Neurology

Spinal Cord: Spinal Nerves, Cervical Plexus, Brachial Plexus & Gray and White Matter

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While the brain and the spinal cord make up the Central Nervous System (CNS), the Peripheral Nervous System (PNS) is comprised mainly of nerve fibers and ganglion cells. The two systems cannot be clearly distinguished from one another as they are functionally closely interlinked. The PNS conducts information from the CNS, via numerous nerve fibers, to the effector organs and vice versa. The cranial and spinal nerves belong to the PNS. In this article, we address the spinal nerves and the nerve plexuses that supply the extremities, namely the cervical and brachial plexus.
Spinal Nerves
Organisation and Structure of the Spinal Nerves

From the spinal cord segments, emerge the **ventral root** (*radix anterior*; efferent fibers) and the **dorsal root** (*radix posterior*; afferent fibers), which join in the **intervertebral foramen** to form the **spinal nerve**. Therefore, the spinal nerve contains both motor and sensory fibers. Altogether, there are 31 to 32 **spinal nerve pairs** that leave the vertebral canal **caudally** from the respective vertebral body:

- **Neck**: 8 cervical nerve pairs (C1 – C8)
- **Thorax**: 12 thoracic nerve pairs (Th1 – Th12)
- **Loins**: 5 lumbar nerve pairs (L1 – L5)
- **Sacrum**: 5 sacral nerve pairs (S1 – S5)
- **Coccyx**: 1 – 2 coccygeal nerve pairs

**Exception**: As there are only 7 cervical vertebrae, the nerve pairs exit **cranially** from the vertebrae.

Shortly after passing through the intervertebral foramen, the spinal nerve gives off a thin **meningeal branch** (ramus meningeus) which runs back into the spinal canal and provides sensory innervation to the spinal meninges. Next, the spinal nerve divides into an **anterior ramus** and a **posterior ramus**.

While the posterior ramus divides into a **medial branch** and a **lateral branch**, which supply the skin of the back and the autochthonous back muscles, the anterior ramus innervates the **ventrolateral** body wall structures and the limbs and contributes to the **formation of plexuses**.

Furthermore, there is a connection to the sympathetic trunk via the two **rami communicantes**: the white ramus communicans appears white because of the **myelinated** fibers that lead to the sympathetic trunk, while the gray ramus communicans carries **unmyelinated** fibers from the sympathetic trunk to the spinal nerve, which cause the gray colouring.
Segmental Innervation vs. Peripheral Innervation

Each spinal cord segment supplies, with its spinal nerves, a certain part of the body (= segmental or radicular innervation). In the thoracic wall, for example, it is intercostal nerves that provide the motor and sensory innervation.

On the sensory level, the segmental innervation creates so-called dermatomes: areas of the skin which can be assigned to the respective spinal cord segments. Only the C1 segment does not possess a dermatome since it consists of only motor fibers. In the thoracic area, the dermatomes lie in regular strips one above the other.

Note: Th10 approximately corresponds to the height of the navel; the boundary between Th4 and Th5 corresponds to the mamilla.

In the cervical, lumbar, and sacral regions, however, the anterior rami exchange fibers and intermix, thus forming the following nerve plexuses:

- Cervical plexus
- Brachial plexus
- Lumbar plexus
- Sacral plexus

Peripheral nerves emerge from the plexuses which each run to a supply area. Their last branches consist mostly of sensory skin nerves (= peripheral innervation). The nerve fibers again end in a segmental arrangement, so that the limb skin can also be divided into dermatomes.

Note: Segmental and peripheral innervations are not identical!
Knowledge of segmental and peripheral innervation is important for clinical practice as it can help to localise the damage in cases of **sensory loss**: if a *dermatome* is affected, damage is located at the level of the **nerve root**; if the sensory loss occurs on a **peripheral** area of skin, the corresponding **peripheral nerve** will be damaged.

This is, for example, why **shingles (herpes zoster)** causes painful skin blistering in the corresponding dermatomes because the pathogenic virus (**varicella**) attacks dorsal root ganglions.
Autonomous Zones and Segment-Indicating Muscles of Peripheral Nerves

The innervation areas of neighboring peripheral nerves overlap at the edges, leading to a **double innervation**. There are skin areas, however, which are innervated by one peripheral nerve alone. These are known as **autonomous zones**.

<table>
<thead>
<tr>
<th>Examples of Autonomous Zones</th>
<th>Nerve</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small finger</td>
<td>Ulnar nerve</td>
</tr>
<tr>
<td>First interdigital space</td>
<td>Deep peroneal nerve</td>
</tr>
<tr>
<td>Foot sole/heel</td>
<td>Tibial nerve</td>
</tr>
</tbody>
</table>

The same goes for motor innervation: the innervation areas of neighbouring spinal cord segments overlap so that the muscles receive information from several nerves. Muscles which are exclusively innervated by one spinal cord segment are called **segment-indicating muscles**.

<table>
<thead>
<tr>
<th>Segment-Indicating Muscle</th>
<th>Segment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deltoid muscle</td>
<td>C5</td>
</tr>
<tr>
<td>Biceps brachii muscle</td>
<td>(C5 –) C6</td>
</tr>
<tr>
<td>Triceps brachii muscle</td>
<td>C7</td>
</tr>
<tr>
<td>Interosseous muscles</td>
<td>C8</td>
</tr>
<tr>
<td>Quadriceps femoris muscle</td>
<td>(L3 –) L4</td>
</tr>
<tr>
<td>Tibialis muscle</td>
<td>L4</td>
</tr>
<tr>
<td>Extensor hallucis longus muscle</td>
<td>L5</td>
</tr>
<tr>
<td>Triceps surae muscle</td>
<td>S1 (~ S2)</td>
</tr>
</tbody>
</table>

Thus, it is possible to directly trace back the sensory loss in an autonomous zone or the malfunction of a segment-indicating muscle to the respective damaged nerve or spinal cord segment.
Cervical Plexus

The interjoining of nerves in the neck (cervical plexus) is formed by the anterior rami of the spinal nerves of segments C1 – C4 and is located on the side of the transverse processes of the cervical spine between the prevertebral muscles (scalenum, levator scapulae) and below the sternocleidomastoid muscle.

Sensory Nerves of the Cervical Plexus

At the posterior edge of the sternocleidomastoid muscle, the sensory branches of the cervical plexus emerge from the middle third and come up to the surface (= nerve point of the neck or Erb’s point) and innervate the head and neck region. The nerves are also known as cutaneous nerves and include:

- **Lesser occipital nerve** (C2, C3): lateral, the lower part of the back of the head (occiput) i.e. posterosuperior to the auricle.
- **Great auricular nerve** (C2, C3): bottom of the ear and back of the pinna (auricle)
- **Transverse cervical nerve** (C2, C3): lateral and ventral neck; anastomosis with the cervical branch of the facial nerve, thereby forming the ansa cervicalis
- **Supraclavicular nerves** (C3, C4): shoulder and upper chest area

**Note:** Due to the joint outlet of sensory nerves at Erb’s point, the anesthesia of the entire skin surface of the neck and nape of the corresponding side can be administered here.
Motor Nerves of the Cervical Plexus

They are nerves that supply various muscles. They include:

- The ansa cervicalis that gives motor innervation branches of the infrahyoid muscles. It lies between the levator scapulae muscle and the scalene muscles. The ansa cervicalis arises from C1-C3 and results from the anastomosis of a superior root (C1, C2) with an inferior root (C2, C3). The superior root is temporarily attached to the hypoglossal nerve (cranial nerve (CN) XII). The geniohyoid and thyrohyoid are supplied by the C1 part while the rest give supply to the sternothyroid and omohyoid muscles.
- The cervical plexus also gives off smaller branches which are attached to the accessory nerve (CN XI) and supply the trapezius muscle and the sternocleidomastoid muscle.
- Segmental branches also innervate the anterior and middle scalene muscles.

Phrenic Nerve

The phrenic nerve emerges from the C3, C4, and C5 cervical nerve pairs. It extends along the anterior scalene muscle between the subclavian artery and vein into the mediastinum, where it runs between the pleura and the pericardium. It is the only nerve that provides motor innervation to the diaphragm and is therefore essential for breathing.

A unilateral phrenic nerve palsy can lead to an elevated hemidiaphragm on the affected side. The phrenic nerve also provides sensory innervation to the diaphragm, the pleura, the pericardium, and the peritoneum.

Note: Three, Four, Five, keep the diaphragm alive!
Formation of Trunks and Cords of the Brachial Plexus

The spinal nerves of segments C5 - Th1 and, in parts, also of segments C4 and Th2 are involved in the formation of the brachial plexus. They pass through a gap between the scalenus anterior and the scalenus medius muscle (= scalenus gap) in a distal direction. They form the suprACLavicular part of the plexus by joining together above the clavicle as three primary strands that run alongside the subclavian artery in caudolateral direction:

- **Upper trunk**: C5 and C6
- **Middle trunk**: C7
- **Lower trunk**: C8 and Th1

Dorsal of the clavicle, they divide into three anterior strands (anterior divisions) and three posterior strands (posterior divisions). After entering the armpit (axilla) below the clavicle, the primary strands join again as secondary strands, the cords (fasciculi), and form the infraClavicular part of the plexus:

- **Lateral cord**: Upper trunk and middle trunk (C5 – C7)
- **Posterior cord**: Upper, middle and lower trunk (C5 – Th1)
- **Medial cord**: Lower trunk (C8 – Th1)
Supraclavicular Part of the Brachial Plexus

From the supraclavicular part of the brachial plexus, the nerves exit either via the trunks or directly from the spinal nerves to innervate the shoulder girdle muscles:

- **Dorsal scapular nerve** (C4 – C5): levator scapulae muscle, rhomboid major and minor muscle
- **Suprascapular nerve** (C4 – C6): subclavius muscle
- **Long thoracic nerve** (C5 – C7): serratus anterior muscle
- **Subclavian nerve** (C – C6): supraspinatus muscle and infraspinatus muscle

Infraclavicular Part of the Brachial Plexus

The infraclavicular part consists of short nerve branches, which run at level with the fasciculi towards the shoulder, and of long nerves, which represent the terminal branches of the secondary strands and run to the arm. The following three motor and two sensory nerves belong to the short branches:

- **Thoracodorsal nerve** (C6 – C8): latissimus dorsi muscle
- **Subscapular nerves** (C5 – C6): subscapular muscle, teres major muscle
- **Medial pectoral nerve** (C8 – Th1) and **lateral pectoral nerve** (C5 – C7): pectoralis major and minor muscles
- **Medial cutaneous nerve of the arm** (Th1): upper arm skin
- **Medial cutaneous nerve of the forearm** (C8 – Th1): forearm skin
The cords give off long nerves to the arm; those will be discussed in more detail here:

**Musculocutaneous Nerve (C5 - C7)**
The **musculocutaneous nerve** branches off from the lateral cord pierces the **coracobraehialis muscle**, and runs between the **brachial muscle** and **biceps brachii muscle** to the forearm, where it ends as the **lateral cutaneous nerve of the forearm** which supplies sensory innervation to the lateral side of the forearm. The three flexor muscles it passes by receiving motor innervation from it.

**Axillary Nerve (C5 – C6)**

The **axillary nerve** exits the **posterior cord** dorsally and runs with the **posterior humeral circumflex artery** through the **lateral axillary space** to the rear of the **humerus**. There, it runs along the **surgical neck**. It provides motor innervation to the **deltoid muscle** and the **teres minor muscle**. It ends in the **superior lateral cutaneous nerve**—a sensory nerve that innervates the skin on top of the deltoid muscle.

**Note:** Humeral fractures frequently occur at the surgical neck, which is why the axillary nerve is particularly vulnerable due to its proximity to this breaking point.

![Image: "Surgical neck fracture of humerus" by Jojo. License: CC BY-SA 3.0](image)

**Radial Nerve (C5 – Th1)**
The radial nerve runs as a continuation of the posterior cord in a distal direction. Already in the proximal upper arm area, it gives off sensory branches (posterior cutaneous nerve of the arm and inferior lateral cutaneous nerve of arm) that supply the skin and a motor branch for innervation of the triceps muscle.

The radial nerve courses through the groove for the radial nerve (also called a spiral groove) in a spiralling fashion alongside the deep artery of the arm passing behind the humerus; it then pierces through the lateral intermuscular septum and finally, it runs between the brachial muscle and the brachioradialis muscle, which receive motor innervation from it, towards the elbow.

Here, it divides into two branches: the purely sensory superficial branch runs together with the radial artery along the brachioradialis muscle and towards the back of the hand, which it supplies, as well as the radial 2 ½ fingers.

The deep branch supplies and pierces the supinator muscle, and ends at the
**posterior interosseous nerve of the forearm** at the wrist, and innervates all of the **extensors** of the forearm and hand (see table).

<table>
<thead>
<tr>
<th>Location/Nerve</th>
<th>Sensory Innervation</th>
<th>Motor Innervation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before radial tunnel</td>
<td>Lateral upper arm, lower half</td>
<td>Triceps brachii muscle</td>
</tr>
<tr>
<td>Within radial tunnel</td>
<td>Dorsal side of the upper arm and forearm</td>
<td>-</td>
</tr>
<tr>
<td>After radial tunnel</td>
<td>-</td>
<td>Brachoradial muscle; extensor carpi radialis longus muscle; extensor carpi radialis brevis muscle</td>
</tr>
<tr>
<td>Deep branch</td>
<td>-</td>
<td>Supinator muscle; extensor digitorum muscle; extensor digiti minimi muscle; extensor carpi ulnaris muscle; extensor pollicis longus muscle; extensor pollicis brevis muscle; extensor indicis muscle; abductor pollicis longus muscle</td>
</tr>
<tr>
<td>Superficial branch</td>
<td>Dorsal palm (lateral ¾) Radial 2 ½ fingers</td>
<td>-</td>
</tr>
</tbody>
</table>

**Note:** In case of a fracture in the area of the humeral shaft, a lesion of the radial nerve may occur leading to a **wrist drop** (radial neuropathy). Because the extensors are not functioning properly, the hand and finger joints can no longer be stretched.

**Median Nerve (C6 - Th1)**

A branch of the **medial cord**—the **medial root**—unites with a branch of the **lateral cord**—the **lateral root**—before the **axillary artery**, to form the **median nerve**. It primarily innervates the **flexor muscles** of the forearm, as well as the **pronators** (see table).

![Nerves of the left upper extremity](image)

It runs anterior to the **brachial artery** along the upper arm in the **medial bicipital groove** towards the elbow. Here, it pierces the **pronator teres muscle**, which it innervates, runs along the underarm and gives off the **anterior interosseous nerve of the forearm** before it passes between the **flexor digitorum superficialis** and the **flexor digitorum profundus muscle** towards the wrist.

There, it passes through the **carpal tunnel**—which is formed by the **flexor retinaculum**
of the hand (ligamentum carpi transversum)—and divides on the palm into terminal branches to provide motor innervation to the thenar muscles and sensory innervation to the inner side of the radial 3½ fingers (common and proper palmar digital nerves).

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<tr>
<td>Forearm, before passing the carpal tunnel</td>
<td>Thenar eminence (palmar branches of the median nerve); palm (radial 2/3)</td>
<td>Flexor carpi radialis muscle; palmaris longus muscle; flexor digitorum superficialis muscle; flexor digitorum profundus muscle (radial part); flexor pollicis longus muscle; pronator teres muscle; pronator quadratus muscle</td>
</tr>
<tr>
<td>Hand, after passing the carpal tunnel</td>
<td>Radial 3½ fingers (palmar); parts of fingers 2 – 4 (dorsal); autonomous zone: distal fingers 2 and 3</td>
<td>Abductor pollicis brevis muscle; flexor pollicis brevis muscle; opponens pollicis muscle; lumbrical muscles I and II</td>
</tr>
</tbody>
</table>

Note: A lesion of the median nerve proximal to its passage through the carpal tunnel, results in the characteristic appearance of the hand called simian hand or ape hand: the patient cannot bend the thumb, index or middle fingers. Flexion is still possible in the two ulnar fingers (innervation of flexor digitorum profundus by the median nerve and the ulnar nerve).

Median Nerve and Carpal Tunnel Syndrome

Median nerve supplies all the intrinsic muscles of the hand thus has a long course from the brachial plexus all the way through the flexor retinaculum where entrapment and a mononeuropathy ensues. The disorder is known as Carpal Tunnel Syndrome (CTS): however other syndromes have been reported such as the pronator teres syndrome or the anterior interosseous nerve syndrome.
It is characterized by paresthesias of the finger, typically nocturnal (brachialgia paraesthetica nocturna). When it progresses, symptoms may radiate to the entire hand and even arm, and occur also during the day. Further symptoms include painful sensitivity to pressure above the flexor retinaculum, sensory loss of the radial 3½ fingers and atrophy of the thenar muscles.
nerve, tendovaginitis, or polyarthritis. Also, diabetes mellitus or pregnancy predispose to CTS due to the additional connective tissue. Furthermore, a tumor that compresses the median nerve can be the cause of CTS.

A clinical sign is that patients can no longer hold a bottle since the abductor pollicis brevis muscle is weakened. Other indications include Tinel's sign, in which a tap on the flexor retinaculum triggers an electrifying pain in the hand, and the Phalen sign, in which the hand is held in volar flexion for 30 seconds which causes dysesthesia.

Carpal tunnel syndrome is initially treated with a forearm splint that is worn during the night and immobilizes the wrist. For decompression of the nerve, the transverse carpal ligament is surgically split.

Ulnar Nerve (C8 – Th1)
The *ulnar nerve* continues directly from the *medial cord*. It runs behind the *brachial artery* through the *medial bicipital groove*. Since it is relatively exposed in this area and lies directly on top of the bone, this part of the elbow is particularly sensitive to pain ("funny bone"). Still in the area of the upper arm, the *ulnar nerve* courses to the arm’s extensor side by piercing the *medial intermuscular septum*.

At the elbow, it runs underneath the *medial epicondyle* in the *groove of the ulnar nerve*. Together with the *vasa ulnaria*, the nerve passes between the two heads of the *flexor carpi ulnaris muscle* to the wrist. Here, it courses—contrary to the median nerve—above the *flexor retinaculum* in the *Guyon’s canal* to the inner side of the hand where it divides into its terminal branches: *superficial* and *deep branch*.

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<tr>
<th>Location/Nerve</th>
<th>Sensory Innervation</th>
<th>Motor Innervation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forearm</td>
<td>Ulnar side of the dorsal and palmar hand; fingers 4 and 5 (dorsal; dorsal branch)</td>
<td>Flexor carpi ulnaris muscle; flexor digitorum profundus muscle (ulnar part)</td>
</tr>
<tr>
<td>Hand: deep branch – motor; superficial branch – sensory</td>
<td>Fingers 4 and 5 (palmar); Autonomous zone: distal small finger</td>
<td>Palmaris brevis; abductor digiti minimi; flexor digiti minimi; opponens digiti minimi; lumbricals III and IV; palmar and dorsal interossei; adductor pollicis; flexor pollicis brevis</td>
</tr>
</tbody>
</table>

**Note:** Injury to the ulnar nerve, in its groove, leads to the symptom of *claw hand*: When active finger flexors are innervated by the median nerve, it causes the malfunction of lumbrical and interosseous muscles. Also, *hypothenar* and *interosseous atrophy* can be observed.

**Hint:** For remembering the characteristic effects that nerve injuries have on the hand, use the “*Dr. Cuma*” mnemonic: wrist *Drop* – *Radial nerve*, *Claw hand* – *Ulnar nerve*, *Median nerve* – *Ape* hand.

For an overview of sensory innervation of the upper limbs, see the following illustration:
Gray and White Matter

The formation of the spinal nerve from the dorsal and ventral roots
MRI: White matter structure

High resolution data acquired on 3 Tesla magnet and post-processed using automated tracking procedure. Voxels within fiber bundles are color-coded according to their FA values (i.e., blue, low anisotropy; and red, high anisotropy.) by Kubicki M., McCarley R.W., Westin C-F., Park H-J., Maier S.E., Kikinis R., Jolesz F.A., Shenton M.E. A review of diffusion tensor imaging studies in schizophrenia. J Psychiatr Res. 2007 Jan-Feb;41(1-2):15-30. PMID: 16023676. PMCID: PMC2768134.
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Continuation

Keep reading the second part of this article about the spinal cord and peripheral nervous system which addresses the lumbosacral plexus.

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