The Nervous System—An Overall View

Development and Subdivision (A–D)

The nervous system serves processing information within the body in the interest of adapting its reactions. In the most primitive forms of organization (A), this function is assumed by the sensory cells (A–C1) themselves. These cells are excited by stimuli coming from the environment; the excitation is conducted to a muscle cell (A–C2) through a cellular projection, or process. The simplest response to environmental stimuli is achieved in this way. (In humans, sensory cells that still have processes of their own are only found in the olfactory epithelium.)

In more differentiated organisms (B), an additional cell is interposed between the sensory cell and the muscle cell – the nerve cell, or neuron (BC3) which takes on the transmission of messages. This cell can transmit the excitation to several muscle cells or to additional nerve cells, thus forming a neural network (C). A diffuse network of this type also runs through the human body and innervates all intestinal organs, blood vessels, and glands. It is called the autonomic (visceral, or vegetative) nervous system (ANS), and consists of two components which often have opposing functions: the sympathetic nervous system and the parasympathetic nervous system. The interaction of these two systems keeps the interior organization of the organism constant.

In vertebrates, the somatic nervous system developed in addition to the autonomic nervous system; it consists of the central nervous system (CNS; brain and spinal cord), and the peripheral nervous system (PNS; nerves of head, trunk, and limbs). It is responsible for conscious perception, for voluntary movement, and for the processing of information (integration). Note that most textbooks include the peripheral nerves of the autonomic nervous system in the PNS.

The CNS develops from the neural plate (D4) of the ectoderm which then transforms into the neural groove (D5) and further into the neural tube (D6). The neural tube finally differentiates into the spinal cord (D7) and the brain (D8).

Functional Circuits (E, F)

The nervous system, the remaining organism, and the environment are functionally linked with each other. Stimuli from the environment (exteroceptive stimuli) (E9) are conducted by sensory cells (E10) via sensory (afferent) nerves (E11) to the CNS (E12). In response, there is a command from the CNS via motor (efferent) nerves (E13) to the muscles (E14). For control and regulation of the muscular response (E15), there is internal feedback from sensory cells in the muscles via sensory nerves (E16) to the CNS. This afferent tract does not transmit environmental stimuli but stimuli from within the body (proprioceptive stimuli). We therefore distinguish between exteroceptive and proprioceptive sensitivities.

However, the organism does not only respond to the environment; it also influences it spontaneously. In this case, too, there is a corresponding functional circuit: the action (F17) started by the brain via efferent nerves (F13) is registered by sensory organs (F10), which return the corresponding information via afferent nerves (F11) to the CNS (F12) (reafference, or external feedback). Depending on whether or not the result meets the desired target, the CNS sends out further stimulating or inhibiting signals (F13). Nervous activity is based on a vast number of such functional circuits.

In the same way as we distinguish between exteroceptive sensitivity (skin and mucosa) and proprioceptive sensitivity (receptors in muscles and tendons, autonomic sensory supply of the intestines), we can subdivide the motor system into an environment-oriented somatomotor system (striated, voluntary muscles) and an visceromotor system (smooth intestinal muscles).
A–C  Models of primitive nervous systems (according to *Parker* and *Bethe*)

A  Sensory cell with process to a muscle cell

B  Nerve cell connecting a sensory cell and a muscle cell

C  Diffuse neural network

D  Embryonic development of the central nervous system: spinal cord on the left, brain on the right

E  Functional circuit: response of an organism to environmental stimuli

F  Functional circuit: influence of an organism on its environment
Position of the Nervous System in the Body (A, B)

The central nervous system (CNS) is divided into the brain, encephalon (A1), and the spinal cord (SC), medulla spinalis (A2). The brain in the cranial cavity is surrounded by a bony capsule; the spinal cord in the vertebral canal is enclosed by the bony vertebral column. Both are covered by meninges that enclose a cavity filled with a fluid, the cerebrospinal fluid. Thus, the CNS is protected from all sides by bony walls and the cushioning effect of a fluid (fluid cushion).

The peripheral nervous system (PNS) includes the cranial nerves, which emerge through holes (foramina) in the base of the skull, and the spinal nerves, which emerge through spaces between the vertebrae (intervertebral foramina) (A3). The peripheral nerves extend to muscles and skin areas. They form nerve plexuses before entering the limbs: the brachial plexus (A4) and the lumbosacral plexus (A5) in which the fibers of the spinal nerves intermingle; as a result, the nerves of the limbs contain portions of different spinal nerves (see pp. 70 and 86). At the entry points of the afferent nerve fibers lie ganglia (A6); these are small oval bodies containing sensory neurons.

When describing brain structures, terms like “top,” “bottom,” “front,” and “back” are inaccurate, because we have to distinguish between different axes of the brain (B). Owing to the upright posture of humans, the neural tube is bent; the axis of the spinal cord runs almost vertically, while the axis of the forebrain (Forel’s axis, orange) runs horizontally; the axis of the lower brain divisions (Meinert’s axis, violet) runs obliquely. The positional terms relate to these axes: the anterior end of the axis is called oral or rostral (os, mouth; rostrum, beak), the posterior end is called caudal (cauda, tail), the underside is called basal or ventral (venter, abdomen), and the upper side is called dorsal (dorsum, back).

The lower brain divisions, which merge into the spinal cord, are collectively called the brain stem (light gray) (B7). The anterior division is called the forebrain (gray) (B8). The divisions of the brain stem, or encephalic trunk, have a common structural plan (consisting of basal plate and alar plate, like the spinal cord, see p. 12, C). Genuine peripheral nerves emerge from these divisions, as they do from the spinal cord. Like the spinal cord, they are supported by the chorda dorsalis during embryonic development. All these features distinguish the brain stem from the forebrain. The subdivision chosen here differs from the other classifications in which the diencephalon is viewed as part of the brain stem.

The forebrain, prosencephalon, consists of two parts, the diencephalon and the telencephalon or cerebrum. In the mature brain, the telencephalon forms the two hemispheres (cerebral hemispheres). The diencephalon lies between the two hemispheres.

A9 Cerebellum.
A Position of the central nervous system in the body

B Axes of the brain: median section through the brain
Neuroglia

The neuroglia (glia, glue) is the supporting and covering tissue of the CNS and has all the functions of connective tissue: support, metabolite exchange, and, in pathological processes, digestion of degenerating cells (phagocytosis) and scar formation. It is of ectodermal origin. After Nissl staining, only cell nuclei and cytoplasm are visible; visualization of cellular processes is achieved only by special impregnation methods and by immunocytochemistry. We distinguish three different types of neuroglia: astroglia (macroglia), oligodendroglia, and microglia (A).

Astrocytes have a large, clear cell nucleus and numerous processes which give the cell a starlike appearance (A, C). There are protoplasmic astrocytes with few processes (usually present in gray matter) and fibrous astrocytes with numerous long processes (predominantly present in white matter). The latter produce fibers and contain glial filaments in cell body and processes. They form glial scars after damage to the brain tissue. Astrocytes are regarded as supporting elements, since they form a three-dimensional scaffold. On the outer surface of the brain, the scaffold thickens to form a dense fiber felt, the glial limiting membrane, which forms the outer limit of the ectodermal tissue against the mesenchymal meninges. Astrocytes extend processes to blood vessels and play a role in metabolite exchange (p. 45 A, B).

In addition, astrocytes play a decisive part in maintaining the interior environment of the CNS, particularly the ion balance. Potassium ions released upon excitation of groups of neurons are removed from the extracellular space via the network of astrocyte processes. Astrocytes probably also take up CO₂ released by nerve cells and thus keep the interstitial pH at a constant value of 7.3. Astrocyte processes enclose the synapses and seal off the synaptic cleft. They also take up neurotransmitters, and as recent studies have demonstrated, release neurotransmitters and can thus influence synaptic transmission.

Oligodendrocytes have a smaller, darker cell nucleus and only a few, sparsely branched processes. In the gray matter, they accompany neurons (satellite cells) (B). In the white matter, they lie in rows between the nerve fibers (intrafascicular glia). They produce and maintain the myelin sheath (p. 39, B and C). In the peripheral nervous system the myelin sheath is formed by Schwann cells.

Microglial cells have an oval or rodlike cell nucleus and short, branched processes. They exhibit ameboid mobility and can migrate within the brain tissue. In response to tissue destruction, they phagocytose material (scavenger cells) and round up into spheres (gitter cell).

Recent evidence has verified the frequently expressed view that microglia are derived not only from the ectoderm but also from the mesoderm.
A Equivalent images of neuroglia: Nissl staining (top row), silver impregnation (bottom row)

B Oligodendrocytes as satellites of a nerve cell

C Astrocyte in tissue culture
Cross Sections of the Spinal Cord (A–D)

Cross sections at different levels (left, myelin stain; right, cellular stain) vary considerably. In the regions of cervical enlargement and lumbar enlargement, the cross-sectional area is larger than in the rest of the spinal cord; it is largest at the C4–C5 and L4–L5 levels. In both swellings, the numerous nerves that supply the extremities cause an increase in gray matter.

The white matter is most extensive in the cervical region and diminishes gradually in caudal direction; the ascending sensory tracts increase in number from the sacral to the cervical region as more fibers are added, while the descending motor tracts decrease from the cervical to the sacral regions as fibers terminate at various levels.

The butterfly configuration of the gray matter changes in shape at the various levels, and so does the posterolateral tract (Lissauer’s tract) (A–D1).

The posterior horn is narrow in the cervical spinal cord; its tip ends in the cap-shaped marginal zone (nucleus posteromarginalis) (A2). The lateral angle between the posterior and anterior horn is occupied by the reticular formation (AD3). The gelatinous substance (Rolando’s substance) (A–D4) contains small, mostly peptidergic neurons where posterior root fibers of various calibers terminate; it also contains descending fibers from the brain stem (raphe nuclei, p. 108, B28; reticular formation, p. 146). Unmyelinated processes of neurons ascend or descend for one to four root levels within the posterolateral tract (Lissauer’s tract) and then reenter into the gelatinous substance. Some of the processes run within the lateral spinothalamic tract to the thalamus (p. 328). The fibers of proprioceptive sensibility in the muscles (muscle spindles) terminate in the posterior thoracic nucleus (dorsal nucleus of Clarke) (AB5) where the tracts to the cerebellum begin. The reduced gray matter of the thoracic spinal cord has a slender posterior horn with a prominent dorsal nucleus. In the plump posterior horn of the lumbar and sacral spinal cords, the gelatinous substance (CD4) is much enlarged and borders dorsally on the narrow band of the marginal zone (CD2).

The lateral horn forms in the thoracic spinal cord the lateral intermediate substance (B6). It contains sympathetic nerve fibers mainly for the vasomotor system, the efferent fibers of which emerge via the anterior root. Sympathetic neurons also lie medially in the intermediomedial nucleus (B7). In the sacral spinal cord, parasympathetic neurons form the intermediolateral nucleus (B7) and intermediomedial nucleus (D8).

The anterior horn expands in the cervical spinal cord and contains several nuclei with large motor neurons, all of which are cholinergic.

Medial group of nuclei
- Anteromedial nucleus (A9)
- Posteromedial nucleus (A10)

Lateral group of nuclei
- Anterolateral nucleus (A11)
- Posterolateral nucleus (A12)
- Retroposterolateral nucleus (A13)

In the region supplying the upper limbs, the anterior horn is far more differentiated than in the thoracic spinal cord where only a few cell groups can be identified. The expanded, plump anterior horn of the lumbar and sacral spinal cords, which supplies the lower limbs, again contains several groups of nuclei.
Transverse Sections of the Spinal Cord

A  Cervical spinal cord

B  Thoracic spinal cord

C  Lumbar spinal cord

D  Sacral spinal cord

Ascending Pathways (A–D)

Tracts of the Anterolateral Funiculus (A)

Lateral spinothalamic tract (A1). The afferent, poorly myelinated posterior root fibers (A2) (first neuron of sensory pathway) bifurcate in the posterolateral tract (Lissauer's tract) and terminate at the cells of the gelatinous substance of the posterior horn. The fibers of the tract originate here, cross in the white commissure to the opposite side, and ascend in the lateral funiculus to the thalamus (second neuron). This pathway transmits pain and temperature sensation, exteroceptive and proprioceptive impulses. It is somatotopically subdivided; sacral (S) and lumbar (L) fibers are located dorsolaterally, while thoracic (T) and cervical (C) fibers are located ventromedially. Fibers for pain sensation probably lie superficially, while those for temperature sensation lie more deeply.

Anterior spinothalamic tract (A3). The afferent fibers (A4) (first neuron) bifurcate into ascending and descending branches and terminate at posterior horn cells, the fibers of which cross to the opposite side and ascend in the anterior funiculus to the thalamus (second neuron). They transmit crude touch and pressure sensations. Together with the lateral tract, they form the pathway of protopathic sensibility (p. 328).

The spino-tectal tract (A5) carries pain fibers to the roof of the midbrain (contraction of pupils when in pain).

Pathways of the Posterior Funiculus (C, D)

Fasciculus gracilis (of Goll) (C6) and fasciculus cuneatus (of Burdach) (C7). The thick heavily myelinated fibers ascend without relay in the ipsilateral posterior funiculi. They belong to the first neuron of the sensory pathway and terminate at the nerve cells of the posterior funiculus nuclei (second neuron) (p. 140, B5, B6). They transmit exteroceptive and proprioceptive impulses of the epicritic sensibility (exteroceptive, information on localization and quality of tactile sensation; proprioceptive, information on limb position and body posture). The posterior funiculi are somatotopically subdivided; the sacral fibers lie medially, followed laterally by the lumbar and thoracic fibers (fasciculus gracilis). The fibers from T3 to C2 lie laterally and form the fasciculus cuneatus.

Short ascending collaterals (C8) branch from the ascending fibers. They terminate at the posterior horn cells and form compact bundles, namely, the comma tract of Schultze (D9) in the cervical spinal cord, Flechsig’s oval field (D10) in the thoracic spinal cord, and the Phillippe–Gombault triangle (D11) in the sacral spinal cord.

Cerebellar Pathways of the Lateral Funiculus (B)

Posterior spinocerebellar tract (Flechsig’s tract) (B12). The afferent posterior horn fibers (first neuron) terminate at the cells of the dorsal nucleus of Clarke (B13) from where the tract (second neuron) originates. It runs along the margin of the ipsilateral lateral funiculus to the cerebellum and transmits mainly proprioceptive impulses (from joints, tendons, muscle spindles).

Anterior spinocerebellar tract (Gowers’ tract) (B14). The cells of origin lie in the posterior horn. Their fibers (second neuron) ascend ipsilaterally as well as contralaterally along the anterolateral margin of the spinal cord to the cerebellum, to which they transmit exteroceptive and proprioceptive impulses. Both cerebellar pathways are somatotopically subdivided; the sacral fibers lie dorsally, the lumbar and thoracic fibers ventrally.

The spino-olivary tract (B15) and vestibulospinal tract (B16) arise from the posterior horn cells of the cervical spinal cord; they transmit mainly proprioceptive impulses to the inferior olive of the opposite side and to the vestibular nuclei.

A–C17 Neurons in the spinal ganglion (first neuron) (p. 71, A7).
Cranial Nerves (V, VII – XII)

Hypoglossal Nerve (A, B)

The twelfth cranial nerve is an exclusively somatomotor nerve for the tongue muscles. Its nucleus, the nucleus of the hypoglossal nerve (B1), forms a column of large multipolar neurons in the floor of the rhomboid fossa (trigon of hypoglossal nerve). It consists of a number of cell groups, each of which innervates a particular muscle of the tongue. The nerve fibers emerge between pyramid and olive and form two bundles that then combine into a nerve trunk.

The nerve leaves the skull through the canal of the hypoglossal nerve (B2) and descends laterally to the vagus nerve and the internal carotid artery. It forms a loop, the arch of the hypoglossal nerve (A3), and reaches the root of the tongue slightly above the hyoid bone between the hypoglossal muscle and the mylohyoid muscle, where it ramifies into terminal branches.

Fiber bundles of the first and second cervical nerves adhere to the hypoglossal nerve. They form the deep cervical ansa (branches for the lower hyoid bone muscles) by branching off again as superior root (A4) and combining with the inferior root (A5) (second and third cervical nerve). The cervical fibers for the geniohyoid muscle (A6) and the thyrohyoid muscle (A7) continue to run in the hypoglossal nerve. The hypoglossal nerve gives off the lingual branches to the hypoglossal muscle (A8), the genioglossal muscle (A9), the styloglossal muscle (A10), and to the intrinsic muscles of the body of the tongue (A11). Innervation of the tongue muscles is strictly ipsilateral.

Clinical tip: Injury to the hypoglossal nerve causes hemilateral shrinkage of the tongue (hemiatrophy). When the tongue is stuck out, it turns to the affected side because the genioglossal muscle, which moves the tongue to the front, dominates on the healthy side.

Accessory Nerve (C, D)

The eleventh cranial nerve is exclusively a somatomotor nerve; its external branch supplies the sternocleidomastoid muscle (D12) and the trapezius muscle (D13). Its nucleus, the spinal nucleus of the accessory nerve (C14), forms a narrow cell column from C1 to C5 or C6. The large multipolar neurons lie at the lateral aspect of the anterior horn. The cells of the caudal section supply the trapezius muscle, and those of the cranial section supply the sternocleidomastoid muscle. The nerve fibers emerge from the lateral aspect of the cervical spinal cord between posterior root and anterior root and combine to form a bundle that enters the skull as the spinal root (C15) alongside the spinal cord through the foramen magnum. Fiber bundles from the caudal part of the ambiguous nucleus join the nerve here as cranial roots (C16). Both components pass through the jugular foramen (C17). Immediately after passing, the fibers change from the ambiguous nucleus as internal branches (C18) over to the vagus nerve (C19). The fibers from the cervical spinal cord form the external branch (C20), which supplies as accessory nerve the sternocleidomastoid muscle and the trapezius muscle. It passes through the sternocleidomastoid muscle and reaches the trapezius muscle with its terminal branches.

Clinical tip: Injury to the accessory nerve causes the head to tilt (plagiocephaly). The arm can no longer be lifted above the horizontal.
Eleventh and Twelfth Cranial Nerves

A Muscles supplied by the hypoglossal nerve

B Nuclear region and exit of the hypoglossal nerve

C Nuclear region and exit of the accessory nerve

D Muscles supplied by the accessory nerve