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BIOPHYSICS OF HEAT EXCHANGE IN THE HUMAN BODY

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Abstract:
The biophysics of heat exchange governs how the human body maintains a stable core temperature by balancing internal metabolic heat production with physical and environmental transfer mechanisms. Heat gain arises as a byproduct of cellular metabolism and/or exposure to external temperatures greater than the body surface. Heat loss occurs via conduction, convection, radiation and evaporation, the rates of which are governed by the physical properties of the skin (surface area, skin temperature and wettedness) and the environment (ambient and radiant temperatures, air movement, barometric pressure, ambient vapor pressure, clothing insulation) (Gagge and Nishi, 1977). The purpose of this review is to present a current understanding of the biophysical factors that contribute to individual variability in the thermoregulatory responses to heat.

Keywords: Thermoregulation, Metabolic Heat Production, Conduction, Convection, Radiation, Evaporation, Thermal Homeostasis, Human Physiology, Oxygen Consumption (VO_2), Heat Balance Equation, Thermal Energy,

Introduction
One of the remarkable features of the human thermoregulatory system is that we can maintain a core temperature near 37°C over a wide range of environmental conditions and during thermal stress. In response to metabolic or environmental disturbances to heat balance, the autonomic nervous system initiates cutaneous

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vasodilation and eccrine sweating to facilitate higher rates of dry (primarily convection and radiation) and evaporative transfer from the body surface; however, absolute heat losses are ultimately governed by the properties of the skin and the environment.

Heat balance equation: The heat balance equation is one of the fundamental concepts for any discussion of human energy exchange and core temperature regulation. It basically describes how the body maintains a stable internal temperature by balancing heat production and heat loss.

$$S=M\pm R\pm C\pm K-E$$

In accordance with the First Law of Thermodynamics, the rate of body heat storage (S) is equal to the difference between rates of metabolic energy expenditure (or metabolic rate, M), dry heat exchange from the skin by conduction (K), radiation (R), convection (C), evaporative heat loss (E) from body's surfaces. The SI unit for rates of energy conversion is watts (W); however, heat balance parameters are often expressed per square meter (W/m2) of total body surface area (A_D), which is conventionally estimated from body mass and standing height (DuBois and DuBois, 1916; Tikuisis et al., 2001).
Metabolism always represents a source of heat gain; dry heat avenues can lead to heat gain or loss depending on the temperature gradient between the skin and environment, but heat can only be lost from the body mainly by evaporation from the respiratory tract and skin. To maintain heat balance (S=0), the rate of total heat gain from metabolic and environmental heat sources must be equal to the rate of total heat loss from the body. It follows that heat storage and internal temperature rise if the rate of total heat gain exceeds the rate of total heat loss (S>0); conversely, heat storage and internal temperature fall if the rate of total heat loss outweighs the rate of heat gain (S<0). The change in body heat content

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(i.e., change in thermal energy) in kilojoules is the product of time and the net difference between rates of heat gain and loss.

Metabolic Heat Production: The rate of metabolic energy expenditure describes how quickly the body releases energy from the breakdown of carbohydrates, fats, and amino acids in order to regenerate adenosine triphosphate (ATP), which is necessary for cellular functions such as muscle contraction, transport processes, and biosynthesis. During rest and low- to moderate-intensity exercise, energy is mainly produced through oxidative metabolism, meaning that metabolic rate is closely related to oxygen consumption (VO_2). Whole-body metabolic rate is commonly estimated by indirect calorimetry using steady-state oxygen uptake and the non-protein respiratory exchange ratio (RER), which considers the different energy values of carbohydrates and fats (Murgatroyd et al., 1993). Metabolic energy is eventually transformed into two primary forms: mechanical energy used to perform external work and thermal energy released as heat. Under laboratory conditions, the rate of external work is commonly controlled using an ergometer or calculated based on factors such as body mass, movement speed, and incline angle during weight-bearing activities (Snellen, 1960). By integrating measurements obtained from indirect calorimetry with ergometric data, researchers can determine the rate of metabolic heat production as the difference between total metabolic energy expenditure and the amount of external work performed. At rest, no external mechanical work is produced; therefore, nearly all metabolic energy is converted into heat. During physical activity, heat production increases due to the elevated oxygen consumption (VO_2) necessary to satisfy the higher energy requirements of working muscles.
Although heat production increases as exercise intensity becomes greater, the amount of heat generated at a given workload depends on mechanical efficiency or movement economy, which reflects how effectively the body converts metabolic energy into useful movement or external work. Gross efficiency is

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defined as the proportion of total metabolic energy expenditure transformed into external work, and during activities such as cycling or rowing, it is typically no more than 25% (Fukunaga et al., 1986; Gaesser and Brooks, 1975; Moseley et al., 2004).

Conduction occurs through direct contact between the body and another object. Heat moves from a warmer surface to a cooler one. Although conduction usually contributes less to total body heat loss, it becomes important when touching cold surfaces or water. According to Fourier's Law, conduction is related to the temperature gradient between surfaces, the thermal conductivity of the material, and the thickness and area of contact between surfaces. Conduction with the external environment is generally considered negligible unless the skin is in contact with highly conductive surfaces for a prolonged duration.

Radiation: Radiation is one of the principal mechanisms of heat exchange in the human body. It involves the transfer of thermal energy through electromagnetic waves, primarily in the form of infrared radiation, without the need for direct physical contact or movement of air. Because the temperature of the human body is generally higher than that of the surrounding environment, the body continuously emits radiant heat toward cooler objects and surfaces.

Under normal indoor environmental conditions, radiation represents a major pathway of body heat loss and may account for approximately 50–60% of total heat dissipation at rest. The rate of radiative heat exchange depends largely on the temperature gradient between the skin and surrounding surfaces. When surrounding objects are cooler than the skin, heat is lost from the body; however, if environmental surfaces are warmer, the body may absorb radiant heat instead.

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Convection: Convective Heat Loss Caused by Air Movement

Heat produced by the body is initially transferred from the skin to the surrounding air through conduction, after which it is removed by circulating air currents through convection.

A certain degree of convection normally occurs around the body because the air near the skin becomes warmer and rises upward. As a result, even in a comfortable environment without noticeable air movement, approximately 15% of total body heat loss occurs through conduction to the surrounding air followed by convective transfer away from the body.

Cooling Effect of Win: Exposure to wind significantly increases convective heat loss. Moving air continuously replaces the warm layer of air surrounding the skin with cooler air, thereby accelerating heat dissipation. The cooling influence of wind at lower speeds is generally proportional to the square root of wind velocity.

Conduction and Convection of Heat From a Person Suspended in Water**.** Water has a specific heat several thousand times greater than air, so each unit portion of water adjacent to the skin can absorb far greater quantities of heat than can be absorbed by air. Also, heat conductivity in water is much greater than in air. Consequently, it is impossible for the body to heat a thin layer of water next to the body to form an "insulator zone" as occurs in air. Therefore, if the temperature of the water is below body temperature the rate of heat loss to water is usually many times greater than the rate of heat loss to air.

The rate of blood flow into the skin venous plexus can vary from barely above zero to as great as 30% of the total cardiac output. A high rate of skin flow causes heat to be conducted from the body core to the skin with great efficiency, whereas reduction in the rate of skin flow can greatly decrease heat conduction from the core to very little.

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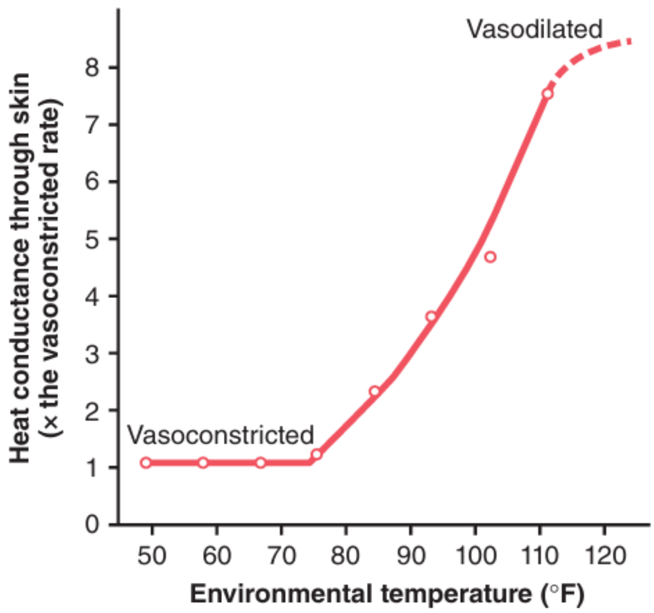

Figure 1. Effect of changes in the environmental temperature on heat conductance from the body core to the skin surface

Fig. 1 shows quantitatively the effect of environmental air temperature on conductance of heat from the core to the skin surface and then conductance into the air, demonstrating an approximate 8-fold increase in heat conductance between the fully vasoconstricted state and the fully vasodilated state. Therefore, the skin is an effective controlled "heat radiator" system, and the flow of blood to the skin is a most effective mechanism for heat transfer from the body core to the skin.

Evaporation: When water evaporates from the body surface, 0.58 Calorie (kilocalorie) of heat is lost for each gram of water that evaporates. Even when a person is not sweating, water still evaporates insensibly from the skin and lungs

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at a rate of about 600 to 700 mL/day. This insensible evaporation causes continual heat loss at a rate of 16 to 19 Calories per hour.

Evaporation Is a Necessary Cooling Mechanism at Very High Air Temperatures. As long as skin temperature is greater than the temperature of the surroundings, heat can be lost by radiation and conduction. However, when the temperature of the surroundings becomes greater than that of the skin, instead of losing heat, the body gains heat by both radiation and conduction. Under these conditions, the only means by which the body can rid itself of heat is by evaporation. Therefore, anything that prevents adequate evaporation when the surrounding temperature is higher than the skin temperature will cause the internal body temperature to rise. This phenomenon occurs occasionally in human beings who are born with congenital absence of sweat glands. These people can tolerate cold temperatures as well as people with normal sweat glands, but they can become severely stressed and die of heatstroke in tropical zones because, without the evaporative refrigeration system, they cannot prevent a rise in body temperature when the air temperature is greater than that of the body.

Conclusion:

In conclusion, heat exchange in the human body is a complex biophysical process that is essential for maintaining thermal homeostasis and normal physiological function. Metabolic heat production serves as the primary internal source of heat, while mechanisms such as conduction, convection, radiation, and evaporation regulate the transfer of thermal energy between the body and the environment. The effectiveness of these mechanisms depends on environmental conditions, blood circulation, physical activity, and skin properties. Proper coordination of these processes allows the body to maintain a stable internal temperature despite external temperature changes. Understanding the biophysics of heat exchange is important not only in physiology and medicine, but also in sports science, environmental health, and biomedical engineering.

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