Physiology of the central nervous system

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Abstract. The central nervous system (CNS) is the highest regulator of the body's vital functions. It integrates sensory information, controls motor activity, regulates internal organs, and performs higher mental functions. This article examines the fundamental physiological principles of CNS function, including neuronal structure, excitation conduction, synaptic transmission, and the functioning of the spinal cord, brainstem, cerebellum, and cerebral cortex. Particular attention is paid to the mechanisms of reflex activity and neuroplasticity.

Keywords: CNS, neuron, synapse, brain, reflex, neurotransmission, cortex, excitation.

Introduction. The central nervous system (CNS) is the central link in the regulation and coordination of all vital processes in the human body. It is a highly organized biological structure comprising the brain and spinal cord, billions of neurons, and trillions of synaptic connections. Thanks to the functioning of the central nervous system, a person is able to perceive and analyze information from the environment, respond to stimuli, control voluntary and involuntary movements, and develop higher mental functions such as consciousness, thinking, speech, memory, and emotions.

From a physiological perspective, the central nervous system integrates the activity of all organs and systems. It receives and processes signals from receptors, generates responses, and regulates homeostasis—the body's internal stability despite changes in external conditions. The central nervous system not only responds to stimuli but also actively anticipates possible scenarios, adapting an individual's behavior to enhance survival and the effectiveness of interactions with the external environment.

At the cellular level, the central nervous system consists of specialized nerve cells—neurons—and support cells—neuroglia. The primary function of neurons is to conduct nerve impulses and participate in synaptic transmission, while glial cells provide support, nutrition, protection, and regulation of the environment necessary for neuronal function. The complex connections between billions of these cells form a dynamic network capable of learning, adapting, and recovering from injury.

Modern CNS physiology actively studies the mechanisms of nerve impulse generation and conduction, the principles of synaptic transmission, the functional organization of various brain regions, and the mechanisms of interstructural interactions. Much attention is paid to the study of neuroplasticity—the brain's ability to change under the influence of experience, which underlies learning, memory, and functional recovery after injury.

Thus, the central nervous system is not only the anatomical and physiological control center of the body, but also the foundation of individuality, consciousness, and cognition of the surrounding world. Understanding its functions is key to medicine, psychology, neuroscience, and a number of related disciplines aimed at maintaining and restoring human health.

Neurons and neuroglia: the cellular basis of the CNS. The central nervous system is composed of two main cell types—neurons and neuroglia—each performing unique but closely interconnected functions that support the complex functioning of the brain and spinal cord. Neurons are the basic structural and functional units of the nervous system. They are specialized cells capable of excitation and transmission of electrical signals—nerve impulses. Each neuron consists of a cell body (soma), containing a nucleus and organelles; dendrites, which receive signals from other cells; and an axon, along which the impulse is transmitted. At the end of the axon are synapses—structures that facilitate chemical transmission of signals to other neurons, muscles, or glands.

Neurons are classified by the functions they perform: Afferent (sensory) neurons transmit information from receptors to the central nervous system. Efferent (motor) neurons direct impulses from the central nervous system to the effector organs—muscles and glands. Interneurons (association) neurons communicate between afferent and efferent neurons and form complex neural networks within the brain and spinal cord. Although neurons make up a minority of the central nervous system's cell population, they are responsible for information transmission, signal processing, and the implementation of all higher brain functions.

Neuroglia are support cells that significantly outnumber neurons. Their role cannot be underestimated: they provide structural and metabolic support for neurons, participate in maintaining ionic balance, form the myelin sheath, regulate synaptic transmission, participate in the brain's immune responses, and even in learning and memory processes.

The main types of glial cells include: Astrocytes, which perform barrier, trophic, and regulatory functions. They participate in the formation of the blood-brain barrier, regulate blood flow in the brain, and utilize excess neurotransmitters and ions, promoting homeostasis of the nervous tissue. Oligodendrocytes, which form the myelin sheath around axons in the central nervous system, ensure rapid and efficient conduction of nerve impulses. Microglia, which perform a protective function, act as macrophages in the central nervous system. These cells actively participate in the removal of damaged cells and pathogens, as well as in the modulation of inflammatory processes.

Thus, neurons and glial cells form a tightly integrated and interdependent system. Without neurons, information transmission and processing are impossible, but without neuroglia, neurons would not function properly and would be subject to rapid degradation and loss of viability. The coordinated work of these cells underlies the diverse functions of the central nervous system.

Nerve impulse transmission and synapses. Information transmission in the central nervous system is accomplished through electrochemical processes occurring in neurons. These processes are based on changes in membrane potential associated with the movement of ions across the cell membrane.

Resting membrane potential. At rest, the neuron membrane has a potential difference between the inner and outer surfaces of approximately -70 mV. This membrane potential is created and maintained by the uneven distribution of sodium (Na^+), potassium (K^+), chloride (Cl^-), and other ions.

The sodium-potassium pump (Na^+/K^+-ATPase) plays a key role, actively pumping 3 sodium ions out of the cell and 2 potassium ions into the cell, consuming ATP energy.

As a result, the inner membrane remains negatively charged compared to the outer membrane.

Action potential generation and conduction. When a neuron receives an excitatory signal, the membrane depolarizes: sodium channels open, and Na^+ ions rapidly rush into the cell, reducing the negative charge. If depolarization reaches a threshold (approximately –55 mV), an action potential is generated—a short and sharp change in membrane potential. Potassium channels then open, and K^+ ions exit the cell, causing repolarization and restoration of the initial state. This process lasts milliseconds but ensures signal transmission along the axon over long distances.

Impulse conduction along the axon can be: Continuous—in unmyelinated fibers; Saltatory (jumping)—in myelinated axons, where the impulse "jumps" from one node of Ranvier to another, significantly accelerating the transmission speed (up to 120 m/s).

Synapses: Structure and Function. A signal from one neuron to another is transmitted through a synapse—a specialized junction between the presynaptic neuron and the postsynaptic cell (another neuron, muscle, or gland).

The synapse consists of: a presynaptic membrane; a synaptic cleft (20–30 nm); and a postsynaptic membrane containing receptors.

When an action potential arrives at the presynaptic terminal, calcium channels open, and Ca^{2+} ions stimulate the release of neurotransmitters from vesicles into the synaptic cleft. Neurotransmitters (e.g., acetylcholine, glutamate, dopamine, serotonin, GABA) bind to receptors on the postsynaptic membrane, causing either depolarization (excitatory effect) or hyperpolarization (inhibitory effect).

Synaptic plasticity. Synapses have a unique capacity for plasticity—changing the efficiency of signal transmission in response to experience, learning, or injury. Synaptic plasticity underlies memory, learning, and adaptation. The most well-known forms of synaptic plasticity are long-term potentiation (LTP) and long-term depression (LTD), which alter the strength of synaptic transmission over long periods of time.

Synapses play a key role in neurophysiology, connecting all parts of the nervous system into a single information network. They facilitate signal integration, cellular decision-making, and the fine-grained regulation of all bodily functions.

Structure and Functions of the Central Nervous System. The central nervous system (CNS) consists of the spinal cord and brain, each of which performs specific functions in the coordination, regulation, and integration of all processes occurring in the body. Each part has a complex structure and interacts with other levels of neural regulation, ensuring homeostasis, adaptation, and voluntary and involuntary actions.

Spinal cord. The spinal cord is an elongated tubular structure located within the spinal canal. It consists of gray matter (inside, shaped like a butterfly) and white matter (outside), containing conduction pathways. The spinal cord is segmented—it has 31 segments, each of which gives rise to a pair of spinal nerves innervating a specific area of the body.

Main functions: Conductive—transmitting sensory information from the periphery to the brain and motor signals from the brain to the organs. Reflexive—providing simple automatic reactions, such as the knee jerk, pulling a hand away from a hot object, urination, and defecation. These reflexes are mediated by reflex arcs that do not require conscious involvement.

Brainstem. The brainstem includes three main parts: the medulla oblongata, the pons, and the midbrain. These are the oldest parts of the brain, maintaining the basic functions of life.

Functions: Vital centers: The medulla oblongata contains the centers for respiration, cardiac activity, blood pressure regulation, as well as the center for vomiting, swallowing, and coughing. Conduction function: The brainstem connects the spinal cord with the higher parts of the brain, conducting sensory and motor impulses. Cranial nerve nuclei: The brainstem contains the nuclei of cranial nerves III through XII, which control eye movement, facial expressions, swallowing, and other functions. Regulation of wakefulness and sleep: Part of the reticular formation of the brainstem is involved in maintaining consciousness, attention, and sleep.

Cerebellum. The cerebellum is a structure located in the posterior cranial fossa, with a characteristic sulcal surface and two hemispheres.

Functions: Motor coordination: The cerebellum integrates signals from the cerebral cortex, vestibular apparatus, and proprioceptors to ensure smooth and precise movements. Balance control ensures stable body posture and gait. Muscle tone regulation helps maintain a constant level of muscle tension. Motor skill learning plays an important role in the automation of movements (e.g., riding a bicycle, playing a musical instrument).

Damage to the cerebellum causes ataxia—impaired motor coordination, unsteadiness of gait, and tremors of the limbs during purposeful movements.

Hypothalamus and thalamus. These structures form the diencephalon and play a key role in regulating homeostasis and integrating sensory information. The thalamus is a large, paired structure that functions as a sensory relay center: all sensory information (vision, hearing, touch, pain impulses) passes through the thalamus, where it is processed and sent to the appropriate areas of the cerebral cortex.

The hypothalamus is the main coordinating center of the autonomic nervous and endocrine systems. It regulates: body temperature; hunger and thirst; sexual behavior; Circadian rhythms (sleep-wake); emotional reactions (interaction with the limbic system); production of pituitary hormones (via hormone-releasing factors).

The hypothalamus is vital for the body's adaptation to internal and external changes.

The cerebral cortex. The cortex is the highest level of organization of the central nervous system, consisting of six layers of neurons that perform complex cognitive, sensory, and motor functions. The cortex is divided into four main lobes:

Frontal lobe: responsible for planning, speech (Broca's area), voluntary movements, behavioral control, and decision-making. Parietal lobe: processes information from cutaneous receptors and muscles, and is involved in spatial orientation. Temporal lobe: enables sound perception, speech comprehension (Wernicke's area), and is involved in memory and emotional processing. Occipital lobe: responsible for processing visual information.

The interconnections between the cortex's regions support higher nervous system functions: learning, consciousness, motivation, and self-awareness. Neuroplasticity—the brain's ability to change its structure and functional connections—is particularly pronounced in childhood but persists throughout life.

Principles of the CNS: Reflex Arc and Plasticity. The CNS operates on the principle of reflex activity—the body's response to stimulation.

A classic reflex arc includes: Receptor; Afferent neuron; Central integrating element; Efferent neuron; Efferent neuron (muscle or gland).

Neuroplasticity—the ability of the nervous system to restructure itself—underlies recovery from injury, learning, and the formation of new skills. The development of synapses, the formation of new axons, and the influence of environmental factors (experience, training, stimulation) contribute to CNS adaptation.

Conclusion. The physiology of the central nervous system reveals the subtle mechanisms that govern all bodily functions. Understanding the structure and functions of the central nervous system is important not only for medicine and biology, but also for psychology, pedagogy, and neuroscience. Modern research in neurophysiology opens up new perspectives in the treatment of diseases, patient rehabilitation, and the creation of brain-computer interfaces. The central nervous system is a remarkable and dynamic control center that ensures the integrity of the human personality and its interaction with the outside world.

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