Journal of Thermal Biology 46 (2014) 72–101

Contents lists available at ScienceDirect

Journal of Thermal Biology

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

Review

Considerations for the measurement of core, skin and mean body temperatures

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ARTICLE INFO

Article history:
Received 5 August 2014
Received in revised form
24 October 2014
Accepted 27 October 2014
Available online 30 October 2014

Keywords:
Calorimetry
Core temperature
Mean body temperature
Measurement
Muscle temperature
Skin temperature
Thermoregulation

ABSTRACT

Despite previous reviews and commentaries, significant misconceptions remain concerning deep-body (core) and skin temperature measurement in humans. Therefore, the authors have assembled the pertinent ***Laws of Thermodynamics*** and other first principles that govern physical and physiological heat exchanges. The resulting review is aimed at providing theoretical and empirical justifications for collecting and interpreting these data. The primary emphasis is upon deep-body temperatures, with discussions of intramuscular, subcutaneous, transcutaneous and skin temperatures included. These are all turnover indices resulting from variations in local metabolism, tissue conduction and blood flow. Consequently, inter-site differences and similarities may have no mechanistic relationship unless those sites have similar metabolic rates, are in close proximity and are perfused by the same blood vessels. Therefore, it is proposed that a gold standard deep-body temperature does not exist. Instead, the validity of each measurement must be evaluated relative to one's research objectives, whilst satisfying equilibration and positioning requirements. When using thermometric computations of heat storage, the establishment of steady-state conditions is essential, but for clinically relevant states, targeted temperature monitoring becomes paramount. However, when investigating temperature regulation, the response characteristics of each temperature measurement must match the forcing function applied during experimentation. Thus, during dynamic phases, deep-body temperatures must be measured from sites that track temperature changes in the central blood volume.

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http://dx.doi.org/10.1016/j.jtherbio.2014.10.006
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1. Introduction

Given existing reviews on body-temperature measurement (Woodhead and Varrier-Jones, 1916; Selle, 1952; Vale, 1981; Togawa, 1985; Brengelmann, 1987; Sawka and Wenger, 1988; Fulbrook, 1993; Ogawa, 1997; Moran and Mendal, 2002; Ring, 2006; Byrne and Lim, 2007; Pušnika and Miklaveca, 2009; Wartzek et al., 2011; Langer and Fietz, 2014; Werner, 2014), another contribution might seem unwarranted. However, following a presentation designed for students (Taylor, 2011), and arising from a debate on the cooling of hyperthermic individuals (Casa et al., 2010), it became apparent the assumed common knowledge on temperature measurement was not quite so common, nor could its existence be presumed. Therefore, in this communication, the authors aimed to draw together the relevant first principles, along with older and more recent physiological evidence that must be understood and considered when measuring body temperatures.

1.1. *First principles in thermodynamics*

Homoeothermic species employ sophisticated autonomic and behavioural temperature regulatory mechanisms to maintain body temperature within a somewhat narrow range. A vast circulatory network, with counter-current heat exchange capabilities (Bernard, 1876; Forster et al., 1946; DuBois, 1951; Scholander and Schevill, 1955; He et al., 2003), transports and distributes metabolically derived and exogenous heat among the body tissues. These are enclosed within a membrane that permits energy and particle exchanges with the environment. As a consequence, homoeotherms are open thermodynamic systems, yet they adhere to the same physical principles governing non-biological energy exchanges, and these first principles moderate physiological processes.

> “*A great deal of misconception could have been cleared by an application of the simple laws of heat flow.*” (DuBois, 1951; P 476).

The ***Laws of Thermodynamics*** define energetic relationships within thermodynamically closed (no material exchange) and isolated structures (no material or energy exchange). Whilst humans are rarely (if ever) in those states, these laws still apply, and provide the scientific foundation for understanding temperature measurement. Moreover, they define the principles of heat transfer. Therefore, several salient concepts, and their physiological implications, are highlighted below; readers are also directed to other treatments (Quinn, 1983; Narasimhan, 1999).

The energy possessed and exchanged by animals is made up from dynamic (kinetic) and static forms (potential: mass-, chemical-, nuclear- and force-related energies). This energy cannot be created, nor can it be destroyed. Instead, it may be converted into another form (***First Law of Thermodynamics***), and within a thermodynamic system, it can be used to perform work on another system (external work), transferring energy to that system (Joule, 1850). The total amount of energy possessed by an object is known as its enthalpy, which is minimal (but not absent) at temperatures approaching absolute zero (***Third Law of Thermodynamics***). It varies with the pressure and volume (mass) of each system, and its kinetic component causes sub-atomic and cellular movement and collisions, releasing thermal energy. Thus, heat content is a function of this collision frequency (Worthing, 1941), and it is quantified using temperature measurements and calorimetry.

Consider a closed (inanimate) system with an outer membrane (diathermal wall) permissive to energetic, but not to material exchange. If that system was placed within a stable environment, the collision frequency of its particles would eventually stabilise, and a state of thermal equilibrium (steady state) would exist. The temperature of that object would now be constant, whilst particle motion continued. If another system with a lower enthalpy comes into physical contact with the former, energy will be exchanged across their contacting walls towards the latter. That is, thermal energy moves down energy gradients (***Second Law of Thermodynamics***), either through a change of state (solid, liquid, gas) or via conductive (molecule to molecule), convective (mass flow) or radiative transfers. This establishes thermal gradients within and between these systems, with both systems eventually attaining a common thermal equilibrium. For homoeothermic species in a steady state, thermal equilibration among tissues and organs is imperfect. This is because of the continuous and widely variable metabolic heat production and mass (convective) transport of heat that occur throughout the body.

1.1.1. *First principles in a physiological context*

To illustrate the implications of these principles for physiological measurements, a thermodynamically closed system is used (a steel sphere). Its enthalpy was changed from one steady state to another on three occasions. Each trial commenced from a different thermal steady state (stirred water baths: 15, 25 and 35 °C). Following equilibration, the sphere was placed in a water bath regulated at a higher energy level (38.5 °C). At its centre was a temperature sensor, with Fig. 1A showing output from that sensor. On each occasion, energy was conducted down a thermal gradient