microscope is mandatory. The three most frequent microsuturing techniques of the peripheral nerves are the epineurial, the fascicular, and the epi-perineurial suturing [18].

Epineurial suturing

It is an end-to-end suturing of the peripheral nerves, where the epineurial blood vessels are used as guidance for the fascicular alignment. In both ends, the sutures pass through the epineurium (Fig. 1). The advantages of this technique are the minimal surgical intervention through the fascicles of the nerve; it is easier than the fascicular nerve repair, and fewer suture threads are used [19, 20]. On the other hand, misdirection of the regenerating nerve fibers may be noted [18].

Fascicular suturing

The fascicular method of suturing of the peripheral nerves was first introduced by Sunderland [21] and Hakstian [22]. The idea is the suturing of two relative fascicles in order to minimize the possibility of misdirection (Fig. 2). It consists a more demanding technique compared to the epineurial suturing with longer operating time and greater tissue reaction at the suture site [18]. An alternative of this technique is the group fascicular suturing which may facilitate the repair in nerves with many fascicles (e.g., the median nerve) minimizing the degree of fibrosis.

Epi-perineurial suturing

In rare cases, the epi-perineurial nerve suturing technique may be used. This technique consists of a combined

Table 3 Nerve suture and nerve-bridging techniques

Nerve suturing			Nerve-bridging techniques		
	Advantages	Disadvantages		Advantages	Disadvantages
Epineurial	Easy Minimal surgical intervention Fewer suture threads	Misdirection of the regenerating fibers	Nerve autografts (Golden standard)	Nonimmunogenic scaffold	Danger for neuroma formation Donor site morbidity
Fascicular	Better orientation of the regenerating neuraxons	Demanding Longer operation time Greater tissue reaction	Nerve conduits	No donor site morbidity Readily available	Small gaps (≤ 3 cm) Lack of laminin scaffold and Schwann cells
Epi-perineurial	Better orientation than epineurial	More demanding	Nerve allografts	No donor site morbidity Readily available	Side effects of immunosuppresion
			Nerve transfers	No donor site morbidity Earlier reinnervation	Loose function Donor may no be acceptable
			End-to-side neurorrhaphy	Good results in sensory nerves	Unsuccessful in recovering motor deficits without donor axonal injury

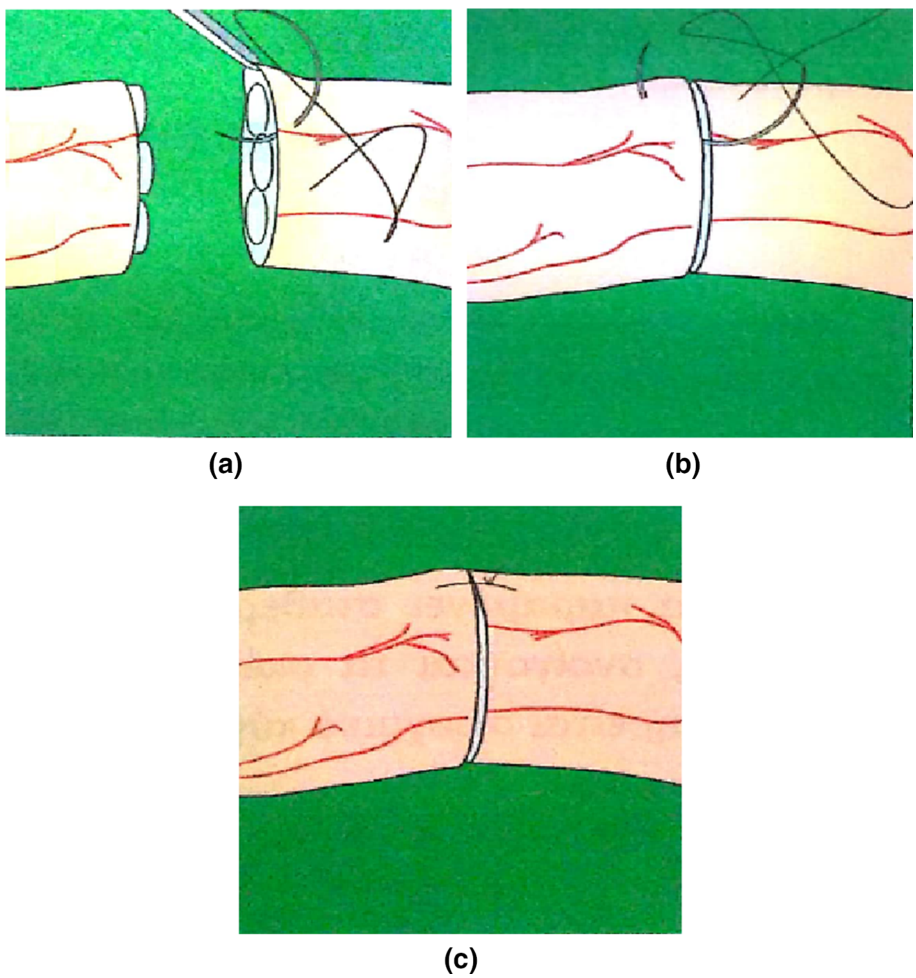

Fig. 1 Epineurial nerve suturing. The stumps of the nerve are coapted taking into consideration the alignment of the epineurial nutrient vessels. **a** Passing the needle from the epineurium of the proximal stump 1–2 mm from the edge; **b** passing the needle from the opposite nerve stump; **c** making the knot

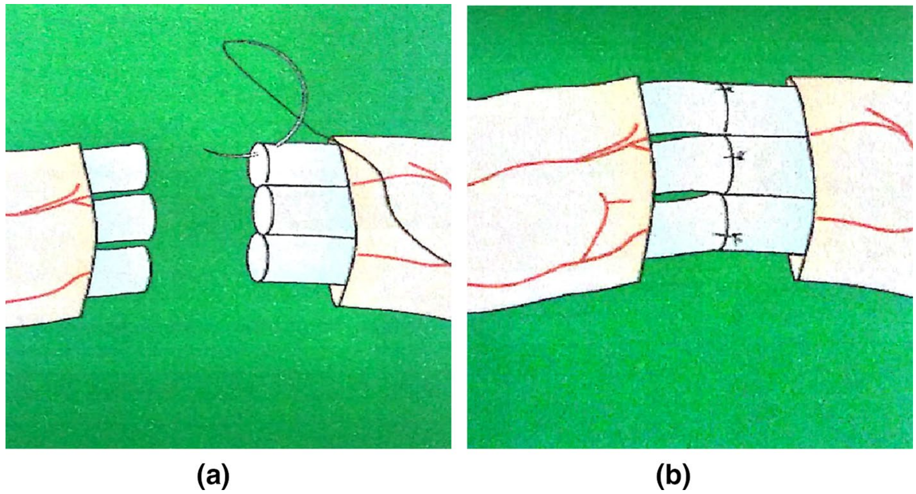

Fig. 2 Fascicular nerve suturing. **a** Passing the suture from the fascicles; **b** fascicles have been sutured

Fig. 3 Cable graft in a patient with peroneal nerve defect. The autograft is divided, and the three grafts are placed flat in order to facilitate revascularization of the nerve

technique where the needle passes through the epineurium and the perineurium of nearby group of fascicles at the same time. This technique allows better joining of the fascicular groups [23] providing better guidance after the nerve repair.

Management of peripheral nerve gaps (Table 3)

Nerve autografts

One of the major principles in peripheral nerve suturing is the absence of tension [24]. Nerve autografts remain the gold standard in bridging peripheral nerve defects, and they also offer guidance for the regeneration of the neuraxons. The nerve autografts can be characterized as trunk grafts, which have limited success due to central fibrosis [25], cable grafts (Fig. 3), and interfascicular grafts [26, 27] which permit better graft vascularization. There have also been described vascularized nerve grafts [28] where a whole nerve is used (e.g., the ulnar nerve) along with the supplying artery, but the complexity and the level of difficulty of the procedure did not seem to offer better results than the avascular grafts. Their indications are limited in rare cases of avascular bed.

The most common nerve autograft is the sural nerve which can be harvested in 30–40 cm of length from the lateral malleolus till the lower part of the knee [29] (Fig. 4). Other nerve autografts are the cutaneous antebrachii medialis nerve, the cutaneous femoris lateralis nerve, the cutaneous antebrachii dorsalis nerve, the superficial branch of the radial nerve, and the intercostal nerves and the saphenous nerve.

The nerve autografts consist of a nonimmunogenic scaffold which provides the nerve regeneration with Schwann cells and intact endoneurial tubes. On the other hand, there is the danger of neuroma formation, the morbidity of the skin incision, the sensory loss at the donor area, and the limited supply of the graft. In general, the result of nerve reconstruction with the use of nerve autograft is inferior to primary repair without tension [30], but it is the gold standard for bridging peripheral nerve defects.

Nerve conduits

The need for minimizing the complications of harvesting a nerve autograft such as the risk of neuroma formation and the skin scar and lack of sensation resulted in the use of conduits for bridging nerve gaps without the interference of a nerve graft. The desirable properties of nerve guidance conduits are permeability (nutrients and oxygen should be able to diffuse into the site of regeneration) and flexibility (for the avoidance of mechanical injury) in cases of rigid conduits. The rate of degradation is also of high importance because high rates may lead to swelling and inflammation whereas low rates can cause chronic immune rejection [31]. The use of nerve conduits is limited in defects of up to 3 cm [30].

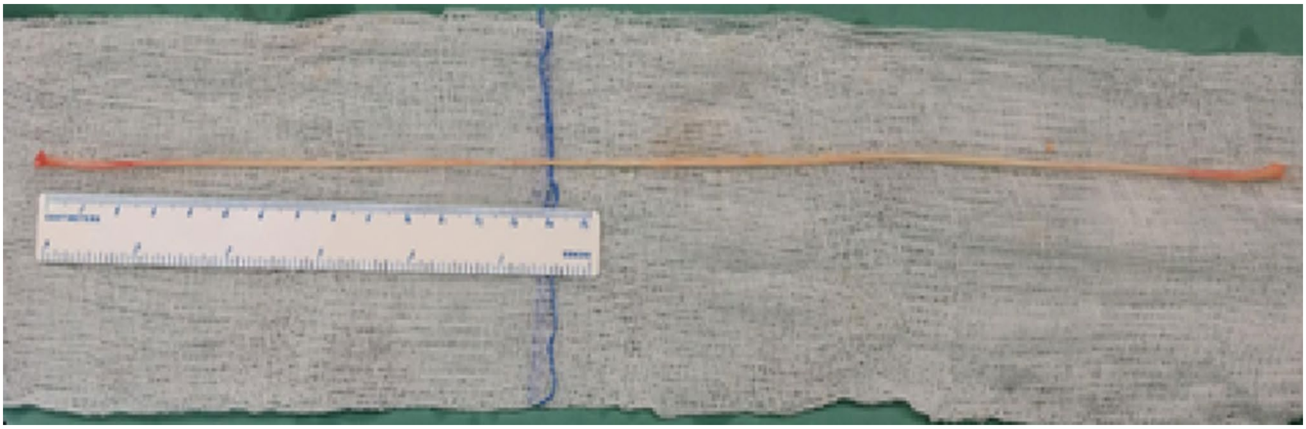

Fig. 4 Sural nerve autograft which was used as cable graft for a bridging a peripheral nerve defect

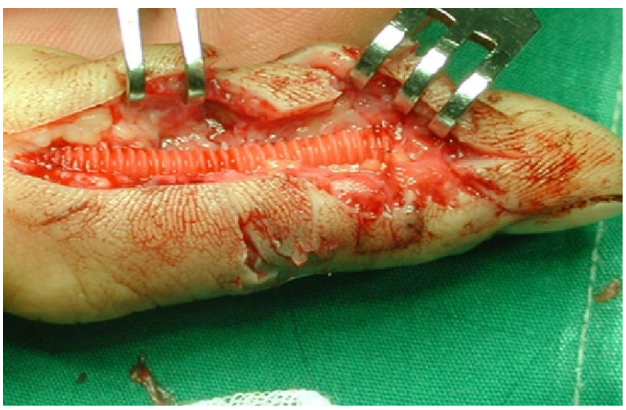

Fig. 5 Intraoperative image of a degretable nerve conduit for digit nerve repair

There are biological autologous nerve conduits and synthetic nerve conduits which are divided into the nondegradable and degradable ones. The biological nerve conduits are usually autologous arteries, veins, and muscles. They can also be isotype variants, heterogenous collagen tubes, muscle basal lamina, and human amniotic membrane [32, 33]. These materials have the advantage that they can degrade in innocuous products after the regeneration of the nerve. The synthetic nondegradable nerve conduits are made from silicone, plastic, and polytetrafuoroethylene. The degradable nerve conduits (Fig. 5) are mostly manufactured by collagen [34], chitin [35], polyglycolic acid conduit, glycolide trimethylene carbonate conduit, polylactic acid conduit [36], polycarbolacton, poly(lactide-co-glycolide), natural collagen, and hydrogel.

The use of nerve conduits offers several advantages. First of all, they allow the bridging of nerve defects without donor site morbidity. They are also readily available, and they can act as a barrier to scar tissue. On the other hand, the disadvantages include their limited use in gaps less than 3 cm, the lack of laminin scaffold as well as Schwann cells, and the variability of the results after their use [30].

Nerve allografts

Nerve allograft consists of an alternative in the management of peripheral nerve defects. Their structure is very similar to a peripheral nerve providing good adhesion and support to the regenerating axons [37]. The nerve allografts can be used in cases of devastating or segmental injuries of the peripheral nerve, and they are able to provide viable donor Schwann cells. They can cover a nerve gap up to 7 cm of length, and due to the neurotropic effect they provide, it seems to be more efficient than empty conduits [38]. Despite the fact that they provide a readily available graft without donor site morbidity, the side effects of immunosuppression should seriously be taken into consideration. Nevertheless, in the last years, nonimmunogenic nerve allografts have been used with promising results [39].

Nerve transfers

The concept of nerve transfer, or neurotization, aims to alter a proximal injury to a distal one by transferring "nearby" nerve function to a distal denervated nerve close to the target [30]. Several authors have reported promising results after nerve transfers [40, 41] despite the fact that there is no clearly established evidence for their use. The past few decades have seen a shift from nerve repair or grafting in proximal injuries toward nerve transfer [17]. With the use of nerve transfers, the use of nerve autograft is avoided and as a result the associated morbidity of the donor area. There is also the advantage of earlier reinnervation. On the other hand, the function from the donor nerve site is lost, and the donor muscle may not serve as an acceptable donor for muscle transfer [30].

End-to-side neurorrhaphy

Since 1873, Letievant [42] expressed the idea that in cases of large substance loss, the surgeon could try to suture the distal stump of the severed nerve on a healthy nerve after freshening the surface of one of its sides. Lundborg et al. [43] supported that end-to-side neurorrhaphy is an important therapeutic tool that perhaps can be used in very specific situations in which routine surgical methods do not offer a solution. The regeneration of the nerve after this kind of repair is controversial. The three main hypotheses are the collateral sprouting, the terminal sprouting, and the axonal contamination from the proximal stump of the transected nerve [44]. Current evidence is that with end-to-side neurorrhaphy, the sensory sprouting is generally easier than motor sprouting [45] resulting in better results for the sensory nerves after the application of this technique. “Double” end-to-side neurorrhaphy was introduced by Viterbo et al. [46]. According to this technique, both ends of the recipient nerve (proximal and distal stump) are sutured with end-to-side neurorrhaphy to the trunk of the donor nerve. Despite the extensive experimental investigation [47, 48] suggesting that reinnervation of the distal stump of a transected nerve may occur, the clinical results are still debated [49].

Authors' commentary

In our clinical practice, our first goal after a peripheral nerve injury is the primary reconstruction with end-to-end epineurial suturing of the nerve without tension. For large peripheral nerve defects, we prefer the autologous nerve graft (usually the sural nerve) and use it as a cable graft, depending on the size of the recipient nerve. We prefer the cables to be in a row so as to provide better revascularization of the graft. For smaller defects (less than 3 cm) in peripheral nerves (e.g., the median nerve) initially we used to bridge the defect using nerve autografts. Currently, for these defects especially in the digital nerves, we are using degradable nerve conduits. Concerning the nerve suturing technique, we mostly practice epineurial nerve suturing because, based on our experience, it provides best results with minimum operation time, and additionally, it is the less interventional method.

Conclusion

The management of peripheral nerve defects is a great challenge. There is a variety of techniques offered for their treatment, which are indicated in different situations. The decision of the appropriate technique may be difficult, and it needs to be taken by an experienced microsurgeon. Despite this variety of options, the research still goes on in order to provide further guidance for more promising results and newer methods in the management of nerve injuries [50].

Compliance with ethical standards

Conflict of interest All authors declare that they have no conflict of interest.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Declaration of Helsinki and its later amendments or comparable ethical standards.

Informed consent Informed consent was obtained from all individual participants included in the study.

References

1. Hill C, Riaz M, Mozzam A, Brennen MD (1998) A regional audit of hand and wrist injuries. A study of 4873 injuries. J Hand Surg 23(2):196–200. https://doi.org/10.1016/S0266-7681(98)80174-5
2. Mitsiokapa E, Mavrogenis AF, Drakopoulos D, Mauffrey C, Scarlat M (2017) Peroneal nerve palsy after ankle sprain: an update. Eur J Orthop Surg Traumatol Orthop Traumatol 27(1):53–60. https://doi.org/10.1007/s00590-016-1845-0
3. Macdonald J, McMahon SE, O'Longain D, Acton JD (2018) Delayed sciatic nerve compression following hamstring injury. Eur J Orthop Surg Traumatol Orthop Traumatol 28(2):305–308. https://doi.org/10.1007/s00590-017-2029-2
4. Rasulic L (2017) Current concept in adult peripheral nerve and brachial plexus surgery. J Brachial Plexus Peripher Nerv Injury 12(1):e7–e14. https://doi.org/10.1055/s-0037-1606841
5. Millesi H (1981) Interfascicular nerve grafting. Orthop Clin N Am 12(2):287–301
6. Campbell WW (2008) Evaluation and management of peripheral nerve injury. Clin Neurophysiol: Off J Int Fed Clin Neurophysiol 119(9):1951–1965. https://doi.org/10.1016/j.clinph.2008.03.018
7. Roganovic Z, Petkovic S (2004) Missile severances of the radial nerve. Results of 131 repairs. Acta Neurochir 146(11):1185–1192. https://doi.org/10.1007/s00701-004-0361-x
8. Lundborg G, Dahlin L, Danielsen N, Zhao Q (1994) Trophism, tropism, and specificity in nerve regeneration. J Reconstr Microsurg 10(5):345–354. https://doi.org/10.1055/s-2007-1006604
9. Siemionow M, Brzezicki G (2009) Chapter 8: current techniques and concepts in peripheral nerve repair. Int Rev Neurobiol 87:141–172. https://doi.org/10.1016/s0074-7742(09)87008-6
10. Fowler JR, Lavasani M, Huard J, Goitz RJ (2015) Biologic strategies to improve nerve regeneration after peripheral nerve repair. J Reconstr Microsurg 31(4):243–248. https://doi.org/10.1055/s-0034-1394091
11. Kouyoumdjian JA (2006) Peripheral nerve injuries: a retrospective survey of 456 cases. Muscle Nerv 34(6):785–788. https://doi.org/10.1002/mus.20624
12. Noble J, Munro CA, Prasad VS, Midha R (1998) Analysis of upper and lower extremity peripheral nerve injuries in a population of patients with multiple injuries. J Trauma 45(1):116–122

13. Seddon HJ (1942) A classification of nerve injuries. BMJ 2(4260):237–239
14. Sunderland S (1951) A classification of peripheral nerve injuries producing loss of function. Brain: A J Neurol 74(4):491–516. https://doi.org/10.1093/brain/74.4.491
15. Ferrante MA (2018) The assessment and management of peripheral nerve trauma. Curr Treat Options Neurol 20(7):25. https://doi.org/10.1007/s11940-018-0507-4
16. Mackinnon S, Dellon A (1988) Classification of nerve injuries as the basis of treatment. Surgery of the peripheral nerve. New York: Thieme: pp 35–63
17. Panagopoulos GN, Megaloikonomos PD, Mavrogenis AF (2017) The present and future for peripheral nerve regeneration. Orthopedics 40(1):e141–e156. https://doi.org/10.3928/01477447-20161019-01
18. Hirasawa Y (1996) Peripheral nerve suture. J Orthop Sci 1(3):214–229. https://doi.org/10.1007/BF02349820
19. Kline DG, Hudson AR, Bratton BR (1981) Experimental study of fascicular nerve repair with and without epineurial closure. J Neurosurg 54(4):513–520
20. Snyder C (1981) Epineurial repair. Orthop Clin N Am 12(2):267
21. Sunderland S (1968) Nerves and nerve in juries. E& S Livingstone Ltd, Edinburgh
22. Hakstian RW (1968) Funicular orientation by direct stimulation. An aid to peripheral nerve repair. J Bone Joint Surg Am Vol 50(6):1178–1186
23. Leung P-C, Gu Y, Ikuta Y (1995) Microsurgery in orthopaedic practice. World Scientific
24. Millesi H, Meissl G, Berger A (1972) The interfascicular nerve-grafting of the median and ulnar nerves. J Bone Joint Surg Am Vol 54(4):727–750
25. Jebson PJ, Kasdan ML (2006) Hand secrets. Elsevier Health Sciences, Amsterdam
26. Seddon H (1972) Surgical disorders of the peripheral nerves. Churchill Livingstone, Edinburgh
27. Millesi H (2000) Techniques for nerve grafting. Hand Clin 16(1):73–91
28. Taylor GI, Ham FJ (1976) The free vascularized nerve graft: a further experimental and clinical application of mecrovascular techniques. Plast Reconstr Surg 57(4):413–426
29. Slutsky DJ (2005) A practical approach to nerve grafting in the upper extremity. Atlas Hand Clin 10:73–92. https://doi.org/10.1016/j.ahc.2004.09.005
30. Ray WZ, Mackinnon SE (2010) Management of nerve gaps: autografts, allografts, nerve transfers, and end-to-side neurorrhaphy. Exp Neurol 223(1):77–85. https://doi.org/10.1016/j.expneurol.2009.03.031
31. Muheremu A, Ao Q (2015) Past, present, and future of nerve conduits in the treatment of peripheral nerve injury. Biomed Res Int 2015:237507. https://doi.org/10.1155/2015/237507
32. Geuna S, Tos P, Titolo P, Ciclamini D, Beningo T, Battiston B (2014) Update on nerve repair by biological tubulization. J Brachial Plexus Peripher Nerv Inj 9(1):3. https://doi.org/10.1186/1749-7221-9-3
33. Davis GE, Engvall E, Varon S, Manthorpe M (1987) Human amnion membrane as a substratum for cultured peripheral and central nervous system neurons. Dev Brain Res 33(1):1–10. https://doi.org/10.1016/0165-3806(87)90170-2
34. Kokkalis ZT, Mavrogenis AF, Ballas EG, Papagelopoulos PJ, Soucacos PN (2015) Collagen nerve wrap for median nerve scarring. Orthopedics 38(2):117–121. https://doi.org/10.3928/01477447-20150204-04
35. Ramburrun P, Kumar P, Choonara YE, Bijukumar D, du Toit LC, Pillay V (2014) A review of bioactive release from nerve conduits as a neurotherapeutic strategy for neuronal growth in peripheral nerve injury. BioMed Res Int. https://doi.org/10.1155/2014/132350
36. Xie F, Li QF, Gu B, Liu K, Shen GX (2008) In vitro and in vivo evaluation of a biodegradable chitosan-PLA composite peripheral nerve guide conduit material. Microsurgery 28(6):471–479. https://doi.org/10.1002/micr.20514
37. Battiston B, Titolo P, Ciclamini D, Panero B (2017) Peripheral nerve defects: overviews of practice in Europe. Hand Clin 33(3):545–550. https://doi.org/10.1016/j.hcl.2017.04.005
38. Means KR Jr, Rinker BD, Higgins JP, Payne SH Jr, Merrell GA, Wilgis ES (2016) A multicenter, prospective, randomized, pilot study of outcomes for digital nerve repair in the hand using hollow conduit compared with processed allograft nerve. Hand 11(2):144–151. https://doi.org/10.1177/1558944715627233
39. Zhu S, Liu J, Zheng C, Gu L, Zhu Q, Xiang J, He B, Zhou X, Liu X (2017) Analysis of human acellular nerve allograft reconstruction of 64 injured nerves in the hand and upper extremity: a 3 year follow-up study. J Tissue Eng Regen Med 11(8):2314–2322. https://doi.org/10.1002/term.2130
40. Zyaei A, Saied A (2010) Functional outcome of ulnar nerve fascicle transfer for restoration of elbow flexion in upper brachial plexus injury. Eur J Orthop Surg Traumatol 20(4):293–297. https://doi.org/10.1007/s00590-009-0558-z
41. Samardzic M, Grujicic D, Rasulic L, Bacetic D (2002) Transfer of the medial pectoral nerve: myth or reality? Neurosurgery 50(6):1277–1282. https://doi.org/10.1097/00006123-200206000-00019
42. Letievant E (1873) Traité des sections nerveuses. JB Baillière et fils, Paris
43. Lundborg G, Zhao Q, Kanje M, Danielsen N, Kerns J (1994) Can sensory and motor collateral sprouting be induced from intact peripheral nerve by end-to-side anastomosis? J Hand Surg 19(3):277–282. https://doi.org/10.1016/0266-7681(94)90069-8
44. Beris AE, Lykissas MG (2009) Chapter 13: experimental results in end-to-side neurorrhaphy. Int Rev Neurobiol 87:269–279. https://doi.org/10.1016/s0074-7742(09)87013-x
45. Beris A, Lykissas M, Korompilias A, Mitsionis G (2007) End-to-side nerve repair in peripheral nerve injury. J Neurotrauma 24(5):909–916. https://doi.org/10.1089/neu.2006.0165
46. Viterbo F, Trindade JC, Hoshino K, Mazzoni A (1994) Two end-to-side neurorrhaphies and nerve graft with removal of the epineural sheath: experimental study in rats. Br J Plast Surg 47(2):75–80. https://doi.org/10.1016/0007-1226(94)90162-7
47. Lykissas MG, Korompilias AV, Batistatou AK, Mitsionis GI, Beris AE (2007) Can end to side neurorrhaphy bridge large defects? An experimental study in rats. Muscle Nerv 36(5):664–671. https://doi.org/10.1002/mus.20861
48. Hosseinian MA, Gharibi Loron A, Nemati B, Khandaghy M (2015) Comparison of a distal end-to-side neurorrhaphy with a proximal-distal end-to-side neurorrhaphy: in a rat model. Eur J Orthop Surg Traumatol Orthop Traumatol 25(8):1261–1264. https://doi.org/10.1007/s00590-015-1699-x
49. Artiaco S, Tos P, Conforti LG, Geuna S, Battiston B (2010) Termino-lateral nerve suture in lesions of the digital nerves: clinical experience and literature review. J Hand Surg Eur 35(2):109–114. https://doi.org/10.1177/1753193409337959
50. Mavrogenis AF, Pavlakis K, Stamatoukou A, Papagelopoulos PJ, Theoharis S, Zhang Z, Soucacos PN, Zoubos AB (2013) Intraneural OX7-saporin for neuroma-in-continuity in a rat model. Eur J Orthop Surg Traumatol 23(3):263–272. https://doi.org/10.1007/s00590-012-0996-x