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Computational estimation of body temperature and sweating in the aged during passive heat exposure

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A B S T R A C T

This study discusses the difference in temperature elevation and sweating between younger and older adults during ambient heat exposure. The bioheat equation is solved computationally in an anatomically based human body model to track the variation in the temperature and sweating in the time domain. Our computational code is improved by introducing different blood temperatures in different body regions and taking into account the maximum possible evaporative heat loss. The reduced thermal sensitivity of the hypothalamus in the aged adults (mean age of 73.9 years) is also estimated from literature data and taken into account in a revised formula for the thermoregulatory response. For ambient heat exposure (a temperature of 40 °C and relative humidity of 42%), our computational results are in good agreement with measurement data in the literature for both younger adults (mean age of 23.5 years) and the elderly (67.8 years old), suggesting the effectiveness of our improved bioheat modeling. The reduction in the thermal sensitivity of the hypothalamus is estimated as 0.6 ± 0.2 °C for the aged (mean age of 73.9 years), although it was not significant for the elderly (67.8 years). For an ambient temperature of 35 °C and relative humidity of 60%, the computed core temperature elevation in the model corresponding to the thermophysiological response of the aged is 0.92 °C, which is higher than those for the younger adults, 0.25 °C, and for the elderly, 0.45 °C. This difference in the core temperature elevation is attributable mainly to the decline in the thermal sensitivity of the hypothalamus. The total perspiration at ages of 67.8 years and 73.9 years was 904 g and 645 g, respectively, which is smaller than that of the younger adults, 1090 g.

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1. Introduction

In recent decades, the number of heat waves with fatalities has increased in Europe, North America, and Asia. Heat waves in these areas are projected to become more intense and frequent in the second half of the 21st century [1]. There were 6770 fatalities in Japan due to heat stroke between 1968 and 2007 [2]. More than 60% of the victims were elderly (older than 65 years), and the number of deaths peaks at the age of 80–84 years [3]. A characteristic of heat stroke in the elderly is that they suffer it during everyday life, especially when staying in the home [4]. One of the primary reasons for this tendency may be reduced sweating rates in older individuals compared to those in younger adults during exercise or passive heat exposure [5–9]. This decline in the sweating rate should result in a greater temperature elevation in older individuals [6,7].

Several studies reported a difference in the thermoregulatory responses of younger and older adults [10–15]. In Ref. [15], it was shown that sweat gland functioning exhibits a reduction in output with aging, followed by a decline in the number of heat-activated sweat glands. In Ref. [14], an age-related shift in sweating thresholds and decrements in sweating rates were more significant than the attenuation in cutaneous vasodilation. Another study [13] hypothesized that the dominant factor causing the decline in sweating is the reduced thermal sensitivity of the skin and then proposed that the decline in thermal sensitivity was due to a weaker signal from the periphery to the regulatory centers (hypothalamus). Note that the sweating rate and vasodilation can be expressed reasonably well as a function of the temperature elevations in both the hypothalamus and the skin [16]. In light of these facts, we developed a computational code that tracks the variations in the temperature and sweating rate in numerical human models of younger and older adults [17]. A model of the thermoregulatory responses

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Nomenclature

A	basal metabolism
B	blood perfusion rate
C	specific heat
EV	evaporative heat loss
H	heat transfer coefficient
K	thermal conductivity
PI	insensible heat loss
Q_b	heat exchange between the blood and tissue
Q_{Btot}	rate of heat acquisition of blood from tissue
S	surface area
SW	sweating rate
T	temperature of the tissue
V	total volume
ρ	mass density
φ	relative humidity
γ	sweating dependency of body part
χ	multiplier expressing sweating decline

Subscripts

$( )_B$	associated with blood
$( )_c$	associated with convection
$( )_{,dec}$	associated with sweating decline
$( )_e$	associated with the air
$( )_H$	associated with the hypothalamus
$( )_{HB}$	signal from the hypothalamus
$( )_s$	associated with the skin
$( )_{SB}$	signal from the skin

for younger adults (mean age of 23.5 years) and the elderly (67.8 years) was confirmed and developed from measured data (15 subjects) [17]. The main findings of the computational modeling were i) the thermal sensitivity of the skin in the elderly was approximately 1.5 °C lower, and ii) the input signal due to core temperature elevation cannot be described as marginal, at least for exposure to an ambient temperature of 40 °C and humidity of 42%. In contrast, there were some differences in the time course of core temperature elevation between the measurement and our computational results, especially for exposure durations of less than 30 min. This difference in core temperature elevation may not be neglected when investigating the thermoregulatory response of younger and older adults because it affects the retarded onset of sweating in the older adults.

Only a limited number of studies investigated the decline in the thermoregulatory responses in the aged (~75 years or older) [5,18]. In Ref. [5], the younger adults and the aged, with mean ages of 26.6 and 73.9 years, respectively, exercised on a cycle ergometer for 20 min and were then immersed in 28 °C water. The relationship between the core temperature and sweating rate suggested lower thermal sensitivity in the hypothalamus of older individuals, which was not fully discussed in our previous study [17]. Specifically, the threshold core temperature for sweating activation in the aged was higher than that in the younger subjects by ~0.5 °C.

In the present study, first, our computational code is improved by introducing variable blood temperatures in different body regions and taking into account the maximum possible evaporative heat loss. The decline in the thermal sensitivity of the hypothalamus due to core temperature elevation in the aged (defined here as individuals with a mean age of 73.9 years) is estimated and incorporated into an improved thermoregulatory formula. Using the computational model developed here, the variations in the temperature and sweating rate in younger adults (~25 years old), the elderly (~67.8 years old), and the aged (~73.9 years old) are compared.

2. Model and methods

2.1. Human body models

A Japanese male model was used in our modeling [19]. The adult model is segmented into 51 anatomic regions such as the skin, muscle, bone, brain, and heart, with a resolution of 2 mm. The height, weight, and surface area of the model are 1.73 m, 65 kg, and 1.78 m^2, respectively, corresponding to a surface-area-to-mass ratio of 0.0274 m^2/kg. This human body model is used not only for younger adults (20–30 years old) but also for the elderly, with a mean age of 67.8 years, and the aged, with a mean age of 73.9 years, because no anatomically based numerical model for the elderly has been developed. In the following discussion, we refer to subjects with a mean age of 67.8 years as the elderly, and those with an age of 73.9 years as the aged.

2.2. Thermal analysis

The algorithm for computing the temperature variation with the thermoregulatory response is summarized in Fig. 1. The detailed formula is presented in the following sections.

2.2.1. Bioheat equation

The temperature elevation in the numerical human models was calculated by solving the bioheat equation [20], which models the thermodynamics of the human body. A generalized bioheat equation is given as

$$C(\mathbf{r})\rho(\mathbf{r})\frac{\partial T(\mathbf{r},t)}{\partial t} = \nabla\cdot(K(\mathbf{r})\nabla T(\mathbf{r},t)) + M(\mathbf{r},t) - B(\mathbf{r},t)(T(\mathbf{r},t) - T_B(m,t)) \quad (1)$$

where $T(\mathbf{r},t)$ and $T_B(m,t)$ denote the tissue temperature and blood temperature, respectively, of different body parts (m = 1, …, 5, where $m = 1, 2, 3, 4,$ and 5 represent the head and trunk, right hand, left hand, right leg, and left leg, respectively); C [J/kg °C] is the specific heat of the tissue; ρ [kg/m^3] is the mass density of the tissue; K [W/m °C] is the thermal conductivity of the tissue; M [W/m^3] is the basal metabolism per unit volume; and B [W/m^3 °C] is a term associated with blood perfusion. The boundary condition between air and tissue for Eq. (1) is expressed as

$$-K(\mathbf{r})\frac{\partial T(\mathbf{r},t)}{\partial n} = H(\mathbf{r})\cdot(T(\mathbf{r},t) - T_e(t)) + \mathrm{EV}(\mathbf{r}) \quad (2)$$

where H [J/m °C s], T [°C], and T_e [°C] denote the heat transfer coefficient, body surface temperature, and air temperature, respectively. H includes the convective and radiative heat losses, and EV [W/m^2] is the evaporative heat loss. The heat transfer coefficient from the skin to the air, including the insensible heat loss, was obtained as 5.7 W/m^2/°C. However, the numeric phantom used in the present study is discretized by voxels, so its surface is approximately 1.4 times larger than that of an actual human [21].

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