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HEAT EXCHANGE. HEAT PRODUCTION AND HEAT TRANSFER BALANCE IN THE HUMAN BODY

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Abstract

This article provides a detailed examination and analysis of the main mechanisms of heat exchange in the human body, the balance of heat production and heat transfer, how thermoregulation is carried out in the body, the pathways through which heat is released to the environment (conduction, convection, radiation, evaporation), the role of chemical and physical thermoregulation in maintaining a constant body temperature, as well as skin thermoreceptors, the activity of the thermoregulation center, and methods of thermometry.

Keywords

heat exchange, thermoregulation, conduction, convection, radiation, evaporation, heat balance, thermoreceptors, isothermia, chemical thermoregulation, physical thermoregulation.

It is well known that the vital processes of the human body are accompanied by the continuous production of heat within the body and the release of that heat into the surrounding environment. The exchange of thermal energy between the body and the environment is called heat exchange. Heat production and heat exchange occur as a result of the activity of the central nervous system, which regulates metabolism, blood circulation, sweating, and skeletal muscle activity.

The human body is a self-regulating system with an internal heat source, in which, under normal conditions, the heat produced (the amount of heat generated) equals the amount of heat released to the external environment (heat transfer). The constancy of body temperature is called isothermia. This ensures that metabolic processes in tissues and organs are independent of changes in ambient temperature.

The internal temperature of the human body remains constant (36.5–37°C) due to the body's ability to regulate the intensity of heat production and heat transfer according to external conditions. When exposed to external conditions, the temperature of human skin can vary within a relatively wide range. The leading factor determining the level of heat balance is the ambient temperature.

The thermoregulation mechanism is ensured by the process of heat production and heat dissipation, which are regulated through neuroendocrine pathways. In general, thermoregulation is characteristic only of homeothermic animals (including mammals and birds), which have the ability to maintain the temperature of their body's internal parts at a relatively constant and considerably elevated level. In mammals it is 37–38°C, and in birds it is 40–42°C.

Skin Receptors

According to estimates, humans have approximately 150,000 cold receptors and 16,000 heat receptors that respond to changes in the temperature of internal organs. Thermoreceptors are located in the skin, internal organs, respiratory tract, skeletal muscles, and the central nervous system. Skin thermoreceptors respond not to temperature itself, but to changes in temperature.

The greatest number of receptors is located in the head and neck region, and the fewest in the limbs. Cold receptors are less sensitive: their sensitivity threshold is 0.012°C. The sensitivity threshold of thermal receptors is higher, at 0.007°C. This is likely related to the fact that excessive heat poses a greater danger to the body.

Types of Thermoregulation

Thermoregulation can be divided into two main types: 1) Physical thermoregulation: evaporation (sweating); radiation; thermal conductivity (conduction); convection. 2) Chemical thermoregulation.

Physical thermoregulation (the process of removing heat from the body) ensures the stability of body temperature by altering the body's heat output through conductivity and convection via the skin, as well as through radiation and evaporation of water. The release of heat that is continuously produced in the body is regulated by changes in the thermal conductivity of the skin, subcutaneous fat layer, and epidermis.

Conduction, convection, and radiation are passive heat transfer pathways based on the laws of physics. They are effective only as long as a positive temperature gradient is maintained. The smaller the temperature difference between the body and the environment, the less heat is released.

At low ambient temperatures (15°C and below), approximately 90% of the daily heat exchange occurs through thermal conductivity and heat radiation. Under such conditions, visible sweating does not occur. At an air temperature of 18–22°C, heat conductivity due to thermal conductivity and heat radiation decreases, but the body's heat loss through evaporation of moisture from the skin surface increases.

When ambient temperature rises to 35°C, heat transfer through radiation and convection becomes impossible, and body temperature is maintained solely through evaporation of water from the skin surface and the lung alveoli. If air humidity is high and water evaporation is difficult, overheating of the body and heat stroke may occur.

In a person at rest, at an air temperature of approximately 20°C, total heat output amounts to 419 kJ (100 kcal) per hour. The proportions of total heat loss from the body are: due to radiation

— 66%, due to water evaporation — 19%, due to convection — 15%.

Evaporation (Sweating)

Evaporation (sweating) is the release of thermal energy to the environment through the evaporation of sweat or moisture from the skin surface and the mucous membranes of the respiratory tract. In humans, sweat is continuously secreted by the sweat glands of the skin. At an ambient temperature of approximately 20°C, moisture evaporation amounts to approximately 36 g/hour.

Since 0.58 kcal of thermal energy is expended for the evaporation of 1 g of water in humans, it is easy to calculate that through evaporation an adult human body releases approximately 20% of the total heat dissipated to the environment under these conditions. An increase in external temperature, performance of physical work, and prolonged exposure in heat-insulating clothing increase sweating, which can rise to 500–2,000 g/hour.

A person feels uncomfortable at a relatively low temperature (32°C) in humid air. A person can feel well for 2–3 hours at a temperature of 50–55°C in dry air. Air-impermeable clothing that impedes sweat evaporation obstructs the evaporation of sweat: the layer of air between the clothing and the body quickly evaporates, and further evaporation of sweat stops.

When sweat evaporates, our body loses energy. In fact, through the body's energy, liquid molecules (i.e., sweat) break molecular bonds and transition from a liquid to a gaseous state. Energy is expended to break these bonds, and as a result, body temperature decreases.

Up to 400 ml of water evaporates through the respiratory tract per day, meaning the body loses up to 232 kcal per day this way. On average, approximately 240 ml of water passes through the epidermis per day, by which means the body loses up to 139 kcal per day.

Under comfortable ambient temperature conditions, an average of 400–500 ml of sweat is excreted per day, releasing up to 300 kcal of energy. In a person weighing 75 kg, the evaporation of 1 liter of sweat can lower body temperature by

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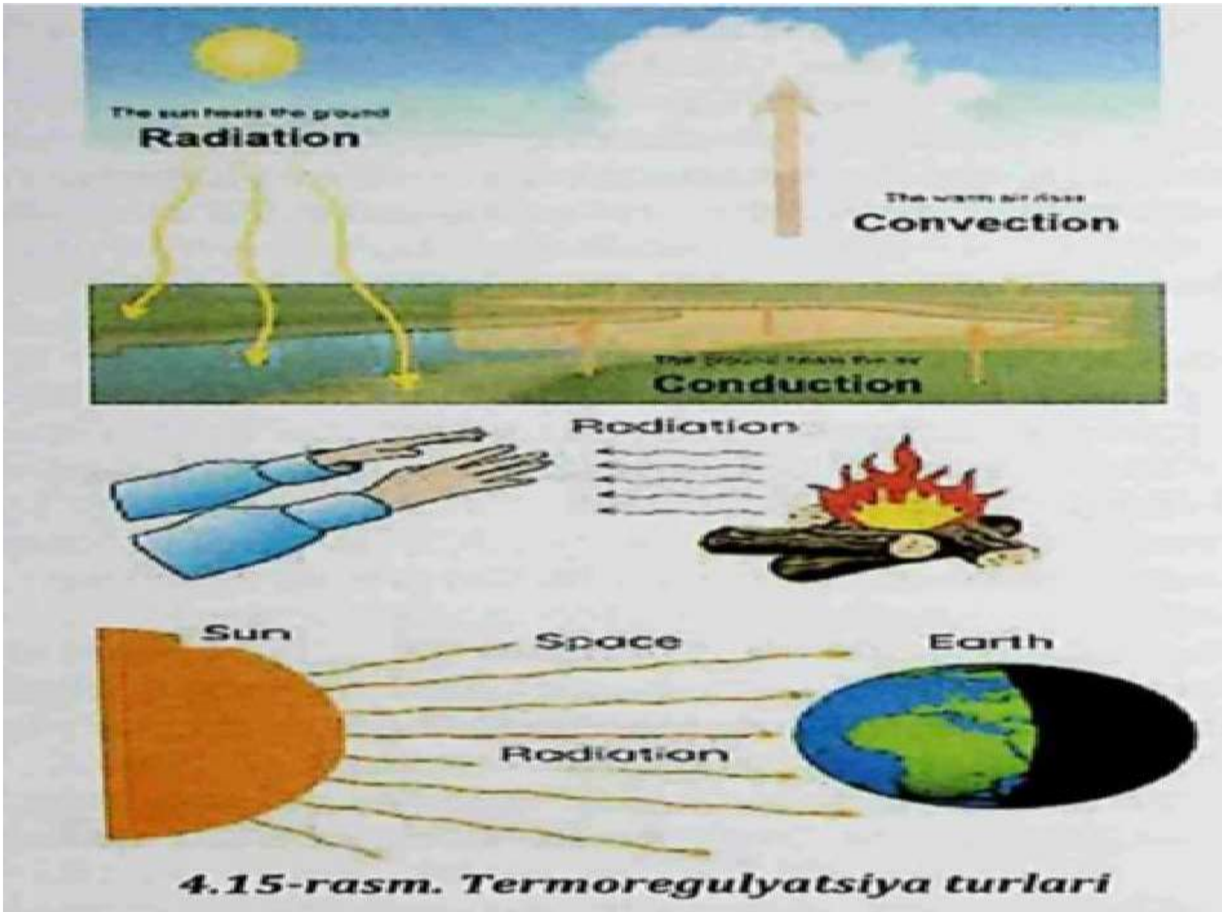
1°C. However, if necessary, the volume of sweating can increase to 12 liters per day.

The effectiveness of evaporation depends greatly on the environment: the higher the temperature and the lower the humidity, the greater the effectiveness of sweating as a heat transfer mechanism. At 100% humidity, evaporation does not occur. Tolerating high

temperatures at high atmospheric humidity is considerably more difficult than



at low humidity.

Figure 1.

Chemical Thermoregulation

The chemical thermoregulation of heat production is achieved through changes in the rate of metabolism (oxidation processes) arising from micro-vibrations (tremors) of the muscles, which leads to changes in heat production in the body. When nutrients are broken down, part of the released energy is stored in ATP, and part is dissipated as heat (primary heat constitutes 65–70% of the energy).

When the high-energy bonds of ATP molecules are utilized, part of the energy is expended on performing useful work, and part is dissipated (secondary heat). Thus, there are two flows of heat — primary and secondary heat production.

Chemical thermoregulation is important for maintaining constant body temperature both under normal conditions and when ambient temperature

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changes. In humans, an increase in heat production is observed due to an increase in the rate of metabolism, particularly when ambient temperature falls below the optimal temperature or the comfort zone. For a person dressed in ordinary light clothing, this zone is in the range of 18–20°C, and for a naked person it is 28°C.

This is because water, which has high heat capacity and thermal conductivity, cools the body 14 times more than air, so metabolism in a cool bath increases significantly compared to air at the same temperature.

The liver and kidneys also play an important role in chemical thermoregulation. The blood temperature of the hepatic vein is higher than the blood temperature of the hepatic artery, indicating intense heat production in this organ. When the body cools, heat production in the liver increases.

Energy is released when organic substances are oxidized. Part of this energy is expended on ATP synthesis (adenosine triphosphate — a nucleotide that plays a very important role in the energy and metabolic processes of the body). This potential energy can be used by the body for other activities. All tissues serve as sources of heat in the body. Blood flowing through the tissues is warmed.

An increase in ambient temperature leads to a reflex decrease in metabolism, as a result of which heat production in the body decreases. When ambient temperature decreases, the intensity of metabolic processes reflexively increases and heat is produced. The activation of chemical thermoregulation occurs when physical thermoregulation is insufficient to maintain a constant body temperature.

Figure 2.
Thermometry

Thermometry is the process of measuring temperature at specific points on the body. There are two methods of thermometry: 1) contactless method — using thermographs; 2) contact method — by applying a thermometer or film to the body surface.

Typically, each area of the body surface displays its own unique thermographic image. For example, head thermography reveals zones of high temperature (on the surface of large blood vessels) and zones of low temperature.

There are circadian (daily) fluctuations in body temperature. The amplitude of these fluctuations amounts to 1°C. These fluctuations run parallel to functional shifts in blood circulation, respiration, digestion, and other processes, and reflect the daily fluctuations in the body's vital activity due to biological rhythms.

The temperature regime of the body is individual and relatively constant for each person; it changes at various periods of life and depends on the nature of activity, the functional state of the body, the environment, and other factors. The individuality of body temperature is determined by the following factors: 1) genetic factors that determine individual metabolism; 2) upbringing; 3) habits related to exercise and hardening; 4) the type of clothing that allows for purposeful changes to the body's temperature regime.

The thermal conductivity of tissues is determined by the nature of the use of the countercurrent vascular system present in the limbs. In cold conditions, venous blood flows mainly through deep vessels rather than through superficial vessels as in warm conditions. As a result, venous blood is warmed in parallel with blood passing through nearby arteries and is not cooled to the same extent as the surface blood flow.

Conclusion

Heat exchange in the human body is a complex physiological process that includes two main components: heat production (thermogenesis) and heat transfer (thermolysis). The balance between them — the thermal balance — maintains body temperature at a constant level of

36.5–37°C.

The main sources of heat production are: oxidation-reduction reactions in cells, muscular work (shivering and movement), and the metabolism of the liver and internal organs. There are four main pathways of heat transfer: conduction (through direct contact), convection (through air or liquid flow), radiation (infrared radiation), and evaporation (sweating).

The hypothalamus, as the main center of thermoregulation, automatically regulates the processes of heat production and heat transfer according to blood temperature. Skin thermoreceptors sense changes in ambient temperature and send signals to the center. The integrated functioning of this system ensures a stable internal environment — homeostasis — for the body.

Understanding the physics of heat exchange enables medical students to correctly understand and treat not only normal physiology, but also clinical pathologies — hyperthermia, hypothermia, heat stroke, and fever.

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