Computational Estimation of Body Temperature and Sweating in the Aged during Passive Heat Exposure

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Abstract

  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.

Keywords

Bioheat equation, the aged, thermoregulatory response, heat stroke, decline in sweating rate

NOMENCLATURE

A	basal metabolism	ρ	mass density
B	blood perfusion rate	φ	relative humidity
C	specific heat	γ	sweating dependency of body part
EV	evaporative heat loss	χ	multiplier expressing sweating
H	heat transfer coefficient		decline
K	thermal conductivity	Subscripts	
PI	insensible heat loss	$(\ )_B$	associated with blood
Q_b	heat exchange	$(\ )_c$	associated with convection
	between the blood and tissue	$(\ )_{,dec}$	associated with sweating decline
Q_{Btot}	rate of heat acquisition of blood	$(\ )_e$	associated with the air
	from tissue	$(\ )_H$	associated with the hypothalamus
S	surface area	$(\ )_{HB}$	signal from the hypothalamus
SW	sweating rate	$(\ )_s$	associated with the skin
T	temperature of the tissue	$(\ )_{SB}$	signal from the skin
V	total volume		

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 6,770 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 [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 [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 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[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

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

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

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

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]. Considering this difference, the actual heat transfer coefficient with insensible water loss is 7.8 W/m^2/°C, which is well within the uncertainty range reported in [22].

2.2.2. Blood Temperature Computation

The key feature of our computational modeling is that the body core temperature variation can be tracked in addition to the temperature in shallow regions of the body, unlike the case in conventional bioheat modeling. The blood temperature varies according to the following equation to satisfy the first law of thermodynamics [23, 24]:

$$T_B(m,t) = T_B(m,0) + \int_t \frac{Q_{Btot}(m,t) \pm Q_B(m,t)}{C_B \rho_B V_B(m)} \mathrm{d}t \tag{3}$$

where Q_{Btot} is the net rate of heat acquisition of blood from the body tissues in body part m, Q_B is the heat exchange between the head and trunk and one of the limbs (m = 2, 3, 4, 5), C_B (= 4,000 J/kg·°C) is the specific heat of blood, ρ_B (= 1,050 kg/m^3) is the mass density, and V_B is the total volume of blood in body part m. V_B over the body is set to 7% of the weight of the corresponding body part [25]. This approach is much simpler than those considering the arterio-venous anastomoses [26-28], which are still difficult to validate.

The heat exchange between the head and trunk and one of the limbs is given as [29]

$$Q_{b,m}(t) = \int h_x (T_{b,1}(t) - T_{b,2,\dots,5}(t)) dV \tag{4}$$

where h_x [W/°C] is the heat exchange coefficient between body parts. In the following discussion, $T_b(1, t)$ is defined as the core temperature.

The thermal constants of human tissues and the heat transfer coefficients used in this study are identical to those used in our previous study [30]. Note that the blood perfusion rate in the elderly is known to be smaller than that in younger adults (e.g., 30% smaller in the thermally steady state in [5]); in addition, the core temperature in the thermoneutral condition is lower.

Even though we set the core temperature of the thermoneutral condition at 36.5 °C for the elderly with a 30% smaller blood perfusion rate, the resultant temperature elevation is almost identical. Thus, the blood perfusion rate and temperature elevation in the thermally steady state for the elderly are assumed to be identical to those for younger adults in this study. The effect of these parameters on the temperature of the elderly for a compartmentalized human body model is discussed in [31].

2.3. Thermoregulatory Response in Younger and Older Adults

2.3.1. Modeling of Evaporative Heat Loss

The evaporative heat loss on the skin EV is

$$EV = \min\{SW \times 40.6 / S, \quad EV_{\max}\} \tag{5}$$

where SW is the sweating rate [g/min] (see below), S [m^2] is the total surface area of the human body, and the factor of 40.6 is a conversion coefficient [J·min/g/s]. The maximum evaporative heat loss $EV_{\max}$ on the skin depends on the ambient conditions according to the following formula [16]:

$$EV_{\max} = 2.2 \times h_c f_{pcl}(P_S - \varphi_e P_A) \tag{6}$$

where h_c is the convective heat transfer coefficient; P_S and P_e are the saturated water vapor pressures at the temperature of the skin and at the ambient air temperature, respectively; φ_e is the relative humidity of the ambient air; and f_{pcl} is the permeation efficiency factor of clothing, which is affected by the speed of air movement [32]. For simplicity, f_{pcl} is assumed to be 1, corresponding to a naked body.

Sweating in younger adults is modeled using the formulas in [29]. The sweating rate SW is assumed to depend on the temperature elevation in the skin and hypothalamus according to the equations

$$SW(\boldsymbol{r},t) = \gamma(\boldsymbol{r})\chi(\boldsymbol{r})\{W_S(\boldsymbol{r},t)\Delta T_S(t) + W_H(\boldsymbol{r},t)\Delta T_H(t)\} \times 2^{(T(\boldsymbol{r})-T_0(\boldsymbol{r}))/10} + PI \tag{7}$$

$$W_s(\boldsymbol{r},t) = \alpha_{11}\tanh(\beta_{11}(T_S(\boldsymbol{r},t) - T_{SO}(\boldsymbol{r})) - \beta_{10}) + \alpha_{10} \tag{8}$$

$$W_H(\boldsymbol{r},t) = \alpha_{21}\tanh(\beta_{21}(T_H(\boldsymbol{r},t) - T_{HO}(\boldsymbol{r})) - \beta_{20}) + \alpha_{20} \tag{9}$$

where T_s and T_H are the temperatures of the skin averaged over the body and of the hypothalamus, respectively, and PI, the insensible water loss, is 0.63 g/min. T_{S0} and T_{H0} represent the set temperatures or upper critical temperatures in the thermoneutral condition [33]. The multiplier $\gamma(\boldsymbol{r})$ denotes the dependence of the sweating rate on the body part (Table 2 in [29]) [34]. The coefficients α and β are determined for the average sweating rate based on measurements [16]. In Eqs. (8) and (9), these coefficients are defined as $\alpha_{10} = 1.20$ [g/(min·°C)], $\alpha_{11} = 0.80$ [g/(min·°C)], $\beta_{10} = 0.19$, $\beta_{11} = 0.59$ [°C^{-1}], $\alpha_{20} = 6.30$ [g/(min·°C)], $\alpha_{21} = 5.70$

[g/(min·°C)], β_{20} = 1.03, and β_{21} = 1.98 [°C^{-1}] for young adults with standard sweating, α_{10} = 0.95 [g/(min·°C)], α_{11} = 0.55 [g/(min·°C)], β_{10} = 0.09, β_{11} = 0.59 [°C^{-1}], α_{20} = 3.80 [g/(min·°C)], α_{21} = 3.20 [g/(min·°C)], β_{20} = 1.80, and β_{21} = 2.70 [°C^{-1}] for those with lower sweating parameters, and α_{10} = 1.35 [g/(min·°C)], α_{11} = 0.95 [g/(min·°C)], β_{10} = 0.15, β_{11} = 0.59 [°C^{-1}], α_{20} = 7.30 [g/(min·°C)], α_{21} = 6.70 [g/(min·°C)], β_{20} = 0.47, and β_{21} = 2.30 [°C^{-1}] for those with higher sweating.

2.3.2. Modeling of Sweating in the Elderly

The maximum sweating rate in most body parts except for the limbs was confirmed to be almost identical in younger adults and the elderly [8, 9, 13, 35]. In our previous study [17], we modified the original Eq. (7) as follows: i) the decline in sweating in the limbs is considered by adding a multiplier $\chi(r)$ = 0.6 in the legs, and ii) the threshold for inducing the sweating response in the elderly is increased by introducing $\Delta T_{S,dec}$ [see Eq. (10)], which represents the decline in the thermal sensitivity of the skin due to aging. This value was estimated to be 1.5 °C in our previous study [17]. In [18], the age dependency of the sweating rate in the forearm was measured at a core temperature of 38 °C. The sweating rate in the forearm decreases rapidly from 50 to 65 years but does not change greatly from 65 to 70 years; the individual difference is more significant. Thus, the value of $\Delta T_{S,dec}$ = 1.5 °C is used even for the aged.

The threshold at which the sweating response is induced in the aged is increased by introducing a shift in the threshold temperature $\Delta T_{H,dec}$, which represents the decline of the thermoregulatory signal that originates from the temperature elevation of the hypothalamus (defined as the reference for the body core). Thus, in the model for the aged, ΔT_S and ΔT_H in Eq. (7) are given by

$$\Delta T_S = \begin{cases} 0 & T_s < T_{s,0} + \Delta T_{s,dec} \\ T_S - (T_{s,0} + \Delta T_{s,dec}), & T_s > T_{s,0} + \Delta T_{s,dec} \end{cases} \tag{10}$$

$$\Delta T_H = \begin{cases} 0 & T_H < T_{H,0} + \Delta T_{H,dec} \\ T_H - (T_{H,0} + \Delta T_{H,dec}), & T_H > T_{H,0} + \Delta T_{H,dec} \end{cases} \tag{11}$$

The value of $\Delta T_{H,dec}$ was determined on the basis of the results in [5]. In that study, subjects first increased their body temperatures by exercising, after which they were immersed in water at 28 °C. During the cooling period in the water, both the body temperature and sweating rate were measured. Figure 2 shows the dependence of the coefficient for the sweating rate [Eq. (9)] on the core temperature elevation for the younger adults [26.6 ± 5.2 (SD) years] and the aged (73.9 ± 4.8 years) taken from [5], together with data listed in [29]. Note that the subjects were not acclimated to a hot environment. As shown in Fig. 2, the data in [5] are within the variation

in those in [29]. Note that the sweating rate in the forehead is approximately adjusted on the basis of the number of active glands [34]. In the thermoregulatory model, the hypothalamus temperature elevation ΔT_H is the prevailing input parameter that governs sweating [29]. If we assume that the change in the hypothalamus temperature ΔT_H is equal to the change in the body temperature ΔT_B in Fig. 2, then, when Eq. (11) is introduced, $\Delta T_{H,dec}$ can be estimated as 0.6 °C (best fit with the measured data on the basis of visual inspection; see the red curve in Fig. 2). The standard deviation of $\Delta T_{H,dec}$ is noted as 0.2 °C [5]. Note that a comparable estimate for $\Delta T_{H,dec}$ can be obtained from the results in [18], which measured the critical temperature for the onset of sweating in exercising subjects and observed significantly higher onset temperatures in the elderly than in control subjects. From the data in [18], $\Delta T_{H,dec}$ for adults older than 70 years can be estimated to be 0.4 °C (the difference in the median critical temperatures of the control and elderly subjects). The coefficients in Eqs. (8) and (9) are assumed to be identical to those for younger adults because of a lack of data, even though the variability of sweating increases with aging.

2.3.3. Blood Perfusion Rate

For a temperature elevation above a certain level, the blood perfusion rate is increased to carry away the excess heat produced [16]. The variation in the blood perfusion rate in the skin through vasodilatation is expressed in terms of ΔT_H and ΔT_S:

$$B(\boldsymbol{r},t) = (B_0(\boldsymbol{r}) + F_{HB}\Delta T_H(t) + F_{SB}\Delta T_S(t)) \cdot 2^{(T(\boldsymbol{r},t)-T_0(\boldsymbol{r}))/6} \tag{12}$$

where F_{HB} and F_{SB} are the weighting coefficients of the signals from the hypothalamus and skin, which were 17,500 W/m^3/°C^2 and 110 W/m^3/°C^2, respectively [23]. Blood perfusion in all tissues except the skin was assumed to be constant, as in [16]; i.e., the increased demand for blood flow to the skin was assumed to be satisfied solely by increased cardiac output, and the potential redistribution of blood flow from visceral organs to the skin was ignored.

2.4 Computational Implementation

The computational thermal model was implemented in an in-house code written in FORTRAN. The bioheat equation (1) and the boundary condition (2) were discretized using a difference method with a six-point stencil in the spatial domain and the explicit Euler method in the time domain; i.e., at each time step, the sweating and blood perfusion rates and blood temperature were updated using the temperature distribution calculated at the previous time step. The discretization size was 2 mm in the spatial domain, corresponding to 8 million degrees of freedom, and 2 s in the time domain. Note that the discretization time was chosen so as to satisfy the stability condition [36]. The simulations were run on a workstation with the CentOS

operating system, a Xeon X5690 (3.47 GHz) processor, and 64 GB of RAM. The computation time required for each simulation was directly proportional to the number of time steps; it was 80 min for a simulation duration of 1 h.

2.5 Exposure Scenarios

In the initial state, the steady-state temperature distribution in the human body is given. This distribution is obtained from the bioheat equation (1) subject to the boundary condition (2) assuming that the body core temperature is 37.0 °C for a given basal metabolism. Note that the core temperature change and thermoregulatory response can be assumed to be nonexistent. Then, the temperature increase is obtained by solving (1).

To verify our computational code, the computational results are compared with experimental data acquired from [13]. In that study, the mean ages for the younger adults and the elderly were 23.5 and 67.8 years, respectively. The exposure scenario in that study was as follows: 1) The subject rested in a thermoneutral room with air and wall temperatures of 28 °C; 2) the ambient temperature was changed gradually from 28 to 40 °C in the first 4 min and then remained at 40 °C for 86 min. Note that the decline in the thermoregulatory signal from the skin is considered in the model [13]. For further verification, an additional set of experimental data was obtained from [8] for the following exposure scenario: 1) The subject wore swimming trunks and maintained a sitting position on a chair in the chamber anteroom, which was set to an air temperature of 28 °C and relative humidity of 45%; 2) the subject entered the environmental chamber, which was maintained at an ambient temperature of 35 °C, and sat on a chair; 3) the subject immersed his legs to the knees into a stirred water bath maintained at 42 °C for 60 min. The mean age for the subjects was 68.4 years.

To clarify the difference between the younger and older adults in terms of the decline in the signals from both the skin and the body core, we applied our computational model at three ambient temperatures, 32.5, 35, and 37.5 °C, with a relative humidity of 60%. The exposure duration was set to 3 h. For comparison, a human model with the thermoregulatory response of the elderly (with the decline in the thermoregulatory signal from the skin) was also considered.

3. Computational results

3.1. Verification of Computational Modeling

To confirm the effectiveness of our model, the core temperature elevation and sweating computed with the improved bioheat model are compared with the measurement data in the literature [13]. In addition, the results computed using a conventional model, which did not consider the variation in the blood temperature in different body parts in Eqs. (3) and (5), are also plotted in Fig. 3. As shown in Fig. 3 (a), good agreement is observed between the computed

and measured core temperature elevation for passive heat exposure. In particular, some retardation of the temperature elevation was simulated in the early stage of exposure (less than 30 min) by introducing blood temperatures that varied with the body part. Note that the revised value of the multiplier $\chi(r)$ in (7) was 0.65 for our improved bioheat model. As shown in Fig. 3 (b), the proposed modeling marginally affects the skin temperature. The differences between measured (10 point averaged) and simulated skin temperature elevations are at most 18% for the younger adult and the elderly, except for the early stage of exposure (less than 15 min). Good agreement is also observed in the time evolution of the sweating rate, as shown in Fig. 3 (c).

As shown in Fig. 4, good agreement is observed between the computed and measured core temperature elevation for both the younger and older adults under a heat load when the improved computational model was used. The difference in the computed core temperatures between the previous and proposed models becomes significant because the heat load was applied only to the legs. The sweating rates are not compared because the sweating rates in the limbs were not measured [8].

3.2. Temperature Elevation and Sweating in Younger and Older Adults

The core temperature elevation in different thermoregulatory models is illustrated in Fig. 5 for an ambient temperature of 32.5 °C and humidity of 60% at 90 min. The figure confirms the higher temperature elevations in the elderly and aged.

Figure 6 shows the core temperature elevation and sweating rate in the young, elderly, and aged adults for ambient temperatures of 32.5, 35, and 37.5 °C with a humidity of 60%. In addition, the core temperature elevation in the aged with lower sweating and a higher threshold for the core temperature is presented. As shown in Fig. 6 (a), the core temperature elevation in the thermally steady state was 0.18 °C with a thermal time constant of 34 min. In contrast, the core temperature in the older adults required more time to reach the thermally steady state, i.e., 38 min and 69 min for the elderly and aged, respectively. This is attributable mainly to the difference in the sweating rate in younger and older adults (see below), which means that younger adults reach balance in a shorter time.

As shown in Fig. 6 (b), a similar tendency was observed at 35 °C; e.g., the core temperature in the younger adults rises by 0.25 °C with a thermal time constant of 34 min. However, as shown in Fig. 6 (c), at 37.5 °C, the core temperature in the younger adults increases gradually with time without reaching the thermally steady state. This is because the thermal load is larger than the evaporative heat loss via sweating for the higher ambient temperature. In addition, Fig. 6 shows that the difference in the maximum core temperature elevation in the younger and older adults becomes smaller at an ambient temperature of 37.5 °C; it is 0.9 °C at ambient temperatures of 32.5 and 35 °C, but 0.7 °C at 37.5 °C.

Figure 7 shows the sweating rate integrated over the body in the human models with different thermoregulatory response models. As shown in Fig. 7 (a), the sweating rate increases more rapidly in the younger adults than in the older adults. In the elderly, the sweating rate increases gradually because of the increase in the core temperature. This tendency is consistent with [31]. In the older adult model (73.9 years), the sweating rate remains at the level of the insensible water loss until 53 min and then increases gradually owing to skin temperature elevation [Eq. (10)]. Then, the sweating rate increases at 88 min after the hypothalamus temperature elevation reaches its threshold in Eq. (11). Among the aged models, that with a higher threshold for the core temperature and a lower sweating rate had the smallest sweating rate. A similar tendency was observed for different ambient temperatures [Figs. 7 (b) and (c)]. For ambient temperatures of 32.5 and 35 °C, the sweat evaporated fully for all the thermoregulatory models. However, the sweat did not fully evaporate for the ambient temperature of 37.5 °C.

The potential evaporative heat loss [$SW \times 40.6/S$ in Eq. (5), which is the evaporative heat loss in the case that all the secreted sweat evaporated] is compared to the maximum evaporative heat loss in Fig. 8 for the ambient temperature of 37.5 °C. The potential evaporative heat loss reaches its maximum capacity for younger adults and the aged. After this maximum heat loss is reached, sweating becomes ineffective. This is one of the reasons that the difference in the core temperature elevation between younger and older adults is small at the ambient temperature of 37.5 °C. Note that the small difference in the maximum evaporative heat loss between the younger adults and the aged is caused by the difference in the skin temperature elevation.

The total amounts of sweating in the younger and older adults for an exposure duration of 3 h are listed in Table 1. As shown in Table 1, the total amount of sweating in the elderly and aged is much smaller than that in younger adults.

4. Discussion

4.1. Difference between Computation and Measurement

The difference in the core temperature elevations between the measurement values obtained from the literature and the data we computed in our previous study was not negligible for exposure durations of less than 30 min, indicating a different thermoregulatory response. In contrast, the computational data obtained by the method proposed here were in good agreement, which is attributed mainly to the introduction of different blood temperatures in different body regions. Thus, the multiplier $\chi(r)$ in (7), which is the main parameter expressing the decline of sweating in the legs, was revised to 0.65. Measured and computed skin temperatures are different by 20% especially in the early stage of exposure (less than 30 min), even though core temperature elevation and sweating rate is in good agreement (Fig. 3). One of the reasons for the skin temperature difference may be attributable to ambient temperature in the early stage (see

Sec. 2.5). Additional reason may be caused by the variability of sites for sampling the temperature in measurement. Note that our computational results are in good agreement with measurement data [30] for adult and child exposed to passive heat.

The body characteristics are known to affect the temperature change in humans during passive heat exposure [37]. We clarified that the dominant factor affecting the core temperature elevation was approximately proportional to the body surface-area-to-mass ratio for passive heat exposure [38]. The limitation of using one anatomically based model is attributable to the fixed surface-area-to-mass ratio. Our discussion was validated by a comparison with the measured data obtained from [13]. The mean surface-area-to-mass ratios for 15 younger and older subjects in the measurement in [13] were estimated as 0.0256 and 0.0242 m^2/kg, respectively, on the basis of [39]. The mean surface-area-to-mass ratios for the younger and older subjects are smaller than that of the numerical Japanese male model by 6.5% and 11%, respectively. Similarly, the surface-area-to-mass ratios for the younger and older subjects in [5] are smaller than that of the Japanese male model by 4.9% and 5.2%, respectively.

Let us discuss the variability of the temperature elevation in the measurement, as we discussed the variability caused only by sweating. The variability has at least three causes. The first is the uncertainty of the disposable probe (3M Tempa-DOT, 3M Health Care) used in [13], which is ±0.1 °C and thus may be obvious in the measured data at 30 min. Second, the morphology causes some variability. For nine younger and aged adult subjects in [5], the variation in the surface-area-to-mass ratios from each mean value ranged from -7.6% to 5.1% and -6.8% to 11.0%, respectively. The computed uncertainty curves may be up- and down-shifted by 5%–10%. Third, specific to the computational conditions and results in Fig. 2, the thermoregulatory signals from the body core of the elderly, which are characterized by ΔT_H, may be reduced in some subjects, which was not obvious for most subjects; the individual difference in the decline in the thermal sensation is obvious [18].

4.2. Effectiveness and Limitations of Thermoregulatory Modeling

This study confirmed the effectiveness of bioheat modeling with the thermoregulatory response for young adults [29], in addition to its extension to older adults. Note that the thermoregulatory model for young adults [29] has been validated for a compartmentalized (simplified) human model under environmental temperatures between 5 °C and 50 °C and exercise intensities between 0.8 met and 10 met. The exposure condition considered here (32.5 to 37.5 °C and 1 met) is within this range. This study improved the computational thermoregulatory model by introducing an anatomically realistically shaped human body model. In addition, the model of the thermoregulatory response was modified using $\Delta T_{H,dec}$ to consider the difference in the threshold hypothalamus temperature at which sweating is activated in the

aged. The mean value and standard deviation of $\Delta T_{H,dec}$ were estimated as 0.6 $\pm$ 0.2 °C from [5], in which subjects first increased their body temperature by exercising and were then immersed in water at 28 °C, and the threshold body temperature at which sweating stopped was measured. The decline in the thermoregulatory response originating from the temperature elevation in the hypothalamus, ΔT_H, may become obvious at ages greater than 70 years [5], although the individual differences are large. This hypothesis may be explained in part by the fact that subjects are classified into two groups, labeled "Control" for the subjects 65 years old or younger and ">70 years" in [18].

4.3. Temperature Elevation in Younger and Older Adults during Ambient Heat Exposure

As shown in Figs. 3 and 4, the core temperature elevation in the elderly is larger than that in the younger adults. This difference can be attributed mainly to a lower sweating rate, as often pointed out in previous studies [5-9]. In [17], the difference in the core temperature elevation between younger adults and the elderly [13] was attributed mainly to a lower sweating rate caused by a higher thermal threshold ΔT_S or the reduced thermal sensitivity of the skin. The time variation in the core temperature elevation and sweating rate were tracked well in the time domain using the thermoregulatory model presented in this study. The developed model was extended to the aged on the basis of the measured data for the critical temperature at which sweating is activated [5]. Direct experimental verification of the model is difficult because experiments involving long-duration ambient heat exposure in individuals of such great ages are difficult for ethical reasons. Note that only the decline in the skin thermal sensation was considered in the original elderly model, whereas the decline in the thermoregulatory signals originating from the temperature elevation in both the skin and the body core were considered in the aged model. As pointed out in Sec. 4.2, the decline in the thermoregulatory response originating from the hypothalamus may not be negligible in some subjects in [13]. The point to be stressed from our computational results is that the body core temperature elevation in the elderly with potentially reduced hypothalamic activity may be significant even at an ambient temperature of 32.5 °C if they remain for a longer duration. Note that dehydration occurs when the amount of sweating reaches about 3% of the body weight [2], corresponding to 1,950 g for the human body model considered. Thus, the computational results presented here become less reliable when the total amount of sweating approaches this value. After the sweating rate given in (7) is not sustained, further temperature elevation may be observed due to lower evaporative heat loss. For the computational example for the ambient temperature of 37.5 °C, the curves presented do not change dramatically because the potential evaporative heat loss is higher than the maximum evaporative heat loss (see Fig. 8); the evaporative heat loss is determined by Eq. (5). For heat exposure for longer durations, the sweating rate may be reduced by dehydration,

resulting in significant core temperature elevation or, ultimately, thermal breakdown.

As seen from Fig. 6 (c) (ambient temperature of 37.5 °C), the body core temperature in the healthy aged with lower sweating and a higher threshold for the core temperature is, however, elevated by at most 1.4 °C, to 38.4 °C, which is much lower than the clinically defined limit for heat stroke of 40.6 °C. Note that heat stroke can progress to death in an individual within hours [40]. In addition, the victims of heat stroke are identified as having a chronic illness or taking some drug. The modeling of these effects is outside the scope of this study because the data were measured only for healthy subjects, so there are no data for those who are ill or taking medication. The other point is that the total amounts of sweating in the older adults are much smaller than that of the younger adults. Our computational results may support the conclusion in [41] because of the physical consideration that the dehydration caused by sweating may not be a direct cause of heat stroke in older adults, regardless of the fact that the total amount of water in the body is smaller in older adults than in the younger adults.

5. Conclusions

This study discussed the temperature elevation and sweating in young and older adults under ambient heat exposure. Our computational code based on the bioheat equation and thermoregulatory response has been extended by introducing different blood temperatures in different body regions and taking into account the maximum possible evaporative heat loss. For an ambient temperature of 40 °C and relative humidity of 42%, our computational results were in good agreement with the measurements for both younger and older adults. The decline in the thermal sensitivity of the hypothalamus was estimated as 0.6 ± 0.2 °C for the aged (~73.9 years old), although it was not significant for the elderly (~67.8 years old). This decline in the thermal sensitivity of the hypothalamus was consistent with another report [18]. For an ambient temperature of 35 °C and humidity of 60%, the computed core temperature elevation in the aged was 0.92 °C, which is higher than that for the younger adults, 0.25 °C, and for the elderly, 0.45 °C. The total amounts of perspiration in the elderly and aged were 904 g and 645 g, respectively, which are much smaller than that in the younger adults, 1090 g, suggesting that the greater core temperature elevation was caused by reduced sweating. This tendency was the same for different ambient temperatures, although the maximum evaporative heat loss affected the time variation in the temperature at an ambient temperature of 37.5 °C.

The computational code and the results obtained herein are expected to be helpful when heat stroke in the elderly is discussed.

FIGURE AND TABLE CAPTIONS

Figure 1. Flowchart of bioheat modeling with thermoregulatory response in computational domain.

Figure 2. Dependence of sweating rate on core temperature elevation $T_H - T_{H0}$. Measured values obtained from [29], together with those for the aged [5], are plotted. The curves for younger adults with lower, standard, and higher sweating rates are drawn, in addition to that for the aged with the standard sweating rate.

Figure 3. Computed and measured (a) core temperature elevations [°C], (b) averaged skin temperature elevations [°C], and (c) sweating rates integrated over the body [mg/min/m^2] for passive heat exposure (40 °C and 42%). The measured data were obtained from [13]. Error bars represent standard deviation of measured data.

Figure 4. Computed and measured temperature elevations [°C] for subject with legs immersed in hot water (42 °C and 42%). The measured data were obtained from [8]. Error bars represent standard deviation of measured data.

Figure 5. Computed temperature elevation distribution on human body surfaces (a) in thermally steady state (28.0 °C) and at ambient heat exposure (32.5 °C and 60%) at 90 min for (b) younger adults, (c) the elderly, and (d) the aged.

Figure 6. Modeled time course of core temperature elevation in human model with different thermoregulatory responses corresponding to those of younger adults, elderly, and aged at ambient temperatures of (a) 32.5 °C, (b) 35.0 °C, and (c) 37.5 °C and relative humidity of 60%.

Figure 7. Modeled time course of sweating rate over the body in human model with different thermoregulatory responses corresponding to those of younger adults, elderly, and aged for ambient temperature and relative humidity of (a) 32.5 °C and 60%, (b) 35.0 °C and 60%, (c) 37.5 °C and 60%, respectively.

Figure 8. Modeled potential evaporative heat loss [($SW \times 40.6/S$ in Eq. (5)] and maximum evaporative heat loss for younger adults and the aged at ambient temperature of 37.5 °C.

Table 1. Total amounts of sweating in younger adults, the elderly, and the aged for 3-h exposure.

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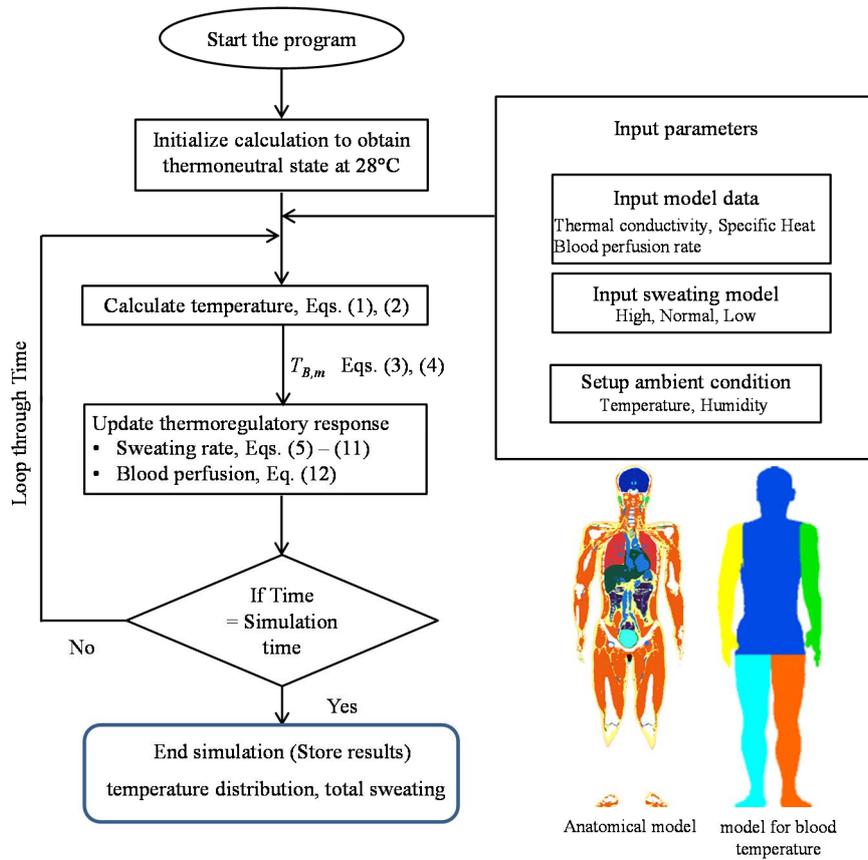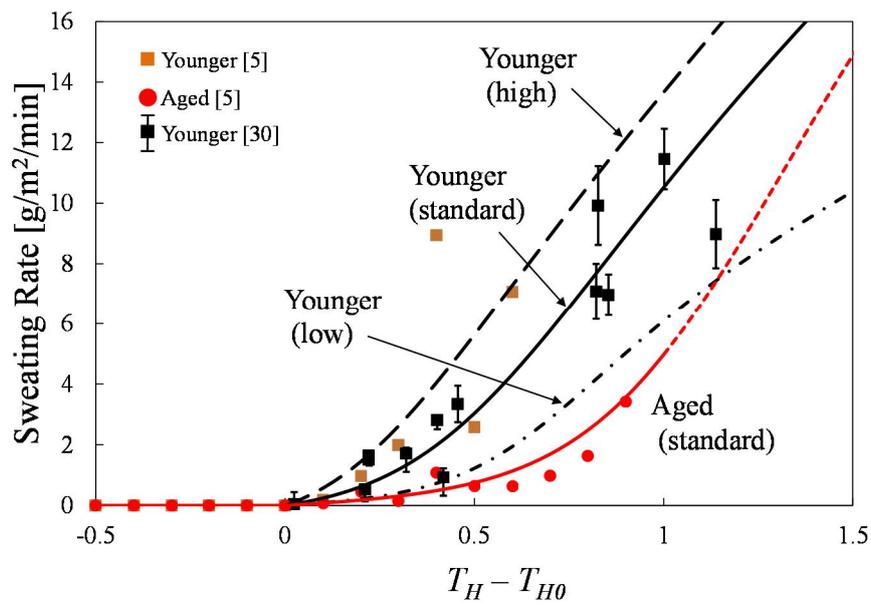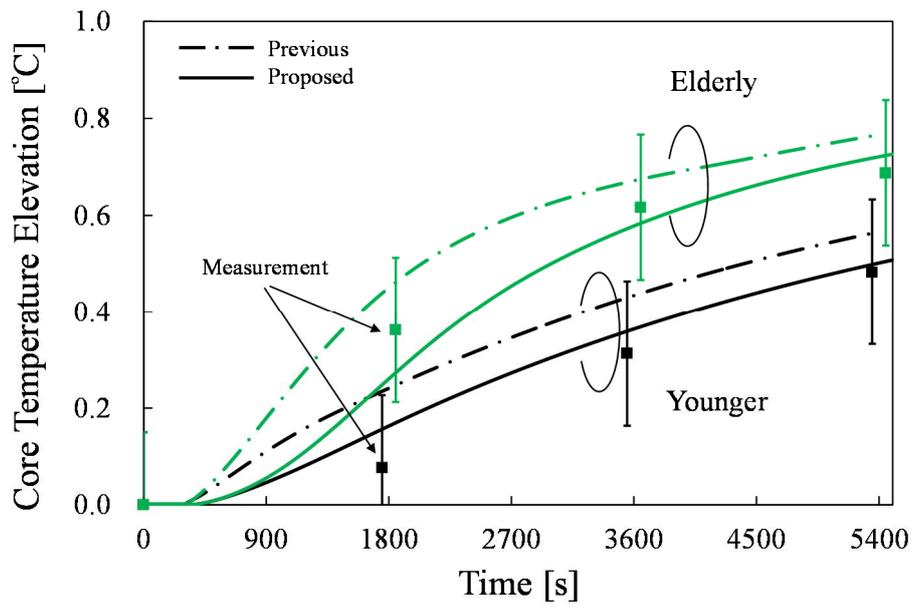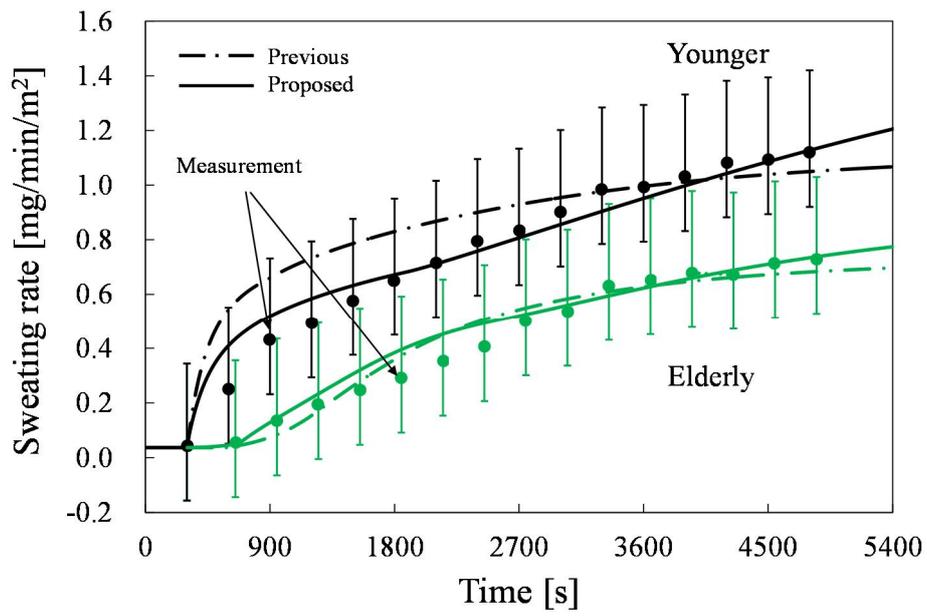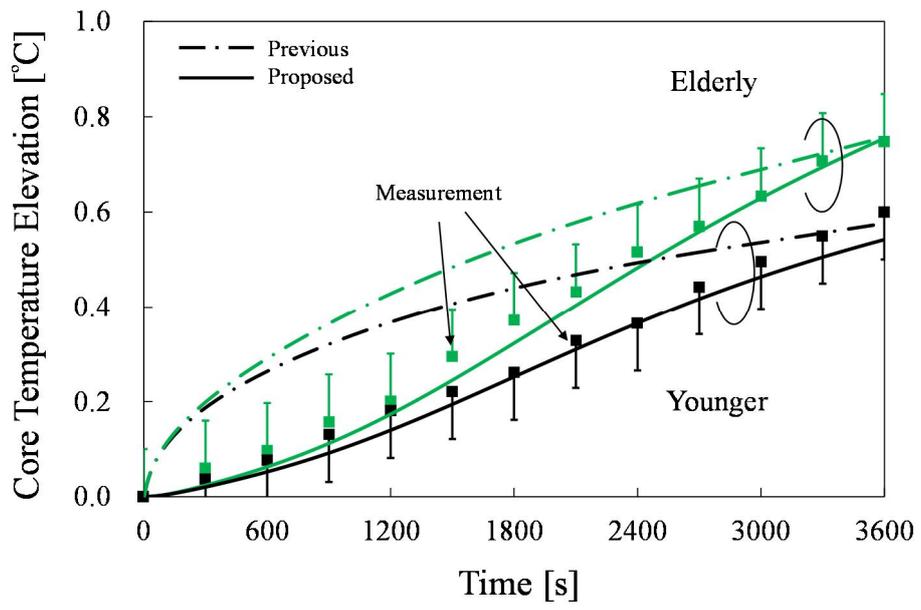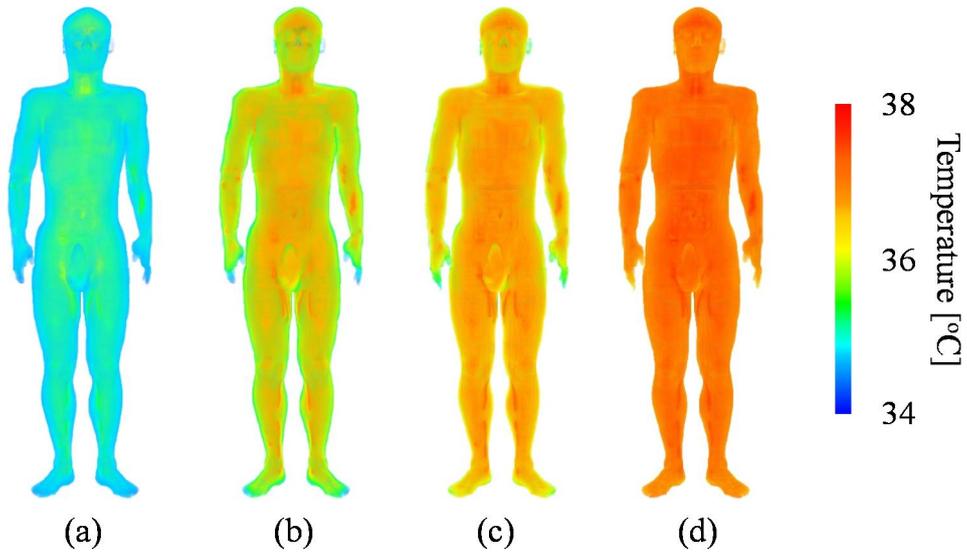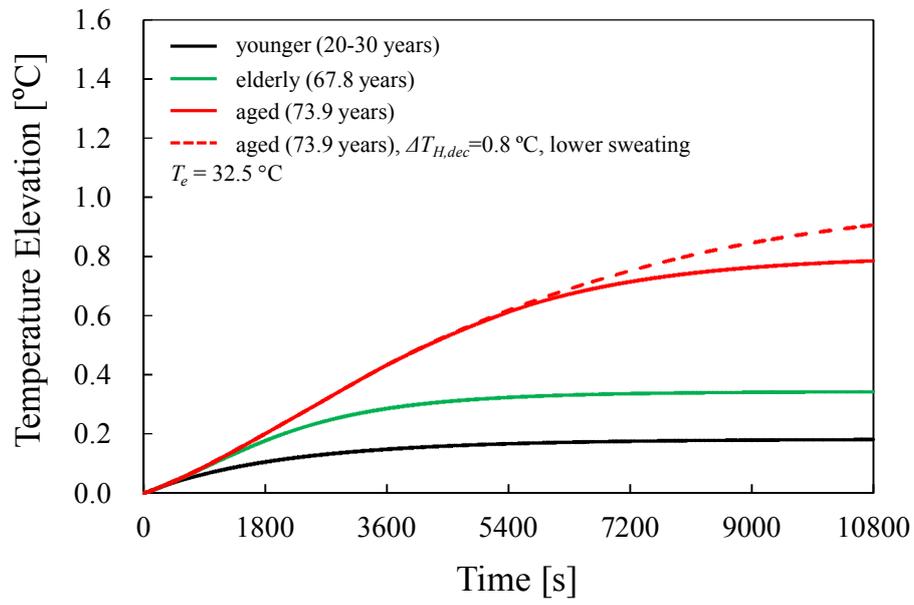
Fig. 1.

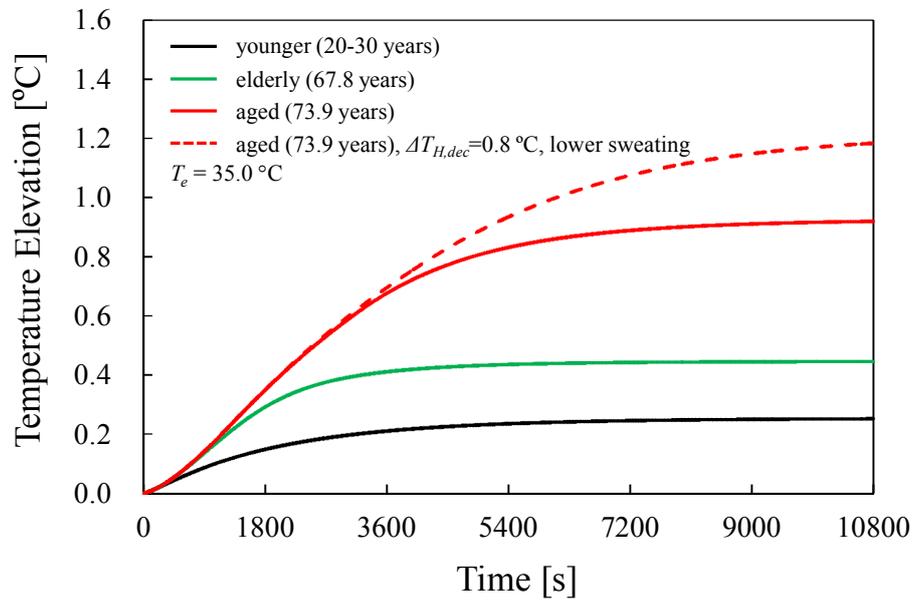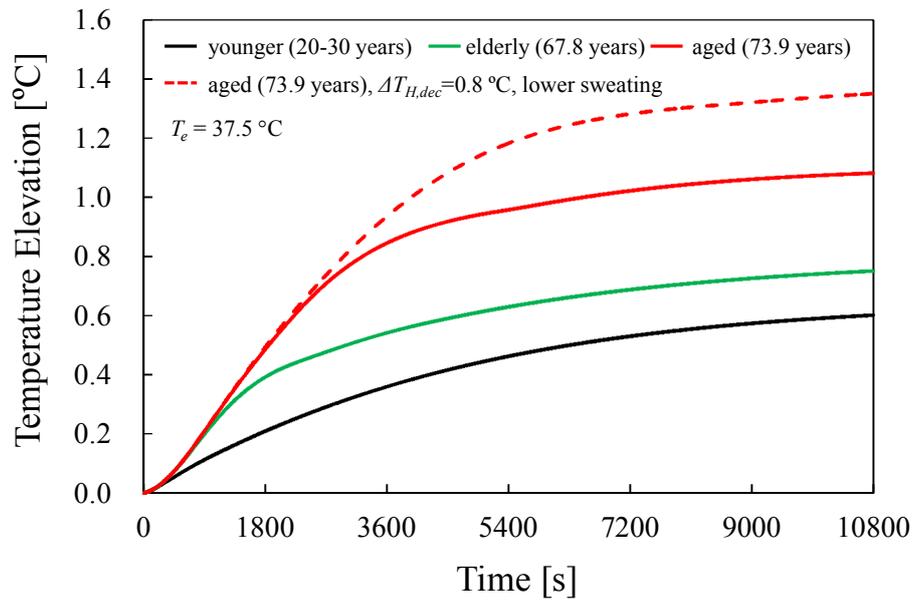
Fig. 2.

(a)

(b)

Fig. 3

Fig. 4.

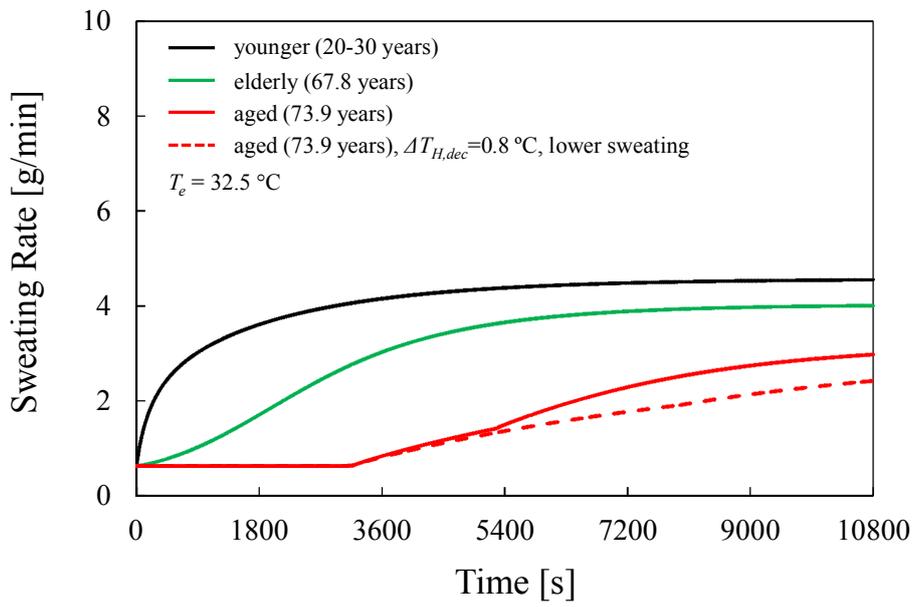

Fig. 5

Fig. 6. (a)

Fig. 6. (b)

Fig. 6. (c)

Fig. 7. (a)
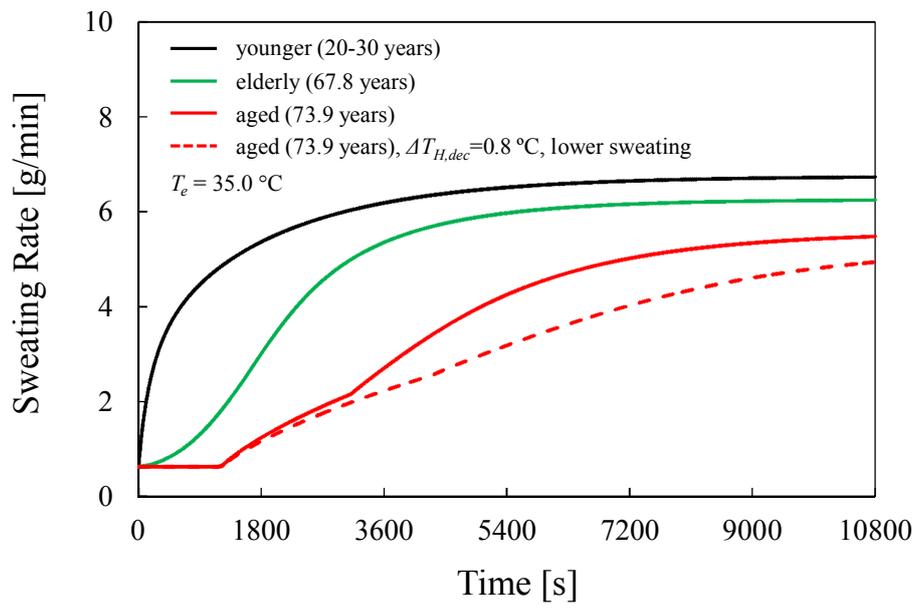
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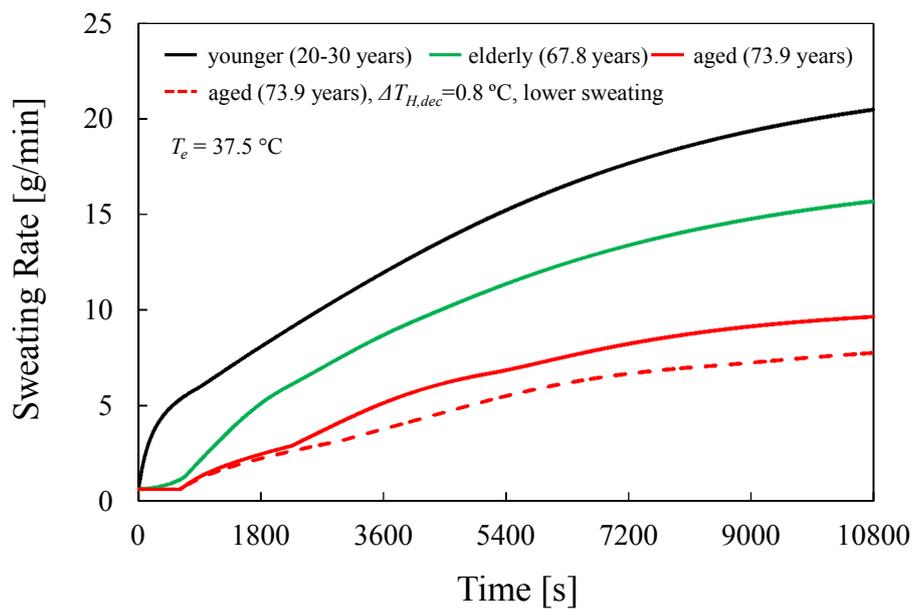
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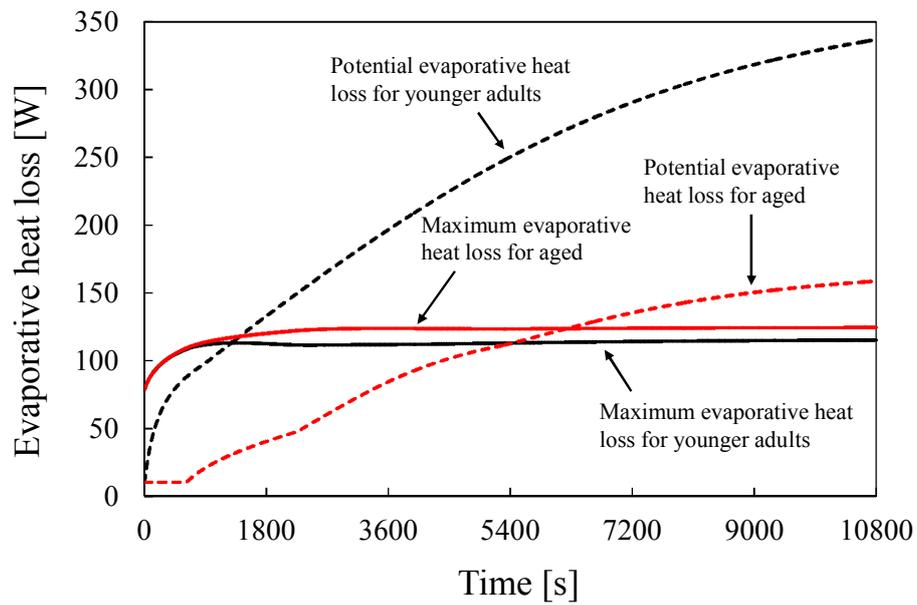
Fig. 8

Table 1.

	32.5 ºC	35.0 ºC	37.5 ºC
younger (20–30 years)	735	1090	2535
elderly (67.8 years)	558	904	1837
aged (73.9 years)	293	645	1106
aged (73.9 years), $\Delta T_{H,dec}$=0.8 ºC, lower sweating	246	537	885