Nerve Surgery

28

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Background
The ability to repair injuries of the peripheral nervous system in order to restore sensitivity and motor function is an essential aspect of reconstructive microsurgery today.

In recent years, the increased understanding of nerve anatomy and pathophysiology has offered new insights, both in terms of comprehending nerve degeneration and regeneration processes and developing new strategies for treatment. Technological improvements have also had a significant impact on this field. The use of high-resolution microscopes and thinner suturing materials, together with a better understanding of nerve regeneration, has facilitated the development of more precise approaches to different types of injuries and enhanced outcomes. The purpose of this chapter is to provide a detailed description of nerve anatomy and present current trends in surgical techniques for the treatment of nerve injuries.

28.1 Introduction

The basic principles of nerve reconstruction are largely based on the understanding of peripheral nerve anatomy and physiology both from a macroscopic and microscopic point of view. In particular, the comprehension of fascicular arrangements in specific nerves, together with the understanding of nerve physiology in terms of neurodegeneration and regeneration, has enhanced results of reconstructive techniques.

28.2 Nerve Anatomy

The peripheral nervous system conveys signals between the spinal cord and the rest of the body, and it can be classified according to the function of its fibers. The *afferent* arm consists of sensory neurons that transfer information from peripheral receptors to the central nervous system. The *efferent* arm is composed of neurons transmitting information from the central nervous system to the effector organ.

The *somatic nervous system* comprises efferent neurons responsible for the conscious and voluntary control of skeletal muscles. In contrast, the *autonomic (or visceral) nervous system* controls the visceral functions of the body, including the regulation of organs, glands, and vessels involved in maintaining the homeostasis of the body.

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Peripheral nerves, composed of various combinations of motor, sensory, and autonomic neurons, can be classified into pure sensory, pure motor, or mixed nerves, based on the different components.

From a microscopic perspective, peripheral nerves are composed of unmyelinated or myelinated axons and Schwann cells. These latter cells play a vital role in maintaining and regenerating the axons of the neurons in the peripheral nervous system. They derive from the neural crest and can be either myelinating or non-myelinating, affecting the degree of conduction velocity. Myelinated axons are enveloped in multilaminated sheets of myelin provided by a single Schwann cell, whereas numerous unmyelinated axons are surrounded by a single Schwann cell-derived membrane.

Nerve fibers constituting peripheral nerves can be classified according to fiber diameter and the degree of conduction velocity (Table 28.1).

- Group A fibers, which present a thick myelin sheath, are the largest in diameter. As they are characterized by high conduction rates, they are involved in somatic muscle contraction, proprioception, and fast pain sensation.
- Group B fibers transmit impulses at moderate speeds since they are lightly myelinated. They are preganglionic autonomic fibers.
- Group C fibers are unmyelinated and present low conduction rates. They are involved in slow pain sensation, thermoreceptors, and postganglionic sympathetic transmission.

The figure represents the cross-sectional anatomy of a peripheral nerve (Fig. 28.1).

The epineurium is the connective tissue layer that both encircles and runs between nerve fascicles. The primary function of the epineurium is to protect and nourish the nerve fascicles. The outer layers of the epineurium form a sheath, termed

Table 28.1 Classification of nerve fibers

Erlanger-Gasser	Lloyd-Hunt	Modality	Myelination	Function	Diameter (μm)	Conduction velocity (m/s)
A α		Motor	Yes	Muscle contraction	12–20	70–120
	Ia	Sensory	Yes	Proprioception (length)		
	Ib	Sensory	Yes	Proprioception (tension)		
A β	II	Sensory	Yes	Proprioception Touch: vibration, stretch Pressure Joint movement	5–12	30–70
A γ		Motor	Yes	Skeletal muscle tone	3–6	15–30
A δ	III	Sensory	Yes	Fast pain, cold temperature	2–5	12–30
B		Autonomic	Yes	Preganglionic sympathetic	<3	3–15
C		Autonomic	No	Postganglionic sympathetic	0.4–1.2	0.5–2
	IV	Sensory	No	Slow pain, cold and warm temperature, crude touch	0.3–1.3	0.7–2.3

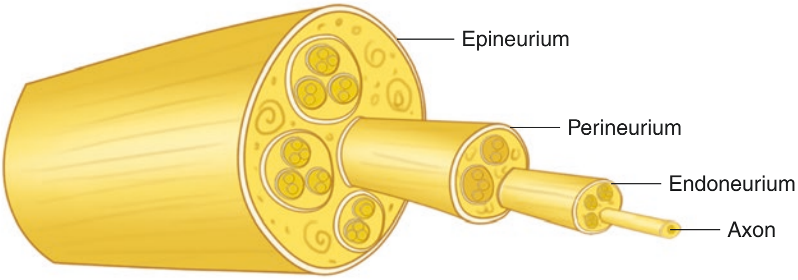


Fig. 28.1 Structure of the peripheral nerve

the external epineurium. Several fascicles lie within and through the epineurium, each surrounded by a perineurial sheath, which is the major contributor to the tensile strength of the nerve. The innermost loose collagenous matrix within the fascicles is the endoneurium. Individual axons are surrounded by the endoneurium and are protected and nourished by this layer [1].

Over the past 20 years, the use of intraoperative direct stimulation has allowed researchers to describe the consistent internal topography of the various nerves in terms of motor and sensory components. According to these findings, in the proximal aspect of the extremity, there is considerable plexus formation between the fascicles within the nerves, but this decreases in the distal extremity. Knowledge of the internal topography of the peripheral nerves is mandatory to achieve proper alignment of fascicles during nerve repair in order to improve results by enhancing the specificity of function-related re-innervation.

Key Points

The connective tissue, essential for nerve fascicles protection and homeostasis, is organized into different layers: the epineurium, the perineurium, and the endoneurium.

Knowledge of nerve internal topography is very important to enhance outcomes of nerve repair.

28.3 Nerve Injury Classification

Peripheral nerve injuries represent a challenge for both patients and surgeons, as they cause a wide range of symptoms, from mild and transitory distress to long-lasting impairment (Fig. 28.2).

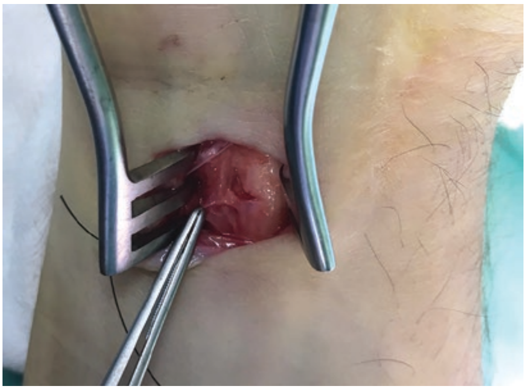


Fig. 28.2 Nerve injury of the median nerve caused by glass fragments

The management of nerve injury is guided by Seddon's and Sunderland's classification systems [2, 3] (Table 28.2).

Table 28.2 Seddon and Sunderland classification of nerve injury

Seddon	Sunderland	Pathophysiologic features of injury
Neurapraxia	Grade I	Focal segmental demyelination
Axonotmesis	Grade II	Axon damaged with intact endoneurium
	Grade III	Axon and endoneurium damaged with intact perineurium
	Grade IV	Axon, endoneurium, and perineurium damaged with intact epineurium
Neurotmesis	Grade V	Complete nerve transection
	Grade VI (Mackinnon and Dellon)	Mixed levels of injury along the nerve

According to *Seddon's classification*, nerve injuries are classified into three categories based on the presence of demyelination and the extent of damage to the axons and the connective tissues of the nerve.

Neurapraxia is the mildest form of nerve injury. It consists of an ischemic injury characterized by segmental demyelination without interruption of axonal or connective tissue continuity. Even though the axons are not injured, a localized conduction block is produced. Mechanical stress is a typical cause of this injury, often after compression or mild entrapment. As the axons are not damaged, no peripheral Wallerian degeneration occurs, and nerve regeneration is not required. Remyelination and evidence of recovery are expected in up to 12 weeks.

Table 28.3 Nerve recovery according to classification of nerve injury

Seddon	Sunderland	Spontaneous recovery	Surgery required
Neurapraxia	Grade I	Quick	No
Axonotmesis	Grade II	Slow	No
	Grade III	Slow/partial	No/decompression
	Grade IV	No	Yes
Neurotmesis	Grade V	No	Yes
	Grade VI	Depends on case	Depends on case

Axonotmesis is a more severe form of injury involving direct damage to the axons together with focal demyelination while maintaining continuity of the connective tissues. Axonal damage can be caused by a prolonged increase in perineural pressure. In this case, the segment of the axon located distal to the injury level undergoes Wallerian degeneration. In the meantime, proximally, the nerve fibers regenerate at a rate of approximately 2.5 cm per month. The progress of regeneration can be followed by the advancing Tinel sign.

Neurotmesis occurs when nerve continuity is interrupted both in terms of axons and all connective tissue elements. Surgical repair is necessary for this type of nerve injury.

Sunderland later expanded Seddon's classification by distinguishing the extent of damage affecting the connective tissues.

According to *Sunderland's classification*, **Grade I** and **Grade V** correspond to Seddon's neuropraxia and neurotmesis, respectively. In contrast, axonotmesis is divided into Grades II–IV according to increasing amount of connective tissue damage.

In **Grade II**, axon damage is observed with no damage affecting the connective tissue.

Grade I and **II** injuries, due to the mild level of damage, are usually managed conservatively with favorable outcomes, as demonstrated by clinical experience. A **Grade III** injury involves damage to the endoneurium that prevents the regeneration of some injured axons. Management of these injuries involves surgical decompression if the injury is localized in an area of entrapment. In such cases, the outcome is better than that obtained with a surgical repair or the use of a graft. In **Grade IV–V**, damage to the perineurium is present, with no potential for spontaneous recovery, as the entire population of regenerating axons is blocked. For this reason, a nerve graft repair is indicated in such injuries. A **Grade VI** lesion was later introduced by Mackinnon and Dellon to denote combinations of two or more injury patterns along the course of the damaged nerve. This scenario represents the most challenging situation as it requires differentially treating the various nerve fascicles based on their degree of injury. In particular, it is necessary to identify and differentiate the fascicles that are normal or have the potential to recover from the fourth- and fifth-grade component of the injury pattern that requires reconstruction.

Key Point (Table 28.3)

28.4 Nerve Regeneration

After an injury causing axonal transection, the proximal axon undergoes traumatic degeneration. In most cases, the area of degeneration of the proximal axon is located within the zone of injury, or it extends proximally to the next node of Ranvier. The axon distal to the site of the injury undergoes Wallerian degeneration, during which myelin starts to deteriorate, and the axon becomes disorganized. Myelin and axonal debris are phagocytized by Schwann cells.

After Wallerian degeneration, the basal lamina of Schwann cells persists, as these cells create a supportive environment for axon regeneration. A specialized motile apparatus is formed at the tip of the regenerating axon, the *growth cone*, which releases protease to dissolve the matrix and clear its way to the target organ.

Neurotrophic factors, such as the *nerve growth factor*, aid in neurite survival, extension, and maturation. These macromolecules are present in denervated motor and sensory receptors, as well as in Schwann cells. The nerve growth factor guides axon regeneration and affects growth-cone morphology. Other factors involved in nerve regeneration are the neurite-promoting factors that promote neurite growth, like *fibronectin* as well as *laminin*, which accelerates axonal regeneration across a gap. *Fibrinogen*, a matrix-forming precursor, is an essential substrate for cell migration in nerve regeneration. Other factors involved are fibroblast growth factors, insulin and insulin-like growth factor, electrical stimulation, and hormones such as thyroid hormone, estrogen, and testosterone [1].

28.5 Nerve Reconstruction

28.5.1 Timing

When dealing with nerve injuries, the timing of nerve repair depends on many factors, including not only the general condition of the patient, comorbidities, and associated injuries but also the etiology and degree of injury.

Nerve repair performed within the first 72 h after injury is considered a primary repair. In contrast, a repair performed up to 1 week after injury is classified as delayed primary repair. Secondary repair is a procedure performed more than 1 week following injury. Because nerve repair is not considered an emergency procedure, it can be delayed a few hours in order to be performed by a qualified surgeon during daytime hours.

When a nerve transection is suspected after a penetrating injury from a sharp object, early surgical exploration and reconstruction are recommended, as it is still possible to stimulate the distal stump of the nerve in the first 72 h, facilitating nerve alignment. After this time frame, the surgeon must rely on knowledge of nerve topography for nerve repair. When the nerve is completely transected, the best outcomes can be achieved when repair is performed within the first 3 weeks after the injury, but good results can be obtained with repairs performed in the first 6 months after the injury.

On the other hand, in cases of blunt injuries, it is wise to monitor the patient for signs of spontaneous recovery and delay surgical treatment. Electrodiagnostic studies can be performed, as they will show signs of recovery before clinical evidence of returning muscle function. Nerve recovery should proceed at a steady pace of approximately 1 mm/day; hence, the recovery time is strictly dependent on the injury level.

When patients show no signs of recovery on electrodiagnostic studies or clinical examination within 3–4 months after the injury, surgical exploration and repair should be considered.

Muscle tissue is sensitive to denervation. If not reinnervated within approximately 12 months, fat tissue replacement, atrophy, and muscle fibrosis will occur, leaving motor recovery unlikely.

For this reason, it is essential that motor axons reach the muscle end-plate within 1 year after injury, and functional recovery is inversely proportional to the time of muscle denervation.

Regarding sensory nerves, the repair can be attempted any time after the injury, though improved outcomes are achieved in earlier nerve repairs facilitated by correct nerve alignment [4].

Key Point

Primary repair is performed within the first 72 h, delayed primary repair between 72 h and 1 week, and secondary repair more than 1 week after injury.

28.5.2 General Principles

The main aim of nerve repair surgery is to design the best possible connection between the proximal and distal stump to allow nerve regeneration. This outcome is possible, thanks to meticulous microsurgical techniques performed under adequate magnification and with the use of microsurgical instruments and sutures.

First, nerve stumps must be regularized through sharp neurotomy, which can be performed using the Victor Meyer neurotomy apparatus or a number 11 scalpel blade.

The injured segments of the nerve can be mobilized in order to suture in a tension-free manner, facilitating repair. Small gaps can be overcome by further neurolysis, and the nerve stump can be transposed to gain length for direct suture (e.g., in the case of the ulnar nerve at the elbow).

When a tension-free repair is not feasible, an interposition nerve graft is preferable and should be positioned with the limb in a neutral position.

Whenever the internal topography of the nerve is divided into motor, sensory, or regional components, an effort should be made to correctly align the fascicles to match the sensory and motor modalities to optimize the specificity of nerve regeneration. For this reason, a thorough knowledge of intraneural anatomy is required. The use of intraoperative nerve stimulation can be helpful, together with the detection and alignment of epineural vessels. It is important to remember that surgical results are enhanced by postoperative motor and sensory reeducation.

28.5.3 Techniques

Different techniques have been described for the surgical treatment of nerve injuries. Several factors must be taken into consideration before choosing the most suitable approach, including the type of nerve damage and the situation where a loss of substance causes a gap.

28.5.4 Sutures

Over the years, different techniques for neurorrhaphy aimed at enhancing results have been described. In the clinical setting, each of these different techniques and their modifications will find specific indication [5] (Fig. 28.3).

28.5.4.1 End-to-End Sutures

Epineurial Suture

The epineurial suture is the oldest neurorrhaphy technique, consisting of the juxtaposition of the nerve stumps with epineurial sutures. After fascicles orientation, the epineurial suture starts with two laterally placed 8-0 or 9-0 nylon sutures.

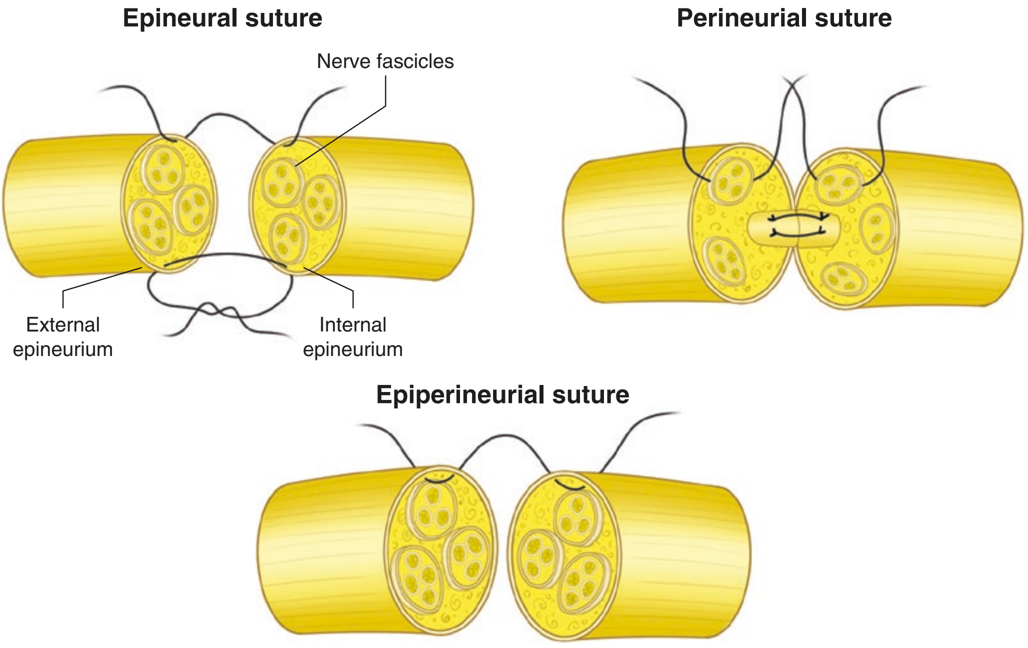


Fig. 28.3 Different nerve suturing techniques

The needle is passed through the epineurium and the internal epineurium and tries to align the fascicles of both nerve stumps, without tying the sutures too tightly, as this would cause the fascicles to twist within the epineurium. Two or three interrupted sutures are added between the first two sutures on the anterior aspect. The nerve is then rotated by pulling the lateral sutures so that the posterior epineurium can be approximated and sutured. The advantage of this technique is that it requires minimal manipulation of nerve stumps, but it can be lacking in terms of precise fascicle approximation. This technique is usually chosen for suturing nerves during primary repair or for nerve transfer. It finds its indication in proximal lesions, where considerable plexus formation is found between the fascicles.

Perineurial Suture

For a perineurial suture, the epineurium is removed from both ends of the nerve stump, and fascicles are meticulously dissected with microsurgery scissors. After orienting and matching each fascicle between both stumps, each single fascicle is sutured with 10-0 nylon. The needle is passed through the perineurium, close to its edge, and the repair is completed by placing three or four sutures. This technique ensures a high level of accuracy in the juxtaposition of the nerve stumps, but it requires greater manipulation of the nerve fascicles. There is also a risk of inaccurate fascicle matching, compromising the outcome. In distal repair, this approach can enhance outcomes due to its accuracy.

Epiperineurial Combined Suture

The epiperineurial combined suture technique allows for a more accurate adaptation of the peripheral fascicles within the epineurium by combining the advantages of both previously mentioned techniques. The 8-0 or 9-0 nylon sutures are passed through the epineurium and perineurium of peripheral fascicles with the same pass of the needle and then tied. In this approach, suturing is performed in a circumferential order, as this allows adapting the remaining fascicles more accurately.

28.5.4.2 End-to-Side Sutures

End-to-side repair is being increasingly used by many authors, representing an alternative when a conventional end-to-end suture cannot be accomplished. This technique involves suturing the end of a recipient nerve to the side of a donor nerve. An epineurial window is created on the side of the donor nerve; usually, two or three 8-0 or 9-0 sutures are enough to approximate the nerve stump. In order for this repairing technique to work, sensory branches must be connected to sensory nerves and motor branches to motor nerves, which can be challenging in certain cases. Moreover, while collateral sprouting spontaneously occurs in sensory nerves, in motor neurons, a proximal axonotmetic injury must be performed on the donor nerve to obtain regenerative sprouting [6].

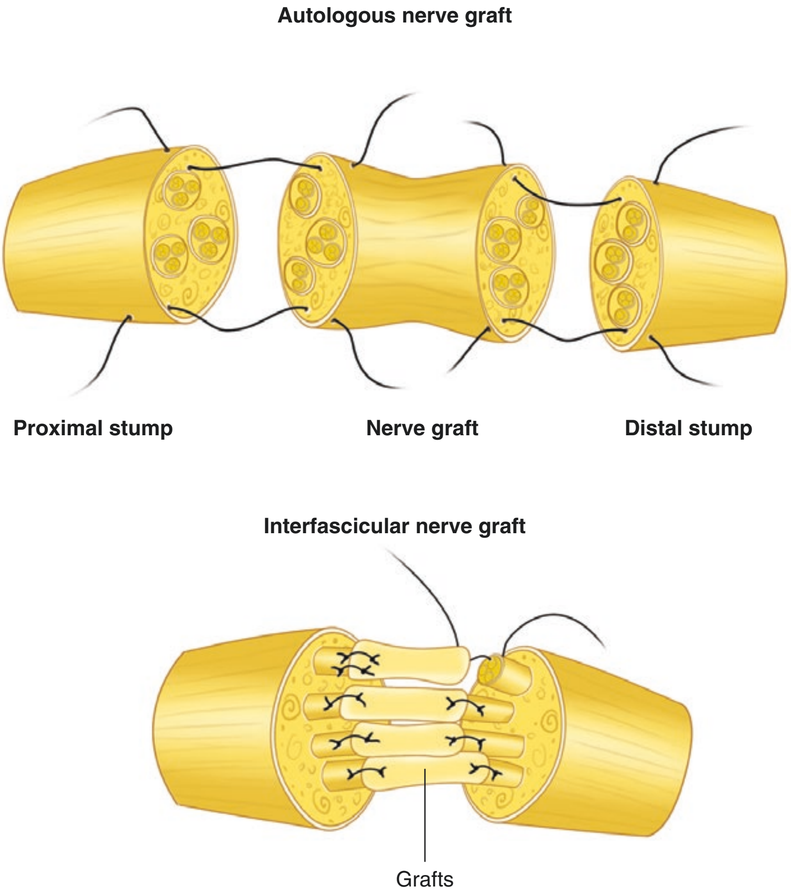
> **Pearls and Pitfalls**
>
> The epineurial suture causes minimal manipulation of nerve stumps, but does not allow precise fascicle approximation. The perineurial suture is highly accurate but requires fascicle manipulation. The epiperineurial combined suture presents the advantages of both abovementioned techniques.

28.5.5 Nerve Grafts

28.5.5.1 Autograft

In cases where a nerve gap exists and it is not possible to perform a direct suture, such as injuries involving loss of substance or nerve stump retraction and neuroma formation, a nerve graft is considered the gold standard procedure (Fig. 28.4). Usually, nerve grafting is not performed immediately but is delayed for approximately 3 weeks after the trauma in order to determine the extent of the injury. Nevertheless, early nerve grafting can be performed when early soft tissue coverage is required, or when a secondary procedure is expected to be particularly difficult. In this case, the proximal and distal nerve stumps should be accurately trimmed to

Fig. 28.4 Different nerve grafting techniques



ensure that the repair sites are located outside the zone of injury.

An autograft provides an immunologically inert scaffold with Schwann cells that facilitate axonal regeneration [7]. The most reliable nerve grafts are those ≤6 cm and with a small caliber, as they are easily revascularized, but various degrees of success have also been reported with longer grafts.

Nerve autografts necessarily cause additional scarring and donor site morbidity with the potential for painful neuromas formation. The most used donor nerves for autograft are the sural nerve, the saphenous nerve, the medial antebrachial cutaneous nerve, and the superficial branch of the radial nerve (Fig. 28.5).

After harvest, nerve grafts are interposed, using the fascicular pattern of the proximal stump as a guide.

When there is a significant difference in size between the recipient nerve and the graft, each individual fascicle can be dissected and separated to match the size of the recipient nerve. The nerve graft reconstruction should align motor fascicles with motor fascicles and sensory fascicles with sensory fascicles.

Fig. 28.5 Harvest of sural nerve graft

In the case of a short nerve gap, it may be possible to use cable grafts to directly connect proximal to distal fascicles. This approach is less achievable in extensive nerve injuries or proximal injuries due to intraneural plexus formation.

Key Point
The nerve graft is considered the gold standard procedure in cases where a nerve gap does not allow direct suture. The nerve graft facilitates axonal regeneration and should align motor fascicles with motor fascicles and sensory fascicles with sensory fascicles.

28.5.5.2 Allograft

Since autologous nerve donor sites are limited, cadaver- or donor-related nerve allografts represent another potential option for nerve reconstruction. This technique provides a temporary scaffold to allow axonal regeneration. The major drawback is that nerve allografts require temporary systemic immunosuppression, increasing vulnerability to opportunistic infections. An alternative to nerve allograft for short gaps in noncritical sensory nerves is the decellularized allograft. These are obtained by processing the donor allograft, making it acellular and non-immunogenic [7].

28.5.5.3 Vascularized Nerve Grafts

Free vascularized nerve grafts were introduced to improve the outcomes of nerve grafting. The use of a free vascularized graft is recommended for gaps larger than 6 cm or concomitant soft tissue loss with poor vascular supply to the area. Moreover, free vascularized grafts are indicated for large-diameter nerves in which vascularization is critical to prevent central necrosis (Fig. 28.6).

After performing vascular anastomoses, the proximal end of the graft is sutured to the recipient nerve. The nerve graft is then folded and divided, paying attention to avoid injuring the vascular network. The divided graft is then anastomosed to the recipient nerve [8].

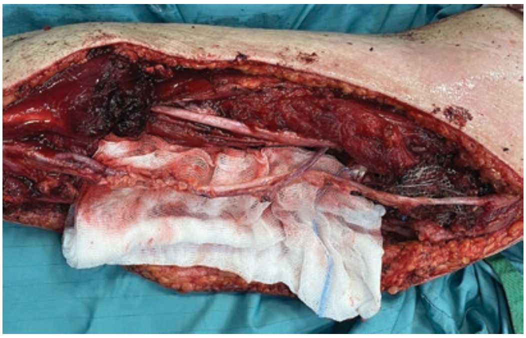


Fig. 28.6 Vascularized nerve graft for ulnar nerve reconstruction

28.5.6 Nerve Conduits

A nerve conduit is a tube used to guide nerve regeneration toward its target. An ideal nerve conduit presents low antigenicity, high availability, and biodegradability. The use of different biological options has been described, including vein, artery, and collagen; more recently, a number of synthetic conduits have also been developed.

Their use is limited to small-diameter, noncritical sensory nerve defects of less than 3 cm or, in the case of large-diameter nerves, for a gap of less than 0.5 cm. In order to enhance regeneration, inserting a piece of nerve graft material into the conduit has been suggested, thus providing trophic factors [9, 10] (Fig. 28.7).

28.5.7 Nerve Transfer

Nerve transfers consist of sacrificing a healthy nerve or nerve branch and suturing it to the distal stump of the injured nerve. The use of nerve transfers is indicated when a proximal stump is not available for primary repair or nerve grafting. This situation is frequent in very proximal peripheral nerve injuries and in cases of root avulsions or severe scarring. In some cases,

Fig. 28.7 Synthetic nerve conduit

nerve transfers can be preferred to grafting if the injury is located in such a proximal position that the transfer ensures a better outcome in terms of motor end-plate reinnervation compared to the graft. Thanks to the detailed knowledge of intraneural topography, it is possible to determine the most suitable expendable donor nerve. In the case of motor reinnervation, it is preferable that the donor nerve originally innervates a synergistic muscle and presents a large number of motor axons located close to motor end-plates, reducing the time needed to reinnervate the target muscle. Sensory nerve transfers require an expendable donor sensory nerve with noncritical sensory distribution and located near the sensory end organs. Common applications of nerve transfers include the restoration of joint flexion, abduction, and intrinsic hand function.

28.5.7.1 Direct Neurotization

When the distal nerve at the contact point with the muscle is avulsed, direct muscular neurotization can represent a good reconstructive option. Under magnification, on the distal aspect of the nerve, the epineurium is removed, and the nerve is divided into artificial fascicles. A corresponding number of slits are prepared in the muscle, and the artificial fascicles of the nerve are introduced and sutured into the slits. The epineurium of the nerve is then sutured to the epimysium of the muscle to prevent detachment.

28.6 Other Techniques of Functional Restoration

28.6.1 Tendon Transfer

The aim of tendon transfers is to provide a temporary or permanent substitute to restore function in the case of peripheral nerve injuries. The technique requires the release of a proximal or terminal tendon insertion and its reinsertion to restore a lost or deficient action. In particular, tendon transfers are used to restore function, recover a specific motion across a joint, or support function during the recovery of a peripheral nerve injury. The procedure allows for the application of an active motor unit across a passively mobile joint. However, it may be ineffective if scar tissue impedes tendon gliding or there is residual joint stiffness. The donor tendon must have sufficient strength to perform its intended function, and its excursion must be similar to that of the tendon it is replacing. Moreover, it must be expendable, not causing functional impairment after the transfer.

Regarding the coaptation style, if tendon transfers are performed in early stages, end-to-side is preferable because the regeneration of the nerve will allow improvement in function. Otherwise, when there is no chance of nerve recovery, either end-to-end or end-to-side transfers can be used. The surgeon's decision depends on different factors, including the length and caliber of tendon available, the site, and tensioning of the transfer. The rehabilitation process after tendon transfers requires a period of immobilization followed by physiotherapy to learn how to use the transfer [11].

28.6.2 Functional Muscle Transfer

Patients who are not candidates for a nerve or tendon transfer can be considered for a functional muscle transfer.

This procedure requires transecting and transferring both the origin and the insertion of a musculotendinous unit in a different setting, for example, across a joint, in order to restore its function. Muscle transfer can be performed using a muscle from a different body area, which needs to be transferred as a free flap, thereby performing a distal revascularization and nerve repair.

A key element in approaching this procedure is understanding muscle physiology. Since skeletal muscle properties highly rely on the restoration of the length-tension relationship, it is important to set the muscle resting tension appropriately in order to maximize muscle contraction forces.

The ideal muscle for a transfer should be powerful and long enough to accomplish the desired function, but it must also present enough tendon and fascia to support origin and insertion attachments. Regarding the neurovascular anatomy of the transplanted muscle, it should have a dominant vascular pedicle with a single motor nervous supply. Moreover, the ideal donor site should cause limited functional loss.

Numerous muscles meet these criteria and are therefore used in clinical practice for functional muscle transfers, including the gracilis, latissimus dorsi, tensor fascia latae, rectus femoris, medial gastrocnemius, serratus anterior, and pectoralis major and minor [12].

Key Point
Tendon transfers and free functional muscle transfers allow function restoration when nerve regeneration is not achievable.

28.7 Facial Nerve Reconstruction

The facial nerve is composed of motor, sensory, and parasympathetic fibers. Its major functions include motor supply to facial muscles, parasympathetic secretomotor supply to salivary and lacrimal glands, taste sensation from the anterior two-thirds of the tongue, and cutaneous sensations from the external auditory meatus.

Regarding its course, the facial nerve exits the skull at the stylomastoid foramen and enters the parotid gland at the midpoint of the line connecting the superior aspect of the tragus to the angle of the jaw. The nerve initially divides into two major trunks, which then further divide into five major branches: temporal, zygomatic, buccal, marginal mandibular, and cervical. As they travel distally to the muscles they innervate, the branches of the facial nerve become more vulnerable.

Facial nerve palsy is a condition in which the function of the facial nerve is partially or completely lost. It can be congenital or acquired. Bell's palsy is a frequent form of acute idiopathic facial paralysis, accounting for 85% of all cases of facial paralysis. It is unilateral and, in most patients, has a spontaneous resolution, although some patients may experience lasting motor deficits. In other cases, a specific cause, such as infection, trauma, or metabolic disorders, can be identified. Iatrogenic injury to the facial nerve is possible during procedures such as parotidectomy, skull base surgery, and facelift.

As previously described, neuropraxia is the mildest form of nerve injury and, in most cases, resolves within 3–6 months. Electrophysiologic studies performed in the early stages after injury can help distinguish neuropraxia from other forms of nerve injury. In these cases, watchful waiting for 6 months is recommended before considering surgical treatment [13].

28.7.1 Treatment of Facial Nerve Injury

After severe forms of facial nerve injury and subsequent paralysis, further treatment is indicated, and different approaches may be used to improve patient appearance.

The use of *dynamic reanimation techniques* aims at directly repairing the facial nerve or restoring dynamic movement, whereas *static treatment techniques* do not restore dynamic movement but still improve patient deficits and appearance. In clinical practice, a combination of these techniques is often used in a multimodal approach [14].

28.7.1.1 Facial Nerve Repair

Primary strategies for facial nerve repair include end-to-end repair, nerve grafting, and nerve transfer.

End-to-end repair is performed by directly suturing the severed ends of a nerve in a tension-free manner. This technique is indicated if the nerve is severed during a surgical procedure. In this case, it should be performed immediately or within 72 h.

Nerve grafting is appropriate if the nerve injury results in a substantial gap between the two ends of the nerve. When multiple branches of the facial nerve are damaged, it is possible to perform multiple separate grafts (Fig. 28.8). Alternatively, biological or synthetic conduits can be used in these cases.

In *nerve transfer approaches*, the nerves most frequently used are the hypoglossal nerve and the masseteric nerve. The hypoglossal nerve is commonly used for immediate reconstruction of the proximal facial nerve during tumor extirpation [15]. Masseteric nerve transfer is characterized by easy dissection, low donor site morbidity, and fast onset of movement (approximately 6 months after surgery). The contralateral facial nerve is also used for motor reinnervation, a technique that requires nerve grafts to be passed across the face and attached to branches of the injured facial nerve (*cross-face*). This approach offers the most natural results as it allows for spontaneous mimetic motion and emotional expression. Since the technique requires a significant amount of time for axons to reach the target, atrophy of the denervated muscles is a risk. For this reason, a temporary anastomosis can be created, with motor nerves (hypoglossal or masseteric nerves) providing a motor input while reinnervation from the contralateral facial nerve is achieved (*baby-sitter procedure*).

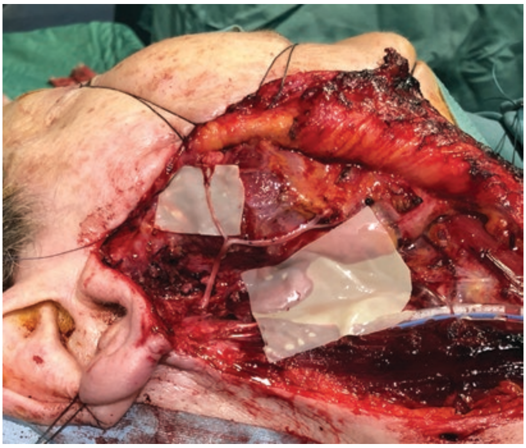


Fig. 28.8 Split nerve graft used to repair nerve gaps of multiple facial nerve branches

In terms of outcomes, early repair is consistently related to better results than late repair. The same applies to nerve grafts or nerve transfer procedures performed within 6 months after injury [16].

Tips and Tricks

End-to-end suture repair should be performed immediately or within 72 h.

Multiple separate *nerve grafts* can be used to treat nerve gaps of multiple facial nerve branches.

The hypoglossal and masseteric nerves are commonly used as donor nerves for facial reanimation.

The *cross-face* technique involves positioning a nerve graft to connect the injured facial nerve to the contralateral nerve.

28.7.1.2 Muscle Transfer for Reanimation

Dynamic facial reanimation in patients affected by long-standing facial paralysis may be achieved using regional or free muscle transfer, as in these patients, facial muscles would not provide useful function after reinnervation.

The temporalis muscle may be transferred to the upper half of the lower lip, allowing for elevation of the oral commissure. This option is indicated in patients who want an immediate solution with a short recovery time. Free muscle transfer involves transplanting a muscle segment, which is then reinnervated using an ipsilateral motor nerve (masseteric nerve) or the contralateral facial nerve via a cross-face graft. The muscles most frequently used for this purpose are the gracilis, the latissimus dorsi, and the pectoralis minor. The gracilis muscle is the most commonly used as it presents numerous advantages, such as fusiform shape, powerful contraction, and low donor site morbidity [17].

28.7.1.3 Static Reconstruction

When facial reanimation is contraindicated or not achievable, such as in elderly patients with comorbidities, several static techniques can be used. The aim of these procedures is to correct functional disability and restore facial symmetry at rest. Brow lift, upper eyelid loading, and tarsorrhaphy may be used to address visual issues and protect the cornea. Other static procedures, including facial muscle plication, facial sling suspension, and neuromodulator injectables, are used to restore symmetry and reduce drooling [18].

28.8 Peripheral Nerve Reconstruction

28.8.1 Brachial Plexus and Upper Limb

While brachial plexus injuries are often devastating, with life-altering consequences, injuries affecting the major nerves of the upper limb result in a variety of different conditions, mainly dependent on the nerve damage and the level of injury.

Immediate surgical treatment is performed when, according to the type of injury, physical examination, and electrodiagnostic and imaging studies, spontaneous recovery is not possible. Otherwise, a delayed procedure can be considered within 6–12 months in the absence of clinical and electrodiagnostic evidence of recovery.

For example, immediate exploration and primary repair are indicated in sharp open injuries with acute nerve deficits. In these cases, whenever possible, a direct end-to-end suture of nerve stumps is advisable if achievable in a tension-free manner. In the case of a blunt open injury with nerve rupture, the stumps of the nerve should be accurately tagged and a delayed repair performed 3–4 weeks later to allow the zone of injury to demarcate and ensure a safer and more effective repair. When a nerve gap is found, it can be addressed with the abovementioned techniques, such as nerve grafts or conduits. In addition, a nerve transfer can be performed to accelerate recovery in high-level injuries by decreasing the distance between the site of the nerve repair and the motor end-plate. Indications for nerve transfers in the treatment of upper extremity nerve reconstruction are many and include proximal brachial plexus injuries, in which grafting is not possible, but also proximal nerve injuries requiring long distances for reinnervation of distal targets. Additional indications include severely scarred regions, patients with delayed presentation, and segmental nerve loss related to major trauma. Other reconstructive options are represented by tendon transfers and free functional muscle transfers. While tendon transfer relies on the presence of functioning muscles, a free functional muscle transfer can be performed if there is a viable donor nerve and an adequate recipient vessel.

Pan-plexus injuries present the greatest variability in reconstructive approaches. The minimal surgical goal would be for shoulder stability and elbow flexion, though newer techniques may be able to offer some recovery of rudimentary grasp. In these complex cases, reconstructive options largely depend on the number of remaining viable spinal nerves [19–21].

28.8.2 Lower Limb

Nerve lesions of the lower limb are less frequently discussed, even though they are relatively common in orthopedic practice. Injuries related to traction or stretching of the nerves are common in work or road accident traumas, as well as those due to skeletal fractures. Furthermore, lower extremity nerve injuries are also related to knee sprain or hip dislocation. Even though most traumatic and iatrogenic nerve injuries of the lower limb are in continuity, they frequently involve axonotmesis and should not be assumed to be simple neuropraxias. For this reason, a thorough history and physical examination, together with serial electrodiagnostic studies and advanced imaging, should be used to assess nerve injury in these cases. Outcomes of nerve recovery in the lower limb vary widely, even between operative and nonoperative treatments. Moreover, while the recovery of the femoral and tibial nerve is often satisfactory, for the sciatic and common peroneal nerve around the knee, outcomes are disappointing. In fact, operative repair of the femoral and tibial nerve has shown superior results compared to the sciatic and common peroneal nerve, in which neurolysis is related to better prognosis than repair or grafting. In general, as previously mentioned for the upper limb, sharp lacerations require early surgical exploration. However, when severe nerve contusion is involved, a delay of several weeks is suggested to allow demarcation of the area of injury. In the case of stretch injuries or blunt trauma, observation is suggested, together with serial physical examination and electrodiagnostic and imaging studies. When no signs of recovery are observed after 2–5 months, nerve exploration is necessary, and nerve damage can be addressed with neurolysis, repair, or grafting, according to the situation [22, 23].

28.9 Assessment of Peripheral Nerve Function

Evaluation of peripheral nerve function after injury and outcome assessment following treatment remains a complex process for therapists and surgeons. A combination of tests is required to aid clinical diagnosis, assess surgical repair, and track rehabilitation progress.

During clinical evaluation, the Hoffman-Tinel sign, more commonly known as the Tinel sign, is a simple yet valuable tool. It is defined as the “pins and needle feeling” provoked by tapping on a nerve, with resulting paresthesia in the corresponding distal distribution of an injured peripheral nerve. The Tinel sign is commonly used as an indication of peripheral nerve compression or regeneration.

Many different measurement instruments can be used in peripheral nerve evaluation, including sensory and motor tests, pain and discomfort assessments, neurophysiological examination, and imaging.

Sensory tests are employed to evaluate sensory acuity. The *Semmes-Weinstein monofilament test* is used to assess the perception of cutaneous pressure threshold, reflecting reinnervation of peripheral targets. The *two-point discrimination test* is an established assessment tool for innervation density, aiming at determining the smallest distance between two points that still results in the perception of two distinct stimuli. Other functional sensory tests include vibration and temperature perception, shape and texture identification, and thickness discrimination.

Evaluation of motor function is based on qualitative, semi-quantitative, and quantitative examinations.

Qualitative evaluation is performed by observing muscle volume and tone. *Manual muscle testing* is a semi-quantitative evaluation used to assess motor innervation by way of a muscle strength grading system. Quantitative examinations involve using dynamometers that measure muscle strength (e.g., hand-held dynamometer).

In contrast, the evaluation of pain is always based on self-report by patients. Moreover, assessing the impact of pain on the quality of life is essential.

Neurophysiological examinations include electroneurography (ENG) and electromyography (EMG). These studies, used to evaluate the electrical activity of nerves and muscles, provide valuable information on the location and pathophysiology of peripheral nerve lesions.

Recent developments in the field of peripheral nerve imaging have extended the capabilities of imaging modalities to assist in the diagnosis and treatment of patients with peripheral nerve injuries. Methods such as MRI and ultrasound are capable of assessing nerve structure and function following injury and relating the state of the nerve to electrophysiological analysis [24].

Key Point

Different measurement instruments are used to assess peripheral nerve status and plan surgical treatment: sensory and motor tests, pain and discomfort assessment tests, neurophysiological examination, US, and MRI.

28.10 Bionic Reconstruction and Future Perspectives

Functional reconstruction of highly specialized body areas is essential in restoring body function and integrity, but it can also interfere in the loop of neural circuits, reducing neural pain. It appears that, in the near future, when surgical attempts at nerve repair or reconstruction fail to restore function, complex mechatronic replacement could represent a valuable option. The challenge in bionic replacement is to achieve ultra-specialized connections with the patient's nervous system to ensure natural, intuitive control of the prostheses. In specialized centers for bionic reconstruction, experts in clinical research together with experienced surgeons and a rehabilitation team are currently working to improve results in clinical use of these new technologies in order to enhance their availability for patients in need [25].

Take-Home Messages

- The management of nerve injury is guided by **Seddon's and Sunderland's classification systems**.
- **Grade I** and **II** injuries are usually managed conservatively. **Grade III** injury involves damage to the endoneurium and requires neurolysis or surgical decompression. In **Grade IV–V** injuries, damage to the perineurium is present, with no potential for spontaneous recovery. A **Grade VI** injury represents the most challenging situation.
- The injured segments of the nerve can be mobilized in order to repair with **direct suture** in a tension-free manner. When there is a gap, an interposition **nerve graft** is preferable.
- **Tendon transfers** and **free functional muscle transfers** allow function restoration when nerve regeneration is not achievable.
- Assessment of peripheral nerve status is performed with **sensory** and **motor tests**, **pain** and discomfort assessment tests, **neurophysiological examination**, **US,** and **MRI**.

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Further Reading

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