Body Systems and Homeostasis

The systems of the body participate in maintaining homeostasis, that is, the relative constancy of the internal environment despite external environmental changes. This review offers a succinct summary of how the body's systems function and mentions various regulatory mechanisms that allow each system to contribute to homeostasis.

The internal environment of the body is tissue fluid, which bathes all cells making up the body. The composition of tissue fluid must remain constant if cells are to remain alive and healthy. Tissue fluid is nourished and purified when molecules are exchanged across thin capillary walls. Tissue fluid remains constant only if the composition of blood remains constant.

Circulatory System

The circulatory system is composed of vessels (arteries and arterioles) that take blood from the heart, thin-walled capillaries where exchange occurs, and vessels (venules and veins) that return blood to the heart. Blood is pumped by the heart simultaneously into two circuits: the pulmonary and systemic circuits. The pulmonary system takes blood through the lungs where gas exchange occurs and the systemic system transports blood to all parts of the body where exchange with tissue fluid takes place.

In practical terms, we can think of the systemic circuit as a means to conduct blood to and away from the capillaries, because only here does exchange with tissue fluid take place. Nutrient molecules leave the capillaries to be taken up by the cells, and waste molecules given off by the cells are received by the capillaries to be transported away. Capillaries abound in all parts of the body, and no cell is more than a few micrometers from a capillary.

Blood is composed of two parts: formed elements and plasma. All of the formed elements contribute to homeostasis, as outlined in table 1. Oxygen is utilized during cellular respiration, a process that provides energy for metabolic activities. Fighting infection keeps the body intact and prevents it from succumbing to disease caused by viruses and bacteria. Clotting of blood when a vessel has been cut prevents the loss of this vital fluid.

Table 1 - Formed Elements

Name	Function
Red blood cells	Transport oxygen and hydrogen ions
White blood cells	Fight infection
Platelets	Assist blood clotting

Plasma, too, contributes to homeostasis, as noted in table 2. The nutrients needed and wastes given off by cells are carried in plasma. Nutrients leave plasma at the capillaries and wastes enter plasma at the capillaries. Blood pressure created by the pumping of the heart forces water out of a capillary at the arteriole end and osmotic pressure maintained largely by proteins draws water back in at the venous end of a capillary. Plasma proteins not only maintain osmotic pressure, but also buffer the blood; a function they share with the salts, as we shall discuss in more detail later.

Table 2 - Plasma

Component	Function
Water	Provides fluid environment
Proteins	Create osmotic pressure, aid clotting, and help buffer blood
Nutrients	Required for cellular metabolism
Wastes	Produced by cellular metabolism
Salts	Aid metabolic activity and help buffer blood
Hormones	Chemical messengers

Lymphatic System

Tissue fluid is constantly refreshed because more water exits a capillary than returns to it. Lymphatic capillaries collect excess tissue fluid, and return it via lymphatic vessels to the systemic veins. Lymph nodes present along the length of lymphatic vessels filter and purify lymph. Lymph nodes are rich in lymphocytes, the type of white blood cell that responds to antigens allowing immunity to develop.

Special lymph capillaries, called lacteals, are found within the villi. They absorb the products of fat digestion.

Nervous System

Since the nervous system does not store nutrients, it must receive a continuous supply from blood. Any interruption to the flow of blood may bring brain damage or death. The nervous system maintains homeostasis by controlling and regulating the other parts of the body. A deviation from a normal set point acts as a stimulus to a receptor, which sends nerve impulses to a regulating center in the brain. The brain directs an effector to act in such a way that an adaptive response takes place. If, for example, the deviation was a lowering of body temperature, the effector acts to increase body temperature. The adaptive response returns the body to a state of normalcy and the receptor, the regulating center, and the effector temporarily cease their activities. Since the effector is regulated by the very conditions it produced, this process is called control by negative feedback (fig. 2).

This manner of regulating normalcy results in a fluctuation between two extreme levels. Not until body temperature drops below normal do receptors stimulate the regulating center and effectors act to raise body temperature. Regulating centers are located in the central nervous system, consisting of the brain and spinal cord (fig. 3a, 3b). The hypothalamus is a portion of the brain particularly concerned with homeostasis; it influences the action of the medulla oblongata, a lower part of the brain, the autonomic nervous system, and the pituitary gland.

The nervous system has two major portions: the central nervous system and the peripheral nervous system (table 3). The peripheral nervous system consists of the cranial and spinal nerves. The autonomic nervous system is a part of peripheral nervous system and contains motor neurons that control internal organs. It operates at the subconscious level and has two divisions, the sympathetic and parasympathetic systems. In general, the sympathetic system brings about those results we associate with emergency situations, often called fight or flight reactions, and the parasympathetic system produces those effects necessary to our everyday existence.

Table 3 - Nervous System

Part	Function
CNS*	
Brain	
Cerebrum	Consciousness, creativity, thought, morals, memory
Lower portions	Reception of sensory data, coordination of muscular activity, homeostasis
Spinal cord	Automatic reflex actions
PNS**	
Cranial nerves, spinal nerves	Carry sensory information to motor impulses from the CNS
Autonomic system	Those cranial and spinal motor nerves that control internal organs

*CNS = Central nervous system
**PNS = Peripheral nervous system

The reflex arc is the action unit of the nervous system. In this arc, a sense receptor initiates nerve impulses that travel by way of a sensory fiber to the central nervous system where integration takes place. Following this, nerve impulses travel by way of motor neurons to either a gland or muscle that then reacts.

The nerve impulse is an electrochemical change that is propagated along the length of a neuron from dendrite to axon. The nerve impulse is the same in all neurons; the specific effect that results is dependent on the organ being stimulated. For example, each part of the cerebrum has a different function: stimulation of the occipital lobes results in vision; stimulation of the temporal lobe produces a sensation of sound. Sensations are the prerogative of the cerebrum since only the cerebrum is responsible for consciousness.

A region of close proximity between neurons is called a synapse. At a synapse, one neuron ends at the presynaptic membrane and the next neuron begins at the postsynaptic membrane. The small gap between is the synaptic cleft. Transmission across a synapse is by means of neurotransmitter substances which are stored in small synaptic vesicles on the axon side of the synapse. Nerve impulses cause the release of neurotransmitter substances, which diffuses across the synaptic cleft to be received by the postsynaptic membrane. If stimulation results, nerve impulses begin in the next neuron (fig. 4).

A neuromuscular junction has the same components as a synapse. In this case, however, the postsynaptic membrane is the membrane of a muscle fiber. Again a neurotransmitter substance diffuses across the synaptic cleft but this time the action potential that travels along the T system of a muscle fiber causes the release of calcium, which triggers a muscle contraction. When a skeletal muscle contracts, the actin filaments slide past the myosin filaments, thereby shortening sarcomeres and therefore, the muscle. While at first it may seem that the muscular system does not play a role in homeostasis, voluntary muscles very definitely do play a role because by their contraction the individual can take the necessary actions to bring about a more favorable external environment.

Endocrine System

The major endocrine glands of the body are listed in table 4. The hormones produced by these glands are chemical messengers that are transported throughout the body by the blood. A hormone is capable of stimulating only its target organ or cells since they alone have receptors for that hormone. The endocrine system and the nervous system both coordinate the activities of body parts. The nervous system reacts quickly to external and internal stimuli, whereas the endocrine system is slower to act but its effects are longer lasting.

Table 4 - Major Endocrine Glands and Their Major Hormones

Name	Hormone	Function
Hypothalamus	Hypothalmic-releasing and release-inhibiting hormones	Regulate anterior pituitary hormones
Anterior pituitary	Thyroid-stimulating	Stimulates thyroid
	Adrenocorticotropic	Stimulates adrenal cortex
	Gonadotropic	Stimulates gonads
Posterior pituitary	Antidiuretic	Promotes water reabsorption by kidney
Thyroid	Thyroxin	Increases metabolic rate
Parathyroid	Parathyroid	Maintains blood calcium and phosphorus levels
Adrenal cortex	Glucocorticoids (e.g., cortisol)	Promotes gluconeogenesis
	Mineralocorticoids (e.g., aldosterone)	Promotes sodium reabsorption by kidneys
Adrenal medulla	Epinephrine and norepinephrine	Stimulates fight or flight reaction
Pancreas	Insulin	Lowers blood sugar level
	Glucagon	Raises blood sugar level
Gonads	Androgens (male) Estrogens and progesterone (female)	Promotes secondary sex characteristics

Respiratory System

Oxygen-laden air is inhaled into the alveoli of the lungs by way of the structures illustrated in fig. 5. Blood within the pulmonary artery is oxygen-poor and contains a large concentration of carbon dioxide. As blood passes through the capillaries surrounding the alveoli, oxygen diffuses into blood and carbon dioxide diffuses out of blood into the alveoli. Thereafter, carbon dioxide is exhaled by moving from the alveoli to the nose. Since the blood within the pulmonary vein is oxygen-rich and contains a small concentration of carbon dioxide, it is clear that carbon dioxide has been traded for oxygen as blood passes through the lungs.

The respiratory center, located in the medulla oblongata automatically discharges nerve impulses to the diaphragm and the muscles of the rib cage. In its relaxed state, the diaphragm is dome-shaped, but upon stimulation, it contracts and lowers. Also the rib cage moves upward and outward. As the thoracic cavity increases in size, air pressure within the expanded lungs lowers and is immediately rebalanced by air rushing in through the nose. This is why it can be said that humans breathe by negative pressure. When the respiratory center stops sending out stimulatory nerve impulses the diaphragm and rib cage resume their original positions and exhalation occurs.

There are chemoreceptors adjacent to the respiratory center in the medulla oblongata that are sensitive to the carbon dioxide content of the blood, and chemoreceptors in aorta and carotid arteries that are sensitive to both the carbon dioxide content and the pH of the blood. When the carbon dioxide concentration rises or when the pH lowers the respiratory center is stimulated and the breathing rate increases. It is interesting to observe that the oxygen content of the blood does not directly affect the activity of the respiratory center.

Digestive System

When blood is pumped from the left ventricle of the heart, much of it passes down the dorsal aorta to the organs of the abdomen. Chief among these organs are those of the digestive tract (fig. 6).

Within the digestive tract the food is broken down to nutrient molecules small enough to be absorbed by the villi of the small intestine. Digestive enzymes are produced by the digestive tract and by the pancreas. In addition the liver produces bile, an emulsifier that plays a role in the digestion of fats. Bile, which is stored in the gallbladder, enters the small intestine along with the pancreatic enzymes. Following the absorption of nutrients, blood passes from the region of the small intestine to the liver by way of the hepatic portal vein.

The liver, which monitors the blood, is a very important organ of homeostasis. The liver breaks down toxic substances like alcohol and other drugs, and it produces urea, the end product of nitrogenous metabolism. The liver produces the plasma proteins and stores glucose as glycogen after eating. In between eating it releases glucose, thereby keeping the blood glucose concentration constant. The liver destroys old blood cells and breaks down hemoglobin--hemoglobin breakdown products are excreted in bile.

Urinary System

As blood passes through the kidneys, urine is made and excreted. Urine is composed of substances not needed by cells: end-products of metabolism (e.g., urea) and excess salts and water. In the process of making urine, blood is first filtered and all small molecules, including both nutrients and wastes, enter a nephron. Then the nutrient molecules and much of the salts and water are reabsorbed back into the blood, while unwanted substances remain within the nephron to become a part of urine. Tubular secretion is another way by which certain molecules enter a nephron just before urine enters a collecting duct. Thereafter urine leaves the body by way of the structures illustrated in fig. 7.

Examples of Homeostasis

Now that we have reviewed the basic contributions of the body's systems we will consider examples of how these systems cooperate in maintaining homeostasis in certain instances.

Control of Temperature

The nude body is capable of maintaining a normal body temperature somewhere between 37° C and 38° C even if the external temperature varies between 16° C and 54° C. The metabolic activity of cells is the furnace of the body because cellular reactions give off heat as a by-product. When the body is at rest, body heat is generated primarily by the liver, heart, brain, and endocrine glands but when the muscles are active they generate many times the heat produced by these organs. Therefore, increased muscle activity by rubbing the hands or stamping the feet is used as a short-term measure to raise body temperature. On a long-term basis, the hormone thyroxin produced by the thyroid gland stimulates cells to a higher metabolic rate. Therefore, we would expect persons living in a cold climate to have a higher metabolic rate than those who live in a moderate climate.

The regulatory center for body temperature, located in the hypothalamus, is sensitive to temperature changes in arterial blood flowing through it. Depending on the body temperature, the regulatory center brings about the adaptive responses listed in table 5, and body temperature then increases or decreases.

Table 5 - Hypothalmic Regulatory Center

Structures	When Body Cools	When Body Warms
Superficial blood vessels	Constricts	Dilates
Sweat glands	Inactivates	Activates
Muscles	Shivering	No shivering

Regulation of the size of superficial arterial blood vessels and the activity of sweat glands is an important means by which body heat can be either conserved or dissipated. We can liken these activities to either closing or opening the windows of a house. The autonomic nervous system controls these reactions; the sympathetic system brings about the effects that conserve heat, and the parasympathetic acts to release heat. The body cools when blood vessels lying in the skin are dilated and the warm blood passing through them loses heat to the environment by radiation. Sweating also cools the body because as perspiration evaporates, the body loses heat. Evaporation is more efficient on dry days than on humid days; humidity, then, does affect our ability to cool off.

If body temperature falls too low, shivering in addition to vasoconstriction will occur. Shivering requires that nerve impulses be sent to the skeletal muscles.

Humans contribute to the regulation of body heat by wearing appropriate clothing. In cold climates, humans wear clothing that traps an insulating layer of warm air next to the body to compensate for a lack of body hair. The formation of "goose bumps" is an ineffective attempt to raise the now absent hairs of the body to achieve a layer of trapped air naturally. In warm climates, clothing is worn to protect the body against the burning rays of the sun, but such clothing should be loose so that heat may still be lost by radiation.

Control of Blood Pressure

Blood pressure, which is the pressure of blood against blood vessel walls, is created by a beating of the heart. The mean arterial blood pressure averages about 100 mm Hg, although it increases progressively from birth to old age due to decreasing elasticity and narrowing of the arteries.

Arterial blood pressure will rise whenever blood volume increases or whenever there is a decrease in the cross-sectional area of the arteries. Sympathetic neurons under the control of regulatory centers (called cardiac and vasomotor centers) located in the medulla oblongata of the brain, can increase the heartbeat and constrict the arteries. A faster heartbeat temporarily increases the amount of blood within the arteries, and constriction of blood vessels, usually those of the skin and intestines, reduces their cross-sectional area.

The vasomotor center can be activated by impulses received from pressoreceptors located in the aorta and carotid arteries. When pressoreceptors are stimulated by a decrease in blood volume, as when we stand up suddenly after lying down, nerve impulses are sent to the vasomotor center and then blood pressure rises. The vasomotor center can also be effective when blood volume suddenly decreases, as when hemorrhaging occurs. At these times, it causes the blood reservoirs of the body (i.e., the veins, spleen, and liver) to contract and send more blood into the arteries.

The kidneys are also involved in monitoring blood pressure because of the role they play in regulating blood volume. When blood pressure decreases, the kidneys release renin, an enzyme that leads to the formation of angiotensin II, a powerful vasoconstrictor that also stimulates the adrenal cortex to release aldosterone. Under the influence of aldosterone, the kidneys retain sodium. As sodium is reabsorbed, water follows passively and both blood volume and blood pressure rise. In the presence of high blood pressure, the heart releases atrial natriuretic hormone, which has the opposite effect on the kidneys. This illustrates that homeostasis is often regulated by the contrary actions of hormones.

Control of pH

The normal pH of arterial blood is 7.4. A person is considered to have acidosis when the pH is below this value and to have alkalosis when it rises above pH 7.4. The lower limit at which a person can live is about pH 7.0 and the upper limit is about pH 7.8. To prevent a change in the pH of the body, all body fluids including cytoplasm are buffered. A buffer is a chemical or a combination of chemicals that can absorb either hydrogen ions (H^+) or hydroxide ions and therefore maintain a relatively constant hydrogen ion concentration.

Proteins are effective chemical buffers both within cells and within blood. Hemoglobin is the most active protein buffer within blood, and it absorbs excess hydrogen ions when it is not carrying oxygen.

There are two other types of chemical buffers in body fluids--the carbonate and phosphate buffer systems. The phosphate system (NaH_2PO_4 and Na_2HPO_4) effectively buffers urine and cytoplasm. The carbonate system (a mixture of carbonic acid, H_2CO_3, and sodium bicarbonate, $NaHCO_3$) is present in both tissue fluid and blood. The concentration of buffering substances is regulated by the lungs and/or kidneys. For example, when carbon dioxide is exhaled by the lungs or the bicarbonate ion is excreted by the kidneys, the concentration of the buffering substances can return to their most effective levels.

If the hydrogen ion concentration of the blood remains high, the respiratory center of the medulla oblongata is stimulated and the breathing rate increases. As carbon dioxide is excreted the pH shifts toward normal. This respiratory regulation of the acid-base balance is a physiological type of buffer system that is an important adjunct to the chemical systems discussed.

The kidneys are a powerful mechanism by which the pH may be regulated. The kidneys may form either an acid or alkaline urine, bringing the hydrogen ion concentration back toward normal. When the kidneys form an acid urine, they excrete H+, and when the kidneys form an alkaline urine, they excrete the bicarbonate ion. However, the full effect of the kidneys is not realized for ten to twenty hours.

Notice that the pH of the body is regulated in three ways. Chemical buffers both within cells and within body fluids react immediately to regulate the hydrogen ion and hydroxide ion concentrations. The pulmonary system requires a few minutes to bring about its effects while the kidneys take from ten to twenty hours. The kidneys, however, are the most powerful of the three.

Control of Glucose Concentration

A number of different hormones are active in keeping the blood glucose level at about 0.1%. The most important of these is insulin. Immediately after eating, increased glucose concentration stimulates the pancreas to release insulin. Insulin also promotes the uptake of glucose by cells including the liver. Insulin stimulates the conversion of glucose to glycogen in the liver. Between eating, when insulin is not being produced, the liver converts glycogen to glucose and therefore the blood glucose level remains constant. This conversion of glycogen is stimulated by both glucagon and, in times of emergency, also adrenalin.

If the supply of glycogen should run out and the blood glucose level remains low, both thyroxin and glucocorticoids stimulate gluconeogenesis, or the conversion of amino acids and glycerol to glucose by the liver.

Summary

The circulatory system is critical to the internal environment in that tissue fluid is nourished and purified by the movement of small molecules across capillary walls. The digestive system contributes nutrients to the blood, while the excretory system removes wastes. The respiratory system takes in oxygen and excretes carbon dioxide. Oxygen is used during cellular respiration and carbon dioxide is a waste product of cellular respiration. The nervous and endocrine systems exert the ultimate control over homeostasis because they coordinate the functions of the body's systems.

Regulation of body temperature, blood pressure, pH, and glucose concentration are four examples of how the body maintains homeostasis. The hypothalamus is involved to a degree in each of these regulations. The hypothalamus contains a regulatory center for body temperature but is also involved in regulation of blood pressure and breathing rate through its control over the medulla oblongata. Through the production of hypothalamic-releasing factors and release-inhibiting factors, the hypothalamus directly controls the pituitary gland and indirectly controls the secretions of other glands, such as the thyroid and the adrenal cortex.

The body has both short-term and long-term measures to control bodily conditions. In regard to temperature control, the short-term measures include shivering and constriction of arteries to conserve body heat, and dilation of arteries along with sweating to lose body heat. A significant long-term measure to increase body temperature is an increase in thyroxin. Thyroxin raises the metabolic rate.

A rapid elevation in blood pressure occurs when the vasomotor center stimulates the constriction of abdominal blood vessels and increases the heartbeat. A longer lasting effect occurs when the kidneys secrete renin leading to a reabsorption of sodium and water. The resulting increase in blood volume increases blood pressure.

The pH of the body is immediately regulated by chemical buffers, while the excretion of carbon dioxide must wait until blood moves through the lungs. The kidneys are also involved in regulating blood pH, but the effect may not noticed for up to twenty hours. The blood glucose level is usually regulated by insulin and glucagon. But other hormones can also have an effect since thyroxin and glucocorticoids promote gluconeogenesis.

A feedback mechanism is often involved in maintaining homeostasis. The temperature-regulating center is activated when the body temperature rises above or falls below a certain level. Once the temperature is within a normal range, the center stops sending out stimulatory nerve impulses. The vasomotor center promotes a rise in blood pressure, but once this has been attained the center is no longer active. If the pH becomes too acidic, the chemoreceptors in the aortic and carotid arteries signal the respiratory center and the breathing rate increases. Once the pH is within a normal range, these bodies no longer signal the respiratory center and breathing rate returns to normal. When glucose concentration is high, insulin is secreted; but once the glucose level falls, insulin is not secreted. These examples make it clear that feedback is a self-regulating mechanism.

Questions

1. As you trace the path of blood through the human body, tell how each exchange surface contributes to homeostasis. (An exchange surface is a region where the composition of blood is altered by substances leaving and/or exiting blood.)

2. Use regulation of body temperature to illustrate maintenance of homeostasis by a feedback mechanism.

3. Use regulation of normal blood pressure to illustrate how the nervous system and the endocrine systems are both involved in maintaining homeostasis.

4. Use the regulation of blood pH to illustrate that there are short-term and long-term mechanisms for maintaining homeostasis.

5. Use the regulation of a normal blood glucose concentration to illustrate that contrary actions of hormones help maintain homeostasis.
