12
Anatomy and Physiology of Peripheral Nerves

INTRODUCTION

This chapter describes the normal anatomy and function of somatic peripheral nerves and different forms of injuries that can occur from trauma and other forms of insults. Since intraoperative monitoring of nerves of the autonomic nerves has not found practical use, this topic is not covered in detail. Chapter 13 provides a description of the practical aspects of intraoperative monitoring and diagnosis of pathologies of peripheral nerves.

ANATOMY

Peripheral nerves of the body are spinal nerves that originate or terminate in the spinal cord; some cranial nerves that originate or terminate in the brainstem also give rise to peripheral nerves (cranial nerves are discussed in Chap. 11). Most peripheral nerves contain somatic motor fibers, sensory nerve fibers, proprioceptive fibers, pain fibers, and some spinal nerves contain visceral and autonomic nerve fibers. In general, sensory fibers of peripheral nerves enter the spinal cord as dorsal roots, and motor fibers exit the spinal cord as ventral roots.

Classification of Peripheral Nerves

Sensory and motor nerves are mostly composed of myelinated nerve fibers. Most mixed nerves also contain nerve fibers that carry pain signals and fibers that belong to the autonomic nervous system. While sensory and motor nerves and some pain fibers are myelinated fibers, some pain fibers and autonomic fibers are unmyelinated.

Myelinated fibers can be divided into three main groups according to the diameter of their axons, usually labeled Aα, Aβ, and Aδ fibers. Unmyelinated fibers are C-fibers. The conduction velocity of nerve fibers is proportional to the diameter of their axons (**Table 12.1**). Motor nerve fibers belong to the Aα groups, and most

From: *Intraoperative Neurophysiological Monitoring: Third Edition*,
By A.R. Møller, DOI 10.1007/978-1-4419-7436-5_12,

Table 12.1
Conduction velocity in nerve fibers of different types

Fiber type	*Function*	*Average axon diameter (mm)*	*Average conduction velocity (m/s)*
Aα	Motor nerves, primary Muscle-spindle afferents	15	100 (70–120)
Aβ	Mechanoreceptor afferents	8	50 (30–70)
Aδ	Temperature and pain afferents	<3	15 (12–30)
C	Pain afferents Sympathetic postganglionic fibers	~1	1 (0.5–2)

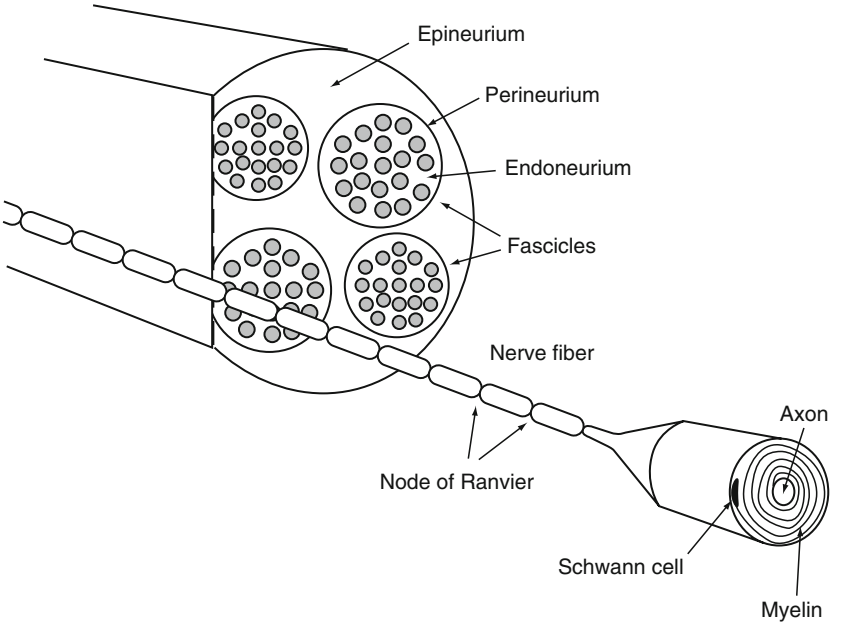

Figure 12.1: Anatomy of a typical peripheral portion of a nerve. After Sunderland 1981 (*1*); (Reprinted (*2*) with the permission of Cambridge University Press).

sensory nerves belong to the Aβ fiber types, while pain fibers belong to the Aδ and C groups.

When peripheral nerves enter or exit the spinal cord or the brainstem, the myelin changes from peripheral myelin to central myelin. Central myelin is generated by oligodendrocytes, while Schwann cells generate the myelin of the peripheral portion of nerves. The transition zone between the peripheral and the central part of nerves occurs near their entry to the central nervous system (CNS) and is known as the Obersteiner–Redlich zone.

Axons of the peripheral portion of nerves are covered by endoneurium to form nerve fibers, and nerve fibers are organized in bundles (fascicles) that are covered by a sheath of perineurium (**Fig. 12.1**). The peripheral portion

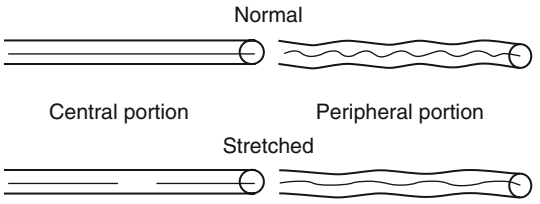

Figure 12.2: Effect of traction and injury on the central and the peripheral portion of a nerve. After Sunderland 1981 (*1*); (Reprinted from (*2*) with permission from Cambridge University Press).

of nerves may consist of a single funiculus, or it can be composed of several funiculi (bundles) that are covered by perineurium. Epineurium covers nerve trunks (*1*).

Funiculi in the peripheral portion of nerves have an undulated form (**Fig. 12.2**). This allows the nerves to be stretched without inducing stress on the individual nerve fibers, but traction that exceeds the stretched length of a nerve causes some of the typical injuries, which often occurs as a result of trauma (*1*).

In the central portion of a nerve, the endoneurium, which consists of collagen fibrils, has finer fibrils than in the peripheral portion, and the perineurium and epineurium are absent. The central part of nerves, therefore, lacks some of the protection that peripheral portions have. Since the central portion of nerves lacks a funicular support structure and undulations are absent (**Fig. 12.2**), the central portion of nerves is more fragile, more sensitive to traction and vulnerable to mechanical stress than their peripheral counterparts. This is especially important for spinal nerve roots (and for cranial nerve roots).

The transition zone between the peripheral and central portion of nerves (the Obersteiner–Redlich zone) has been studied especially in cranial nerves, where it has been shown to be sensitive to irritation from, for example, blood vessels (see Chaps. 7 and 15). Visual inspection does not reveal the location of the transition zone, but histological methods clearly show a difference between the central and the peripheral part of a nerve. This region of nerves is the common anatomical location of Schwannoma, such as vestibular Schwannoma of the auditory vestibular nerve (see page 79, 124, 133, 149, 236). Spinal nerves can also develop Schwannoma, especially in connection with a genetic defect, neurofibromatosis type 2 (NF2).

Sensory Nerves

The fibers of sensory spinal nerves are bipolar nerve fibers that have their cell bodies in the dorsal root ganglia (DRG). Sensory nerves enter the dorsal horn of the spinal cord as dorsal root fibers (see Chap. 5).

Motor Nerves

The motor nerve fibers that leave the spinal cord as ventral spinal roots mostly belong to the Aα group of nerve fibers. The cell bodies (alpha motoneurons) of axons that innervate skeletal muscles are located in lamina IX of the ventral horn of the spinal cord (Chap. 9) (*3*). The nerve fibers that innervate the intrafusal muscle (Aα fibers) travel together with other motor fibers, and their cell bodies are located in lamina IX of the ventral horn of the spinal cord (*3*).

PATHOLOGIES OF NERVES

Trauma can cause specific injuries to nerves, and nerves can be injured because of the ingestion of substance such as alcohol, and by diseases such as diabetes mellitus. Some of these factors can destroy the myelin (demyelination). Inflammation can also cause changes in the morphology and the function of peripheral nerves and age-related changes also affect peripheral and cranial nerves.

Traumatic injuries may affect a limited portion of a (single) nerve (focal injuries), while disorders (and age) more likely affect one or more entire nerves (mononeuropathy or polyneuropathy).

Focal Injuries

Some investigators have classified the focal morphological changes that typically occur in nerves from traumatic injuries into three main types: neurapraxia, axonotmesis, and neurotmesis. Others have divided such injuries in five groups (*4*) (**Fig. 12.3**).

Neurapraxia is the mildest form of focal lesions of a nerve (Sunderland grade 1 (*4*)) (**Fig. 12.3**). It involves partial or complete conduction failure without any detectable structural changes. A nerve can recover totally from neurapraxia without any intervention; full function of the nerve returns within a certain time ranging from several hours to a few days.

Stretching or compression of a nerve containing axons of different diameter affects large diameter axons more than smaller ones (while the effect of local anesthetics on nerves is the opposite). Traction or heating can injure nerves

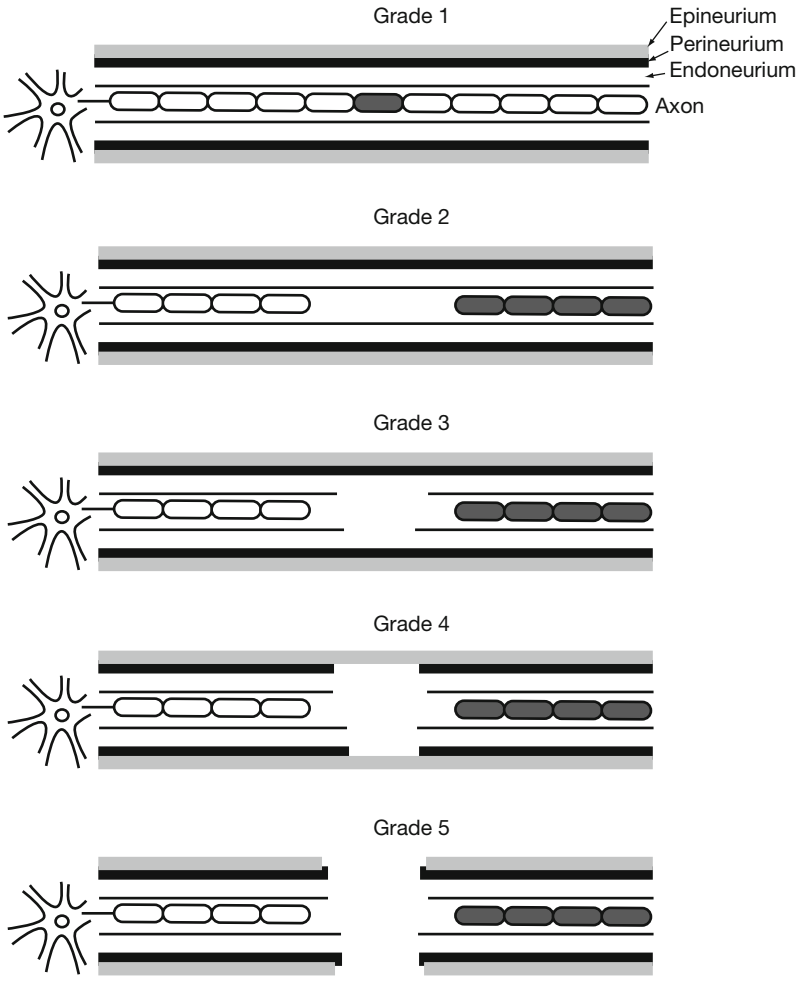

Figure 12.3: Illustration of a nerve with a conduction block without morphological changes (neurapraxia, Sunderland grade 1), and different types of nerve injuries (Sunderland grades 2, 3, 4, and 5) (*4*) Reprinted from (*2*) (Reprinted with the permission of Cambridge University Press).

to various degrees, and the injury can be either temporary or permanent.

Interruption of the axons of a nerve without damage to its supporting structures is known as axonotmesis (Sunderland grade 2). Axonotmesis may be caused by insults such as crushing or pinching of a nerve, or it may occur after stretching a nerve. If such lesion occurs distally to the location of the cell body, the parts of the axons that are distal to the lesion will begin to degenerate immediately after the lesion has occurred (Wallerian degeneration[1]) (*5*). The degeneration of the distal portion is usually complete within 48–72 h after the injury, at which time the nerve no longer conducts nerve impulses. But it is important to keep in mind that the distal portion of the nerve can conduct nerve impulses for some time (24–72 h) after an injury. For bipolar axons, the interruption of axons proximal to the cell body causes similar degeneration of the part of the axons that are proximal to the injury.

If trauma to a nerve also involves the support structure of the nerve, it is known as neurotmesis (Sunderland grades 3, 4 and 5 (*4*)) (**Fig. 12.3**) The lightest form of neurotmesis (Grade 3) involves a mixture of axon damage and some damage to the support structure (loss of Schwann cell basal lamina endoneural integrity). This form of injury may resolve by partial regeneration of axons that can occur without intervention, and some function may be regained. Grade 4 describes more serious injuries where scar formation occurs over the entire cross-section of a nerve. In this kind of injury, the continuity of the nerve is maintained, but spontaneous regeneration is blocked by scar tissue. When a total transection of a nerve occurs, it is labeled a Grade 5 injury. This form of injury requires surgical intervention (grafting) to regain function.

Central segment of peripheral nerves are more vulnerable to injuries than the peripheral segment of the nerves because of the lack of support structures, but trauma to the central segment nerves produces similar kinds of injuries as that of the peripheral segment nerves. Because the central nerves lack an undulating form, they are more vulnerable to stretching (**Fig. 12.2**).

Regeneration of Injured Nerves

When peripheral nerves are injured to the degree that the axons have been interrupted, yet the support structure remains intact (axonotmesis), the axons regenerate. New axons sprout from nerves and begin to grow away from their cell body and toward their normal target using the preserved support structure as a conduit. The regeneration proceeds at a speed of ~1 mm/day, but scar tissue that forms after injuries may act as an obstacle to regeneration. In addition, neurinoma, which can cause various symptoms such as pain, may also result from these sprouting axons.

If the interruption of a bipolar (sensory) axon occurs at a location that is proximal to the cell body, the axon will grow centrally and will make contact with the cells in the spinal cord (or brainstem) to which they were originally connected. Lesions that are located distal to the cell body of axons of sensory nerves cause the axons to grow toward their sensory receptors. New sensory receptors must be created when sensory nerve fibers, such as those innervating cutaneous receptors, reach their normal targets.

Axons of motor nerves that are interrupted grow toward the muscles that the nerves normally innervated, but not all the new motor axons eventually reach their targets and form new motor endplates. Recovery of function after the interruption of axons of a motor nerve requires the formation of new motor endplates. Sprouting of motor nerves consists of multiple fine fibers, many of which would fail to create functional motor endplates. To obtain muscle function, some of these fine filaments must,

[1] Wallerian degeneration: Degenerative changes in a segment of a nerve fiber (axon and myelin) that occur when continuity between the nerve fiber and its cell body is interrupted.

therefore, be eliminated which normally occurs over time without any intervention (*6*). This normally occurs when the outgrowing axon reaches the muscle that it innervated before it was interrupted.

Axons also regenerate (sprout) after more severe injuries to a nerve (neurotmesis), but the success of the sprouts' venture to reach their target depends on the condition of the support structure of the injured nerve. Sufficient regrowth and recovery of function may occur if some of the support structure is intact. Grade 4 and 5 lesions, however, require grafting, either end-to-end or with another nerve, that serves to provide the support structures that can act as conduits for the regenerating axons. Such regenerated nerves have fewer functional nerve fibers than they had before the injury, and many of the new axons activate their targets incorrectly. Misdirected and incomplete regeneration of sensory nerves may cause abnormal sensory input or partial to complete deprivation of input to the CNS (*7*).

SIGNS OF INJURIES TO NERVES

Intraoperative signs of injuries to peripheral nerves are changes in the response to electrical stimulation, spontaneous or mechanically evoked activity from the motor portion of peripheral nerves, and of course, if the injury is a severe, conduction block.

Slight injury to a peripheral nerve causes decreased conduction velocity that manifests electrophysiologically as increased latencies of compound action potentials (CAP) recorded from one location of a nerve while the nerve is stimulated electrically at another location. Slight injury may also cause a broadening of CAP if the conduction velocity is decreased unevenly among the nerve fibers that make up the nerve in question. More severe injuries cause greater changes in the waveform of CAP, and a total conduction block results in a single positive deflection when recorded by a monopolar recording electrode (see Chap. 3).

Mechanosensitivity of Injured Nerves

Normal peripheral nerves are rather insensitive to moderate mechanical stimulation, but slightly injured nerves can be very sensitive to mechanical stimulation. Surgical manipulations and touching injured nerves with surgical instruments can result in contraction of muscles that are innervated by the nerve in question (see page 276). Similar mechanical stimulation of an uninjured nerve elicits little or no muscle contractions, which indicates that the sensitivity to mechanical stimulation of a nerve is related to injury.

Clinically, mechanical sensitivity of peripheral nerves is often present in the carpel tunnel syndrome. Tapping on the skin over the median nerve produces a tingling sensation (paresthesia) in the parts of the hand where the skin is innervated by the injured nerve (the Tinel sign[2]). Mechanosensitivity of DRG is also common and involved in some forms of pain (*8, 9*).

REFERENCES

1. Sunderland S (1981) Cranial nerve injury. Structural and pathophysiological considerations and a classification of nerve injury, in *The Cranial Nerves*, M Samii and PJ Jannetta, Editors. Springer: Heidelberg, Germany. 16–26.
2. Møller AR (2006) *Neural Plasticity and Disorders of the Nervous System*. Cambridge University Press: Cambridge.
3. Brodal P (1998) *The Central Nervous System*. Oxford Press: New York.
4. Sunderland S (1951) A classification of peripheral nerve injuries producing loss of function. Brain 74:491–516.

[2] Tinel sign: a tingling sensation from percussion of the skin over a peripheral nerve such as the nerves at the wrist.

5. Chaudhry V and DR Cornblath (1992) Wallerian degeneration in human nerves; Serial electrophysiological studies. Muscle Nerve 15:687–93.
6. Happel L and D Kline (2002) Intraoperative neurophysiology of the peripheral nervous system, in *Neurophysiology in Neurosurgery*, V Deletis and JL Shils, Editors. Academic Press: Amsterdam. 169–95.
7. Lundborg G (2000) Brain plasticity and hand surgery: an overview. J. Hand. Surg. [Br.] 25:242–52.
8. Howe JE, JD Loeser and JH Calvin (1977) Mechanosensitivity of dorsal root ganglia and chronically injured axons: a physiologic basis for radically pain of nerve root compression. Pain 3:25–41.
9. Rasminsky M (1980) Ephaptic transmission between single nerve fibers in the spinal nerve roots of dystrophic mice. J. Physiol. (Lond.) 305:151–69.