Autonomic Neuroscience: Basic and Clinical 196 (2016) 3–13

Contents lists available at ScienceDirect

Autonomic Neuroscience: Basic and Clinical

journal homepage: www.elsevier.com/locate/autneu

Review

Biophysical aspects of human thermoregulation during heat stress

Matthew N. Cramer [a], Ollie Jay [a,b,c,*]

[a] School of Human Kinetics, Faculty of Health Sciences, University of Ottawa, ON, Canada
[b] Thermal Ergonomics Laboratory, Faculty of Health Sciences, University of Sydney, NSW, Australia
[c] Charles Perkins Centre, University of Sydney, NSW, Australia

ARTICLE INFO

Article history:
Received 1 October 2015
Received in revised form 2 March 2016
Accepted 3 March 2016

Keywords:
Heat exchange
Heat balance
Core temperature
Sweating

ABSTRACT

Humans maintain a relatively constant core temperature through the dynamic balance between endogenous heat production and heat dissipation to the surrounding environment. In response to metabolic or environmental disturbances to heat balance, the autonomic nervous system initiates cutaneous 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. Over the duration of a heat exposure, the cumulative imbalance between heat production and heat dissipation leads to body heat storage, but the consequent change in core temperature, which has implications for health and safety in occupational and athletic settings particularly among certain clinical populations, involves a complex interaction between changes in body heat content and the body's morphological characteristics (mass, surface area, and tissue composition) that collectively determine the body's thermal inertia. The aim of this review is to highlight the biophysical aspects of human core temperature regulation by outlining the principles of human energy exchange and examining the influence of body morphology during exercise and environmental heat stress. An understanding of the biophysical factors influencing core temperature will enable researchers and practitioners to better identify and treat individuals/populations most vulnerable to heat illness and injury during exercise and extreme heat events. Further, appropriate guidelines may be developed to optimize health, safety, and work performance during heat stress.

Contents

* Corresponding author at: Thermal Ergonomics Laboratory, Faculty of Health Sciences, University of Sydney, Lidcombe, NSW 2141, Australia.
E-mail address: ollie.jay@sydney.edu.au (O. Jay).

http://dx.doi.org/10.1016/j.autneu.2016.03.001
1566-0702/

1. Introduction

Heat stress causes a transient or persistent imbalance between heat gained and heat lost to the environment, resulting in body heat storage. 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 ability to restore or maintain heat balance through greater cutaneous vasodilation and eccrine sweating is often within the physical limits imposed by the environment. However, under the most thermally stressful conditions, heat balance may be impossible despite high levels of skin blood flow and rates of sweat production. For a given change in body heat storage, core temperature varies with the mass and composition of body tissues by altering the internal heat sink and average heat capacity of body tissues, respectively. This complex interaction between metabolic heat production, the physical properties of the skin and environment, and body size are the principal components determining core temperature responses (Fig. 1), and ultimately determine whether heat balance is attainable or if core temperature will progressively rise to levels that are potentially harmful to health and performance.

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 stress. The first section provides an overview of the physical properties affecting heat balance. The second section examines the independent and interactive effects of biophysical factors related to heat production and body morphology on the core temperature response to heat stress.

2. Biophysics of human heat balance

A fundamental and useful reference point for any discussion of human energy exchange and core temperature regulation is the conceptual heat balance equation:

$$S = M - Wk \pm K \pm R \pm C \pm C_{res} - E_{res} - E_{sk}\ [W]. \quad (1)$$

In accordance with the law of energy conservation, the rate of body heat storage (S) is equal to the difference between rates of metabolic energy expenditure (or metabolic rate, M), external work (Wk), dry heat exchange from the skin by conduction (K), radiation (R), convection (C), convective heat exchange (C_{res}) and evaporative heat loss (E_{res}) from the respiratory tract, and evaporative heat loss from the skin (E_{sk}). The SI unit for rates of energy conversion is watts (W); however, heat balance parameters are often expressed per square meter (W/m^2) 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). It may also be useful to express these values per kilogram of total body mass (W/kg) for certain applications discussed below. In some contexts, metabolic rate is expressed in kilojoules per minute (1 kJ/min ≈ 17 W), kilocalories per minute (1 kcal/min ≈ 70 W), or metabolic equivalents (1 MET = 58.2 W/m^2).

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 (see below), but heat can only

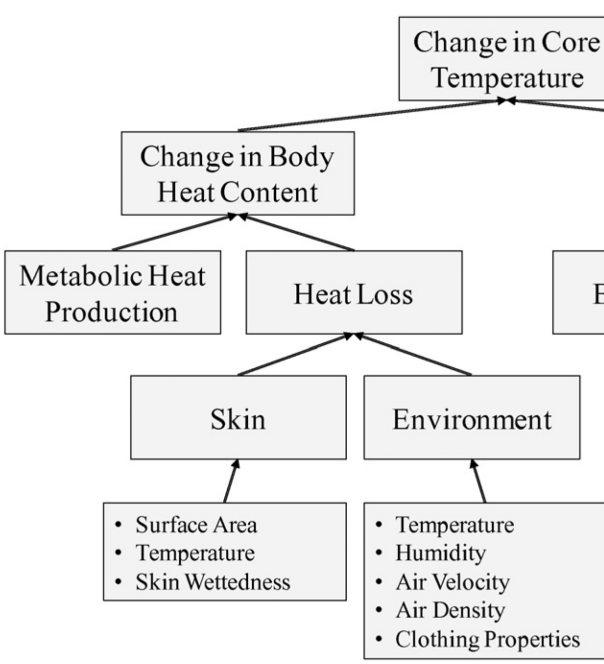

Fig. 1. Biophysical factors affecting the change in core temperature during exercise and environmental heat exposure.