THERMOREGULATION

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Summary

This article presents some basic information concerning the structure and function of the human thermoregulatory system. The possibilities of independent regulation of body temperatures allow humans far more freedom of movement and a greater survival potential in hot rather than cold climates.

The imbalance between capacity of heat removal from the body and heat conservation mechanisms would suggest that humans are better adapted to hot environments. Except for periods of intense physical activity, the large capacity of humans for heat loss through massive cutaneous vasodilation and evaporation of eccrine sweat would be of little use in a cold environment where well-developed mechanisms for heat conservation are necessary.

On the other hand, setting the core body temperature at a normal level of about 37 °C requires rather efficient thermoregulatory responses to heat load, since the limit of tolerance of the elevated body core temperature is 42 °C.

Relative to many other mammalian species, humankind has rather limited physiological possibilities of defense against cold: poor thermal insulation and moderate ability to produce heat by shivering and nonshivering thermogenesis.

However, human beings have been able to create a comfortable thermal microclimate (clothing, housing, heating), thereby protecting themselves against the deleterious effects of exposure to low temperatures when living permanently or staying temporarily in cold climates.

This kind of behavioral thermoregulation cannot help humans much when they are exposed to cold by accident. Under such conditions hypothermia may develop, with all the negative consequences for the organism, and the only solution to keep people alive is a fast rescue operation.

The various sections of this article describe physiological mechanisms of defense against heat and cold, gender differences in thermoregulation, lower and upper limits of tolerance of body temperatures, hyperthermia, hypothermia, and fever. Some aspects of human thermoregulation related to age, physical activity, and acclimatization are also discussed.

1. Introduction

Thermoregulation is defined as a complex of mechanisms regulating heat production within the body (chemical thermoregulation) and regulating heat exchange between the body and the environment (physical thermoregulation) in such a way that the heat exchange is balanced and deep body temperatures are relatively stable.

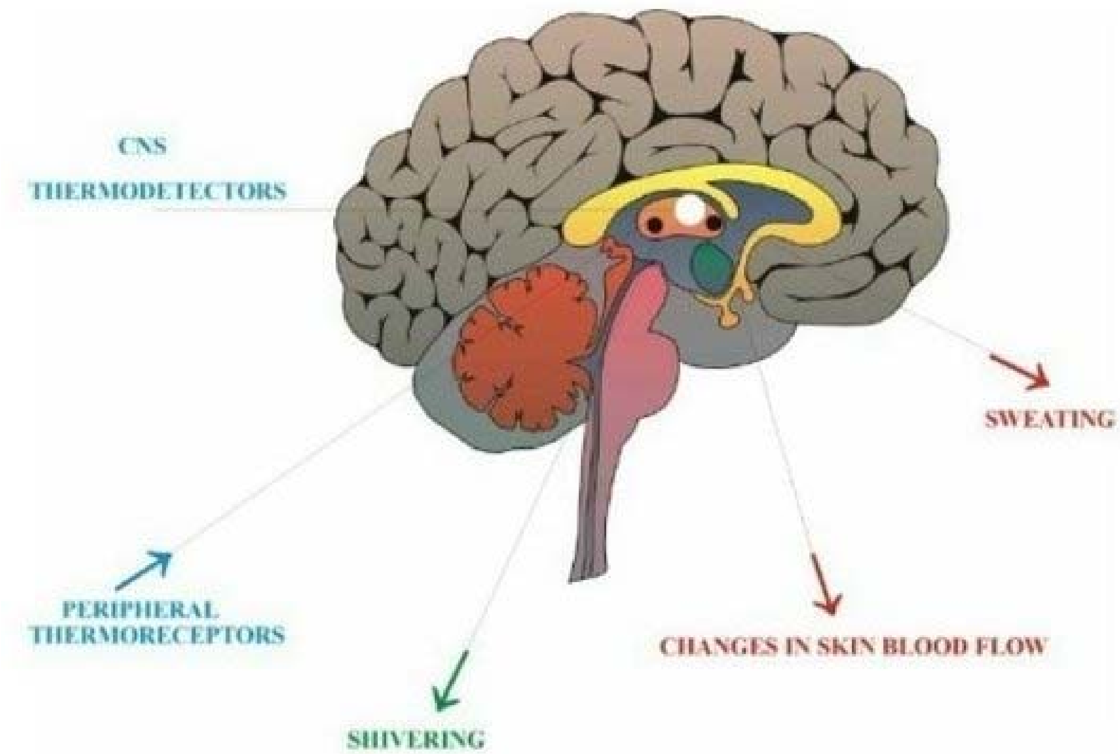

Figure 1. Schematic representation of the role of hypothalamus in the human thermoregulatory system

Human beings, properly protected against heat and cold, can tolerate external temperatures from approximately –50 °C up to +100 °C, with safe deviations of internal body temperature within the range of ± 4.0 °C. Greater variations in internal body temperature could cause some irreversible changes in cellular and enzymatic structures, disturbing temperature-related biochemical life processes. Intensity of the thermal disturbance in the organism depends on the magnitude of the changes in body temperature and the type of tissue exposed to the temperature changes. The most sensitive tissues to great changes in their temperature are the neuronal structures in the central nervous system.

A diurnal variation in body temperature can be observed in healthy people. The core temperature falls to a minimum in the early hours of morning (about 36.2 °C) and reaches its maximum of about 37.4 °C in the afternoon.

2. Basic Elements of the Human Thermoregulatory System

Basic elements of the human thermoregulatory system include regulated variables (body temperatures) and structures of the system: thermal sensors (peripheral thermoreceptors, and central thermodetectors) as well as hypothalamic thermoregulatory centers. Recent studies indicate that some polypeptides termed heat shock proteins (HSPs) may play an important role in survival at both normal and elevated body temperatures.

2.1. Body Temperatures

It is generally accepted that the body core temperature (T_{core}) at rest and under thermoneutral conditions is stable at the level of about 37 °C. However, different tissues in the body exhibit different metabolic rates and blood supply related to their function. This means that each tissue is characterized by its own temperature. These temperatures vary during heat loads and exercise, bringing some confusion in estimation of T_{core}, definition of the temperature set-point and the temperature concept of human thermoregulation.

The temperature of blood reaching the hypothalamus is regarded as a major afferent stimulus for the intensity of sweating, vasomotor activity, and shivering. Since the brain is not available for the temperature measurements in a human being, other sites for T_{core} measurement have frequently been utilized (oral cavity, tympanic membrane, ear canal, pulmonary artery and right heart, rectum, and esophagus). For practical purposes the temperatures of oral cavity, ear canal, and rectum have been assumed to represent T_{core}. Measurement of T_{core} is important, as both an estimate of afferent input in the temperature control system and an estimate of the temperature of blood going to the brain.

The temperature of the skin (T_{sk}) is normally much lower than T_{core} and, under thermoneutral conditions, varies within the range of 32 °C–34 °C. T_{sk} is not homogenic. Its value relates to the metabolic activity of the deep located tissues, the number of active sweat glands, and to local blood flow. Thus, similarly to T_{core}, there is no single value of the skin temperature. The mean skin temperature (T_{sk}) is calculated using factors related to the specific temperature of the chosen skin area. The simplest equation enabling calculation of the mean skin temperature is expressed as:

$$T_{sk} = 0.14\ T_{arm} + 0.36\ T_{thigh} + 0.50\ T_{chest} \quad (1)$$

The mean body temperature (T_{body}) can be calculated as:

$$T_{body} = 0.60\ T_{core} + 0.40\ T_{sk} \quad (2)$$

2.2. Thermoreceptors and Thermodetectors

Thermoreceptors and thermodetectors are nervous structures sensitive to changes in environmental temperature (by sensing the skin temperature) and deep body temperature, respectively.

The peripheral thermoreceptors that increase their firing rate with an increase of temperature are so- called “warm receptors.” Those increasing their firing rate with a decrease of temperature are called “cold receptors.” Both basic types of cutaneous thermoreceptor are free nerve endings that produce action potentials in their small-diameter, unmyelinated or poorly myelinated afferent fibers. The thermoreceptors are mainly located in the skin layers but they can also be found in skeletal muscle, the upper respiratory tract, in some parts of the gastrointestinal system, and in vein walls.

Some neuronal structures in the central nervous system are themselves thermosensitive, responding to both increases and decreases in their own temperature. Because of their location and the temperature-related firing rate, they are considered as thermodetectors. In addition to sensing their own local temperature, most of the thermosensitive neurons receive synaptic inputs from afferent pathways on temperature in the skin and other locations throughout the body. The thermoreceptors are mainly grouped in the rostral hypothalamus, especially in the preoptic and anterior hypothalamus area.

2.3. Thermoregulatory Centers

The regulation of body temperature depends on the ability of the nervous system to sense and integrate thermal information from the environment and deep within the body core. The hypothalamus is the center of integration of information received from thermoreceptors and thermodetectors.

Two specific brain areas play a special role in the regulation of body temperature, and they are regarded as thermoregulatory centers. The first area, localized in the preoptic and anterior hypothalamus, is characterized by a large number of thermodetectors sensitive to increases in their own temperature. These thermodetectors act as a "heat elimination center" activating the main thermoregulatory responses to heat: increase in skin blood flow and sweating.

In the posterior hypothalamus some interferons receive information mainly from "cold" skin thermoreceptors. This thermoregulatory structure acts as a "heat preserve center" activating the main thermoregulatory response to cold: decrease in skin blood flow and shivering.

The thermoregulatory centers exhibit hierarchy in integrating thermal information at different levels of the central nervous system. In the case of destruction of the anterior and preoptic area of the hypothalamus, thermoregulation can still be preserved at the spinal cord level, but with a low efficiency and precision.

2.4. Thermoregulatory Effectors

Effectors of the thermoregulation are some physiological systems (for example, the cardiovascular system), tissues (for example, skeletal muscles, fat) and organs (for example, eccrine sweat glands, liver). The thermoregulatory effectors are:

1. sweat glands
2. smooth muscle around the arterioles
3. skeletal muscles
4. several endocrine glands.

Controlled changes in their activity could lead to heat loss or heat gain in the human body.

3. Body Heat Balance

In order to control the body heat content and body temperatures, the amount of heat produced by an organism should be balanced by the amount of heat removed from the organism to the environment according to the equation:

$$S = M \pm W \pm R \pm C \pm K - E \qquad (3)$$

where:

- S: rate of heat storage in the body
- M: rate of metabolic energy production
- W: rate of external work
- R: rate of heat exchange by radiation
- C: rate of heat exchange by convection
- K: rate of heat exchange by conduction
- E: rate of heat loss by water evaporation from the body.

3.1. Metabolic Heat Production

The endogenous heat load is determined by the rate of metabolic energy expenditure (M) due to basal metabolic rate and muscle activity. Since, on average, about 25% of metabolic energy is transformed into mechanical work (W), physical exercise can considerably increase the total body heat content.

3.2. Radiation

Heat exchange by radiation (R) is defined as a gaining (absorption) or losing (emission) of heat energy at the expense of radiation energy. The emissivity of human skin is equal to 0.997. There is a continuous heat exchange by radiation between the skin surface and material bodies in the environment (for example, solar radiation, walls) when any difference in their temperature exists. The radiation is a very powerful source of energy. Human beings can partly protect against radiation by using special clothes and shields.

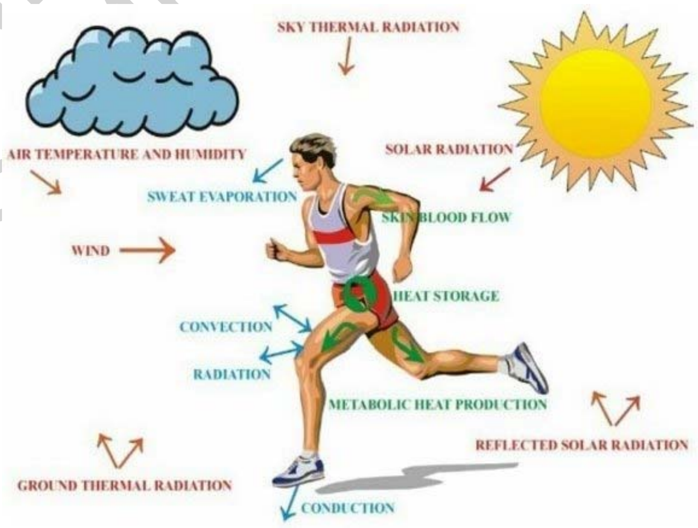

Figure 2. Heat exchange between the body and the environment

3.3. Convection

Heat exchange by convection (C) is based on the movement of particles in gas or liquid that take heat from, or give their heat to, the material body. The intensity of heat exchange by C is proportional to the temperature difference between the two environments. Heat moves from the body core to the skin in circulating blood, and heat is eliminated from the body surface to the environment by movement of air particles. The body cooling by convection can be enlarged by the application of mechanical ventilatory devices (forced convection).

During respiration there is a heat exchange by convection from the respiratory tract (C_{res}). It is related to minute ventilation and the temperature difference between the air in upper airways and environmental air. C_{res} does not play important role in human thermoregulation.

3.4. Conduction

Heat exchange by conduction (K) is related to the temperature differences between two surfaces in direct physical contact. Under normal condition the heat exchange by K is rather low. However, when the body is immersed in water the heat exchange by conduction markedly increases, because the specific heat conductance of water is about 25 times greater than that of air. In cold water this is the main cause of sudden heat loss from the body. When people swim in cold water, the cooling effect of heat conduction may be enlarged by the additional effect of forced convection.

Heat conduction plays an important role when skin touches very cold or warm objects made from materials of high specific heat conductance such as metal.

3.5. Evaporation

The most effective factor in body heat loss is water evaporation, which occurs as evaporation of excreted sweat (E_s), evaporation from the airways (E_{res}) and water diffusion evaporation from the skin (E_{diff}).

The evaporation of sweat (E_s) plays a decisive role in heat elimination from the human body. Within the range of skin temperature from 32 °C to 35 °C, the evaporation of 1 liter of sweat eliminates 2.4 MJ (580 kcal) of heat energy. The intensity of heat elimination by sweat evaporation depends on the number of sweat glands, the level of their activation, the state of body water balance, and the physical properties of the environment. The evaporation decreases with the increase of water saturation of ambient air. In high ambient humidity the secreted sweat drips out without evaporation, thus it does not cool the body. Therefore, the evaporation of sweat can be an effective thermoregulatory mechanism only under low or moderate air humidity.

E_{res} and E_{diff} (*perspiratio insensibilis*) constitute physical evaporation mechanisms, and they are not controlled by the human thermoregulatory system. Under normal conditions their influence on body heat balance can be neglected.

4. Thermoregulatory Reactions to Heat and Cold

Responses of the peripheral vascular system provide the first line of defense against heat stress and cold stress. During heat exposure, decreases in the thermal insulation of the skin layers by increased skin blood flow make possible the removal of heat from the body to the environment. The effectiveness of heat transfer from the body surface to the environment depends mainly on the intensity of sweating and its evaporation.

	Heat	**Cold**
Skin blood flow	⇑	⇓
Sweating	⇑	
Nonshivering		⇑
Shivering		⇑
Behavior	⇓	⇑

Table 1. Thermoregulatory reactions to heat and cold

Exposure to cold stress involves mainly heat conservation responses, including increased heat production by nonshivering and shivering thermogeneses, and increased thermal insulation by constriction of cutaneous arterioles and veins (decreased skin blood flow), which also limit heat conduction from the core to the periphery. There is also the behavioral thermal attitude of humans, in the use of clothing and buildings in order to avoid a direct exposure to severe climatic conditions.

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Biographical Sketch

Dr. Ryszard Grucza, Eng., Dr.Nat.Sc., Professor of Medical Sciences, Director of the Institute of Sport in Warsaw, was born in 1946 in Nakło, Poland. He studied at the Warsaw Technical University where he received the title of Electronic Engineer (Electronic Measurements) in 1971. Since then he has been working in the Medical Research Centre of the Polish Academy of Sciences (PASci), being involved in research concerning human physiology. He obtained his Dr.Nat.Sc. in the Medical Research Centre in 1979, and passed habilitation procedure in the Institute of Immunology and Experimental Therapy of the PASci in 1989. He was nominated in 1991 to the docent position of work physiology in the Faculty of Medicine, Kuopio University, Finland. In the same year he won in competition for the post of Director of the Institute of Sport in Warsaw and obtained his professorship in this Institute. He was made a full professor in 2002. He has spent long-term research visits at the Université de Lille (France), University of

Kuopio (Finland), Yamagata University (Japan) and Université Pierre et Marie Curie, Paris (France). In 1996–1998 he was a member of the Committee of Physical Culture, and in 2000–2002 he was elected to the Committee of Physiological Sciences of the PASci.

Since 1991 he has been a member of the National Commission Against Doping Use in Sport. He was an independent Observer of the World Anti-Doping Agency during the Winter Olympic Games in Salt Lake City. At present Dr. Grucza is Chairman of the Monitoring Group of the Anti-Doping Convention of the Council of Europe (2002).
Dr. Grucza is a specialist in thermophysiology, exercise physiology, and anti-doping policy. He has contributed 68 papers in refereed journals and 73 in proceedings. Since 1998 he has been editor-in chief of the *Biology of Sport*. Since 2000 he has been teaching exercise physiology at the Medical Academy in Bydgoszcz, Poland.