NOTE

Computational estimation of decline in sweating in the elderly from measured body temperatures and sweating for passive heat exposure

Akimasa Hirata, Tomoki Nomura, and Ilkka Laakso

1: Department of Computer Science and Engineering, Nagoya Institute of Technology, Nagoya 466-8555, Japan

Corresponding Author: Akimasa Hirata

E-mail: ahirata@nitech.ac.jp

Abstract

Several studies reported the difference in heat tolerance between younger and older adults, which may be attributable to the decline in the sweating rate. One of the studies suggested a hypothesis that the dominant factor causing the decline in sweating was the decline in thermal sensitivity due to a weaker signal from the periphery to the regulatory centres. However, no quantitative investigation of the skin temperature threshold for activating the sweating has been conducted in previous studies. In this study, we developed a computational code to simulate the time evolution of the temperature variation and sweating in realistic human models under heat exposure, in part by comparing the computational results with measured data from younger and older adults. Based on our computational results, the difference in the threshold temperatures for activating the thermophysiological response, especially for sweating, is examined between older and younger adults. The threshold for activating the sweating in the older individuals was found to be about 1.5 °C higher than that in the younger individuals. However, our computation did not suggest that it was possible to evaluate the central alteration with aging by comparing the computation with the measurements for passive heat exposure, since the sweating rate is marginally affected by core temperature elevation at least for the scenarios considered here. The computational technique developed herein is useful for understanding the thermophysiological response of older individuals from measured data.

Keywords

themoregulation, elderly, heat stroke, computational modelling, decline in sweating rate

1. Introduction

Between 1968 and 2007, there were 6,770 fatalities in Japan due to heat stroke (MOE, 2009). In addition, there were heat waves with some fatalities in North America and Europe. Heat waves in these areas are projected to become more intense, more frequent, and longer lasting in the second half of the 21st century (Meehl and Tebaldi, 2004). Most victims are older individuals. One of the primary reasons for this was attributable to lower sweating rates in older adults than in younger ones during passive heat exposure (Anderson *et al.*, 1996; Crowe and Moore, 1974; Fennell and Moore, 1973; Inoue and Shibasaki, 1996; Inoue *et al.*, 1999). This difference should result in an elevated core temperature in older adults (Crowe and Moore, 1974; Fennell and Moore, 1973).

Several studies have reported that the difference in heat tolerance between younger and older adults is caused by a decreased thermal sensitivity (Hellon and Lind, 1956; Shoenfeld *et al.*, 1978). However, it was unclear whether this decreased sweating was caused by a signal from the hypothalamus or the skin (periphery). Note that the sweating can be expressed reasonably well as a function of the temperature elevations of the hypothalamus and skin (Stolwijk, 1971). Dufour and Candas (2007) hypothesized that the dominant factor causing the decline in sweating is the thermal sensitivity of the skin. Specifically, the decline in thermal sensitivity was due to a weaker signal from the periphery to the regulatory centres. However, no quantitative discussion of the threshold skin temperature elevation was given in that study, while age-dependent thermal sensation thresholds were presented for a thermode.

The computational approach has become common for estimating temperature and thermophysiological response to heat stress; e.g., (Ming and Wenxi, 2012; Psikuta *et al.*, 2008; Samaras *et al.*, 2007). In particular, we developed a computational code that simulates the time evolution of the temperature variation and sweating rate in the numeric human models of adults and children, incorporating a comparison of the computational results with measured data (Hirata *et al.*, 2008). In the present study, based on that computational code and a high-resolution realistic human model, the temperature variation and sweating rate in younger adults (20–30 years old) and older adults (>60 years old) were computed. The difference in the threshold temperatures for activating the thermophysiological response, especially for sweating, was estimated between the older and younger adults by comparing with the measured and computed sweating and body temperatures (Dufour and Candas, 2007).

2. Model and methods

2.1. Human body models

A previously developed Japanese male model was used in our modelling (Nagaoka *et al.*, 2004). The adult model was segmented into 51 anatomic regions like skin, muscle, bone, brain and heart, with a resolution of 2 mm. The height, weight, and surface area of the models are 1.73 m, 65 kg and 1.78 m^2, respectively, corresponding to surface-area-to-mass ratio of 0.0274 m^2 kg^{-1}. This human body model is used both for younger adults (20–30 years old) and older adults (>60 years old) since no anatomically based numeric model for the elderly has been developed. The body characteristics may affect the heat transfer or the temperature change in the human(van Marken Lichtenbelt *et al.*, 2007). We clarified that the dominant factor affecting the heat transfer between the body and the ambient environment was the body surface area-to-mass ratio for passive heat exposure (Hanatani *et al.*, 2011). The average surface area-to-mass ratios for fifteen younger and older subjects in the measurement by Dufour and Candas (2007) were 0.0256 and 0.0242 m^2 kg^{-1}, respectively. The differences of the surface area-to-mass ratio for the younger and older subjects from the Japanese male model are 6.5% and 11%, respectively.

2.2. Thermal Analysis

The temperature elevation in the numeric human models was calculated by solving the bioheat equation (Pennes, 1948), which is an equation modelling the thermodynamics of the human body. A generalized bioheat equation is given as:

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

where $T(\mathbf{r},t)$ and $T_B(\mathbf{r},t)$ denote the temperatures of tissue and blood, respectively, C is the specific heat of tissue, ρ is the mass density of tissue, K is the thermal conductivity of tissue, M is the basal metabolism per unit volume and B is a term associated with blood perfusion. The values used for thermal parameters are described in Hirata *et al.* (2007).The boundary condition between air and tissue for Eq. (1) is expressed as:

$$-K(\mathbf{r})\frac{\partial T(\mathbf{r},t)}{\partial n} = H(\boldsymbol{r})\cdot(T_s(\mathbf{r},t) - T_e(t)) + 40.6\times(SW(\boldsymbol{r},T_s(\mathbf{r},t)) + PI)/S \qquad (2)$$

where H, T_s and T_e denote, respectively, the heat transfer coefficient, the body surface temperature and the air temperature. The heat transfer coefficient includes the convective and radiative heat losses. S is the total surface area of the human body, SW [g min^{-1}] is the sweating rate, and PI, the insensible water loss, is 0.63 g min^{-1} for adults. The value of 40.6 is a conversion coefficient [J min g^{-1} s^{-1}].

The key feature of our computational modelling is that the body core temperature variation can be tracked in addition to the shallow regions of the body, unlike in conventional computational schemes. The blood temperature varies according to the following equation, in order to satisfy the first law of thermodynamics (Bernardi *et al.*, 2003; Hirata and Fujiwara, 2009):

$$T_B(t) = T_{B0} + \int_t \frac{Q_{BTN}(t)}{C_B \rho_B V_B} \mathrm{d}t \qquad (3)$$

where Q_{BTN} is the net rate of heat acquisition of blood from the body tissues, 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. V_B is chosen to be 5,000 ml (ICRP 1975). The thermal constants of the human tissues and the heat transfer coefficients used in the present study are identical to those used in our previous study (Hirata *et al.*, 2008). The computed temperatures in the skin and body core are validated (Hirata *et al.*, 2008) by comparing with measured temperatures in the skin and body core when changing the ambient temperature (Tsuzuki-Hayakawa *et al.*, 1995).

2. 3. Thermoregulatory Response in Adult and Child

2.3.1. Modelling of Sweating Rate

The sweating for the adult is modelled based on the formulas in Fiala *et al* (2001). The sweating rate SW [g min^{-1}] is assumed to depend on the temperature elevation in the skin and hypothalamus according to the equation:

$$SW(\mathbf{r},t) = \gamma(\mathbf{r})\{W_S(\mathbf{r},t)(T_S(t) - T_{So}) + W_H(\mathbf{r},t)(T_H(t) - T_{Ho})\} \times 2^{(T(\mathbf{r})-T_0(\mathbf{r}))/10} \qquad (4)$$

$$W_s(\mathbf{r},t) = \alpha_{11}\tanh(\beta_{11}T_s(\mathbf{r},t) - T_{so}(\mathbf{r})) - \beta_{10}) + \alpha_{10} \qquad (5)$$

$$W_H(\mathbf{r},t) = \alpha_{21}\tanh(\beta_{21}T_s(\mathbf{r},t) - T_{so}(\mathbf{r})) - \beta_{20}) + \alpha_{20} \qquad (6)$$

where T_s and T_H are the temperatures of the skin averaged over the body and hypothalamus, respectively. $T_{s,0}$ and $T_{H,0}$ represent set temperatures or upper critical temperature of thermoneutral condition (Adair and Black, 2003). The dependency of the sweating rate on the body part was considered by introducing the multiplier $\gamma(\mathbf{r})$ based on Table 2 in Fiala *et al.* (2001). The coefficients of α and β are determined for the average sweating rate based on measurements (Fiala *et al.*, 2001). In Eqs. (5) and (6), these coefficients are α_{10}=1.20, α_{11}=0.80, β_{10}=0.19, β_{11}=0.59, α_{20}=6.30, α_{21}=5.70, β_{20}=1.03 and β_{21}=1.98.

The maximum sweating rate in most body parts except for the legs was confirmed to be almost identical between younger and older adults (Dufour and Candas, 2007; Inoue and Shibasaki, 1996; Inoue *et al.*, 1999; Tochihara *et al.*, 2011). Thus, we changed the original equation (4) as follows: *i*) the decline in the sweating in the leg is considered by adding a multiplier $\chi(\mathbf{r})$, and *ii*) the threshold for inducing the sweating response in the older adults is increased by introducing $\Delta T_{S,dec}$ and $\Delta T_{H,dec}$ which represent the decline in thermal sensitivity due to aging. The resulting equation for sweating in older adults is thus

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

where

$$\Delta T_S = \begin{cases} 0 & T_s < T_{s,0} + \Delta T_{s,dec} \\ T_S - (T_{s,0} + \Delta T_{s,dec}), & T_s > T_{s,0} + \Delta T_{s,dec} \end{cases} \qquad (8)$$

$$\Delta T_H = \begin{cases} 0 & T_H < T_{H,0} + \Delta T_{H,dec} \\ T_H - (T_{H,0} + \Delta T_{H,dec}), & T_H > T_{H,0} + \Delta T_{H,dec} \end{cases} \quad (9)$$

2.3.2. Blood Perfusion Rate

For a temperature elevation above a certain level, the blood perfusion rate is increased in order to carry away the excess heat produced(Stolwijk, 1971). The variation of blood perfusion rate in the skin through vasodilatation is expressed in terms of ΔT_H and ΔT_S:

$$B(\boldsymbol{r},t) = (B_0(\boldsymbol{r}) + F_{HB}\Delta T_H(t) + F_{SB}\Delta T_S(t)) \cdot 2^{(T(\boldsymbol{r},t)-T_0(\boldsymbol{r}))/6} \quad (10)$$

where F_{HB}, and F_{SB} are the weighting coefficients of signal from the hypothalamus and skin, respectively. The coefficients of F_{HB} and F_{SB} in Eq. (10) were 17,500 W/m^3/^{o}C^2 and 110 W/m^3/^{o}C^2 (Bernardi *et al* 2003). Blood perfusion in all tissues except the skin was assumed as constant, as is similar to Stolwijk (1971).

3. Computational results

Our computational results will be compared with those measured by Dufour and Candas (2007). 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 minutes, and then settled to a temperature of 40 °C for 86 minutes. The computed sweating rates at the calf and the chest were compared with measurements. The variation of the blood perfusion rate in the skin is not discussed here as Dufour and Candas (2007) did not measure that parameter.

3.1. Effect of threshold average temperature elevation in the skin inducing the sweating

The increase in the threshold for sweating associated with the skin temperature elevation $\Delta T_{S,\,dec}$ was varied from 0.5 to 1.5 °C as the skin temperature elevation in the younger adults was 2.0 °C or so for the exposure scenario given above. As shown in figure 1 (a), the onset time of the sweating rate for the older individuals was retarded by the modelled decline in sensation of the temperature elevation in the skin. The computed and measured sweating rates in the leg were in good agreement with each other when the value of χ associated with sweating rate in the leg of older men was parametrically determined as 0.6. From figure 1 (b), no clear difference was observed in the measured sweating rates of the chest between younger and older adults, as already suggested, which was in fair agreement with our computational results.

3.2. Effect of Threshold for Temperature Elevation in the Hypothalamus Inducing Sweating

The increase in the threshold for sweating associated with the core temperature elevation $\Delta T_{H,}$

$_{dec}$ was varied from 0 to 0.3 °C as the core temperature elevation in the younger adults was at most 0.4 °C for the exposure scenario. As shown in figure 2, the sweating rate was marginally affected by different values of $\Delta T_{H,\,dec}$. The difference in the sweating rates caused by different thresholds associated with the core temperature was 3–5%, which was much smaller than the uncertainty of sweating rate of the individual differences of ±30%, which is estimated from (Fiala *et al.*, 2001).

3.3. Comparison of Temperature Elevation in Younger and Older Men

Figure 3 shows the computed temperature elevation in (a) the body core and (b) the skin. For comparison, measured values are also plotted. For the parameters of older men, $\Delta T_{S,\,dec}$=1.5 °C and $\Delta T_{H,\,dec}$ =0 °C are used based on the findings above. As shown in figure 3, the average skin and core temperatures were in fair agreement with the measured temperatures. Some difference was observed between the measured and computed skin temperatures, especially for times less than 1,800 sec (figure 3(b)).

4. Discussion and summary

Defour and Candas (2007) investigated thermal detection thresholds for different parts of the skin in response to a warm stimulus (thermode). However, as can be seen in Eq. (4), the sweating rate is governed by the average skin and core temperature elevations, not by the local skin temperature elevation. They also suggested a hypothesis that a weaker signal from the periphery to the regulatory centres causes the decline of the sweating rate. However, smaller coefficients in Eq. (4) may not simulate the retarded commencement of the increase of the sweating rate. Thus, it was essential to quantify the difference of the threshold temperature elevation for activating sweating between the younger and older adults.

From our computational results, the threshold temperature elevation in the hypothalamus (blood) marginally affected the sweating rate (figure 2), whereas obvious difference was caused by the threshold temperature elevation of the skin averaged over the body (figure 1). This finding is consistent with the observation in Defour and Candas (2007) and Inoue *et al* (1999) that the dominant factor affecting the sweating in the older individuals is periphery rather than regulatory central. Our computational results suggested that the difference of the average temperature elevation threshold for the skin for activating sweating is the dominant factor causing the difference of the sweating and temperature variation. Specifically, the threshold for activating the sweating in the older individuals was about 1.5 °C higher than that in the younger individuals (figure 1(a)). However, from figure 2, the central alteration with aging was not evaluated from the measurement of sweating and body temperature since the sweating rate is marginally affected by core temperature, at least for the exposure scenario considered in the previous study (Dufour and Candas, 2007).

Some difference was observed in the measured and computed temperatures and sweating rates. One of the possible reasons for the difference in core temperature elevation is our assumption that the blood temperature is spatially constant and varies instantaneously (See eq. (3)) based on the fact that the blood circulates throughout the body in 1 min. However, that assumption may not be fully effective for periphery. As shown in Hanatani *et al.* (2011), the surface-area-to-mass ratio affects core temperature almost linearly for passive heat exposure. Thus, the computational temperature elevations roughly overestimate the temperature elevation in the younger and older adults by 6.5% and 11%, respectively, as suggested in Sec. 2.1.

Furthermore, the ambient temperature of 28 °C was considered as the thermoneutral condition in Defour and Candas (2007), while this was not true for all the subjects. This may affect particularly the computation of the core temperature (Hirata *et al.*, 2008), as can be seen from the difference for elapsed times less than 1800 s. The difference between the computed and measured core temperature may affect the computed temperature elevation in the skin. Finally, the thermal thresholds for different body parts are assumed to be the same due to the limited experimental data available.

Although not shown here to avoid repetition, from the data for the men 40–45 years old (Dufour and Candas, 2007), $\Delta T_{S,\,decl}$ was almost identical to that for men aged 60 years and older, when the sweating rates in the leg and back were reduced by 25%. Note that the decline of the thermal sensitivity in men younger than 60 years has been reported in Guergova and Dufour (2011).

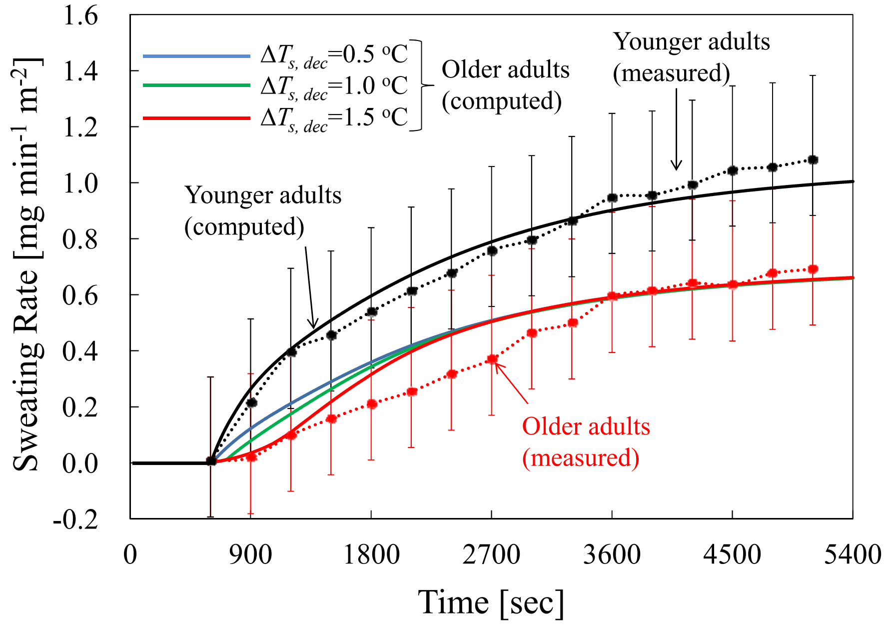
The computational scheme presented here could be used to estimate the decline in the thermophysiological response in the elderly from measurements of body temperature and sweating rate. Measuring sweating rate and temperature variation in different body parts and the development of the numeric human model for the elderly are needed to further clarify the age dependence of $\Delta T_{S,\,dec}$ and the decline in the sweating rate in the leg and back. Future work may also include the uncertainty analysis of temperature elevation for passive heat exposure (e.g.,Laakso and Hirata (2011)).

FIGURE AND TABLE CAPTIONS

Figure 1. Sweating rates in the (a) leg and (b) chest for passive heat exposure for different thresholds of sweating associated with the skin temperature elevation $\Delta T_{S,\ dec}$. The error bars represent the standard deviation of the measured data in Dufour and Candas (2007).

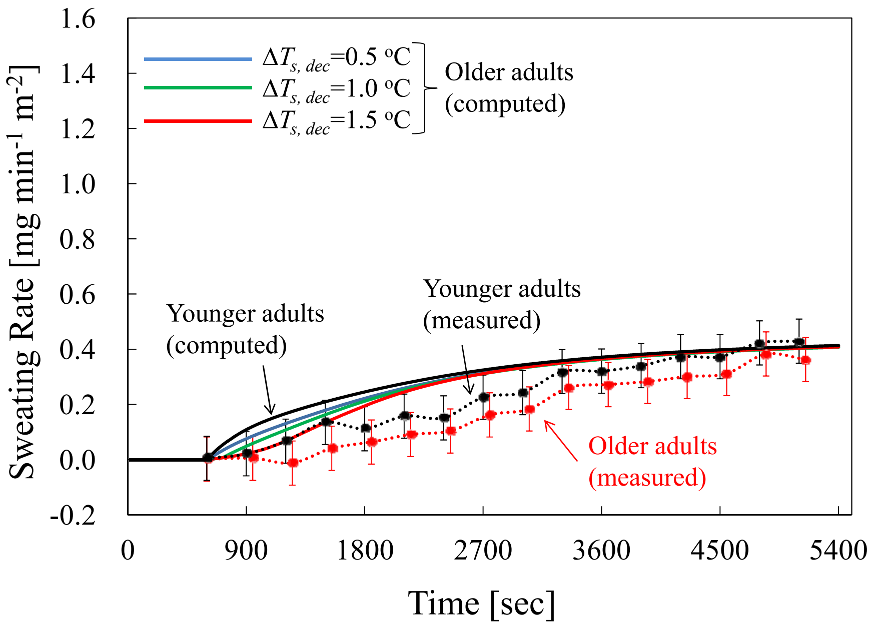
Figure 2. Sweating rate in the (a) leg and (b) chest of older individuals for passive heat exposure for different thresholds of sweating associated with core temperature elevation $\Delta T_{H,\ dec}$.

Figure 3. Temperature variation of (a) body core and (b) the skin averaged over the body for passive heat exposure. $\Delta T_{S,\ dec}$= 1.5 °C and $\Delta T_{H,\ dec}$= 0 °C were used for simulating the older individuals. The error bars represent the standard deviation of the measured data in Dufour and Candas (2007).



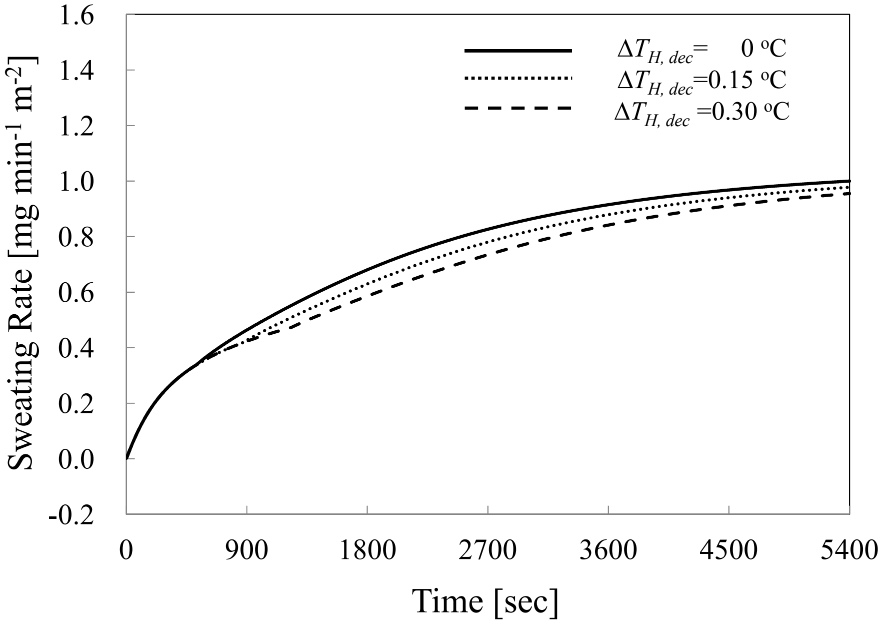
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
Sweating Rate [mg min-1 m-2]
0
900
1800
2700
3600
4500
5400
Time [sec]
ΔTs, dec=0.5 ºC
ΔTs, dec=1.0 ºC
ΔTs, dec=1.5 ºC
Older adults (computed)
Younger adults (measured)
Younger adults (computed)
Older adults (measured)

Fig. 1(a)



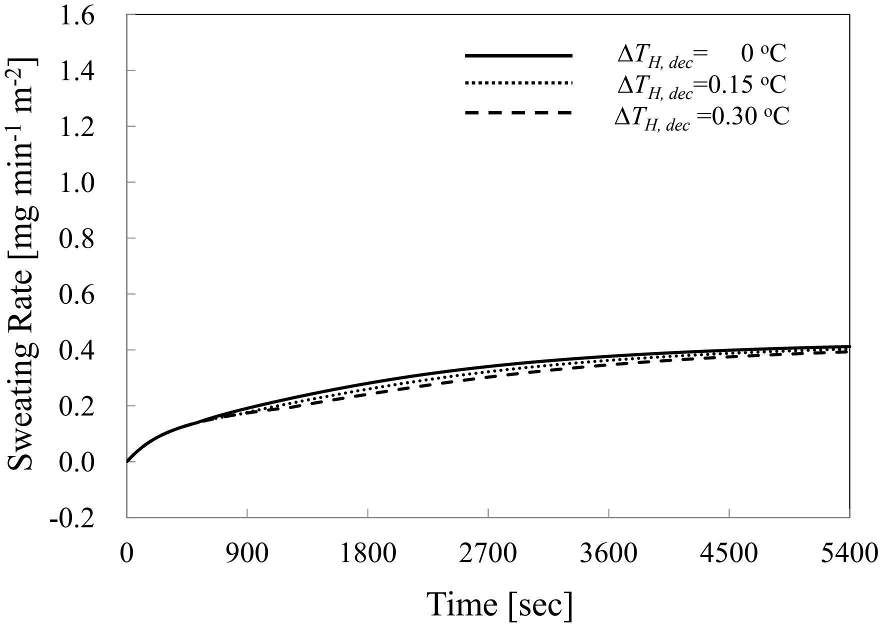
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
Sweating Rate [mg min-1 m-2]
0
900
1800
2700
3600
4500
5400
Time [sec]
ΔTs, dec=0.5 ºC
ΔTs, dec=1.0 ºC
ΔTs, dec=1.5 ºC
Older adults (computed)
Younger adults (computed)
Younger adults (measured)
Older adults (measured)

Fig. 1(b)



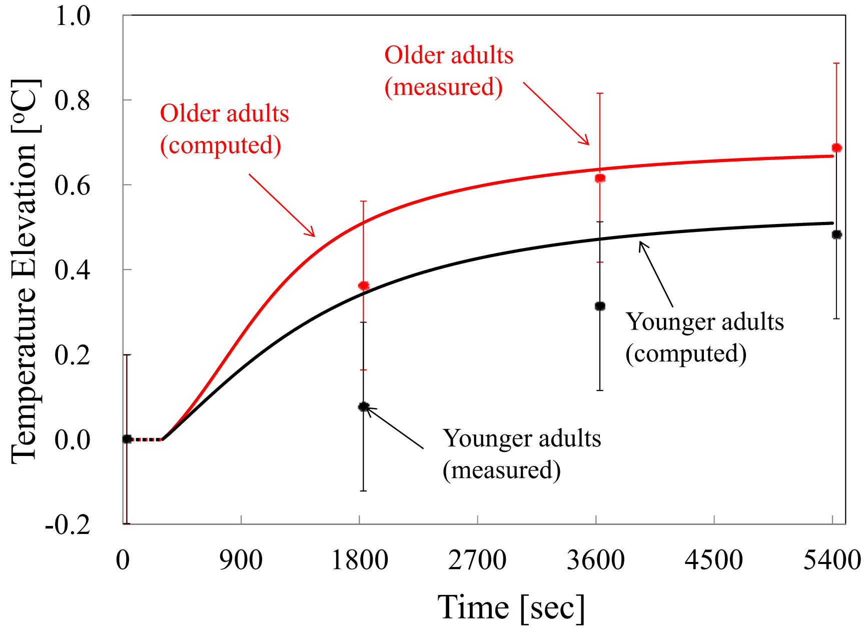
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
Sweating Rate [mg min-1 m-2]
0
900
1800
2700
3600
4500
5400
Time [sec]
ΔT_H, dec= 0 oC
ΔT_H, dec=0.15 oC
ΔT_H, dec =0.30 oC

Fig. 2(a)



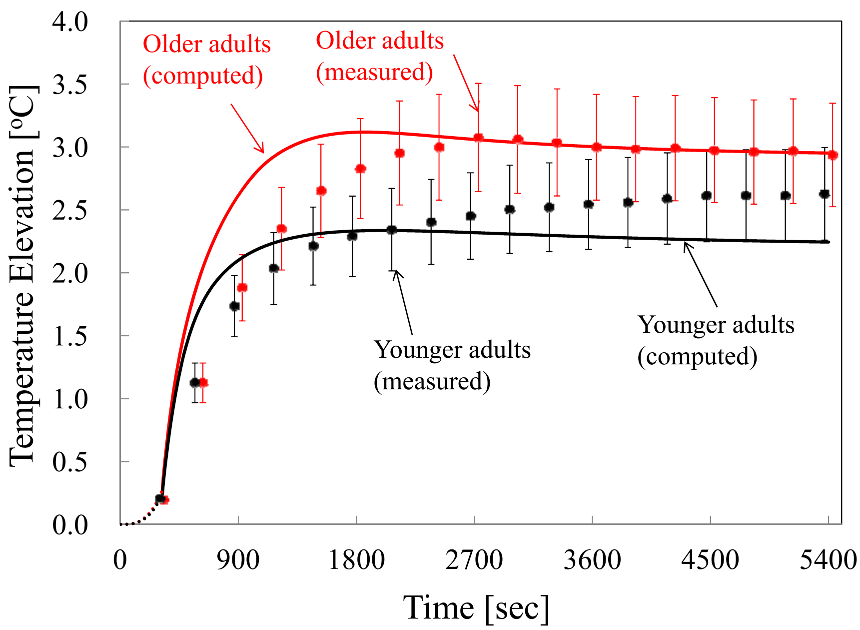
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
Sweating Rate [mg min-1 m-2]
0
900
1800
2700
3600
4500
5400
Time [sec]
ΔT_H, dec= 0 oC
ΔT_H, dec=0.15 oC
ΔT_H, dec =0.30 oC

Fig. 2(b)



1.0
0.8
0.6
0.4
0.2
0.0
-0.2
Temperature Elevation [°C]
0
900
1800
2700
3600
4500
5400
Time [sec]
Older adults
(computed)
Older adults
(measured)
Younger adults
(computed)
Younger adults
(measured)

Fig. 3(a)



4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Temperature Elevation [°C]
0
900
1800
2700
3600
4500
5400
Time [sec]
Older adults
(computed)
Older adults
(measured)
Younger adults
(measured)
Younger adults
(computed)

Fig. 3(b)

References

Adair E R and Black D R 2003 Thermoregulatory responses to RF energy absorption *Bioelectromagnetics* **24** S17-S38

Anderson G, Meneilly G and Mekjavic I 1996 Passive temperature lability in the elderly *European Journal of Applied Physiology and Occupational Physiology* **73** 278-86

Bernardi P, Cavagnaro M, Pisa S and Piuzzi E 2003 Specific absorption rate and temperature elevation in a subject exposed in the far-field of radio-frequency sources operating in the 10-900-MHz range *IEEE Trans. Biomed. Eng.* **50** 295-304

Crowe J P and Moore R E 1974 Proceedings: physiological and behavioural responses of aged men to passive heating *J. Physiol.* **236** 43P-5P

Dufour A and Candas V 2007 Ageing and thermal responses during passive heat exposure: sweating and sensory aspects *European Journal of Applied Physiology* **100** 19-26

Fennell W H and Moore R E 1973 Responses of aged men to passive heating *J. Physiol.* **231**

Fiala D, Lomas K J and Stohrer M 2001 Computer prediction of human thermoregulatory and temperature responses to a wide range of environmental conditions *International Journal of Biometeorology* **45** 143-59

Guergova S and Dufour A 2011 Thermal sensitivity in the elderly: A review *Ageing Research Reviews* **10** 80-92

Hanatani R, Laakso I, Hirata A, Kojima M and Sasaki H 2011 Dominant factors affecting temperature elevation in adult and child models exposed to solar radiation in hot environment *Progress In Electromagnetics Research B* **34** 47-61

Hellon R F and Lind A R 1956 Observations on the activity of sweat glands with special reference to the influence of ageing *J. Physiol.* **133** 132-44

Hirata A, Asano T and Fujiwara O 2007 FDTD analysis of human body-core temperature elevation due to RF far-field energy prescribed in the ICNIRP guidelines *Phys. Med. Biol.* **52** 5013-23

Hirata A, Asano T and Fujiwara O 2008 FDTD analysis of body-core temperature elevation in children and adults for whole-body exposure *Phys. Med. Biol.* **53** 5223-38

Hirata A and Fujiwara O 2009 Modeling time variation of blood temperature in a bioheat equation and its application to temperature analysis due to RF exposure *Phys. Med. Biol.* **54** N189-N96

Inoue Y and Shibasaki M 1996 Regional differences in age-related decrements of the cutaneous vascular and sweating responses to passive heating *European Journal of Applied Physiology and Occupational Physiology* **74** 78-84

Inoue Y, Shibasaki M, Ueda H and Ishizashi H 1999 Mechanisms underlying the age-related decrement in the human sweating response *European Journal of Applied Physiology and Occupational Physiology* **79** 121-6

Laakso I and Hirata A 2011 Dominant factors affecting temperature rise in simulations of human thermoregulation during RF exposure *Phys. Med. Biol.* **56** 7449

Meehl G A and Tebaldi C 2004 More Intense, More Frequent, and Longer Lasting Heat Waves in the 21st Century *Science* **305** 994-7

Ming H and Wenxi C 2012 Theoretical study on the inverse modeling of deep body temperature measurement *Physiol. Meas.* **33** 429

MOE 2009 Heat Stoke, manual of environmental health *MOE. Environmental Health Department. Environmental Safety Division* http://www.env.go.jp/chemi/heat_stroke/manual.html

Nagaoka T, Watanabe S, Sakurai K, Kunieda E, Taki M and Yamanaka Y 2004 Development of realistic high-resolution whole-body voxel models of Japanese adult males and females of average height and weight, and application of models to radio-frequency electromagnetic-field dosimetry *Phys. Med. Biol.* **49** 1-15

Pennes H H 1948 Analysis of tissue and arterial blood temperatures in the resting human forearm *J. Appl. Physiol.* **1** 93-122

Psikuta A, Richards M and Fiala D 2008 Single-sector thermophysiological human simulator *Physiological Meas.* **29** 181

Samaras T, Kalampaliki E and Sahalos J N 2007 Influence of Thermophysiological Parameters on the Calculations of Temperature Rise in the Head of Mobile Phone Users *Electromagnetic Compatibility, IEEE Transactions on* **49** 936-9

Shoenfeld Y, Udassin R, Shapiro Y, Ohri A and Sohar E 1978 Age and sex difference in response to short exposure to extreme dry heat *J. Appl. Physiol.* **44** 1-4

Stolwijk J A J 1971 Mathematical model of physiological temperature regulation in man *NASA Contractor Reports*

Tochihara Y, Kumamoto T, Lee J-Y and Hashiguchi N 2011 Age-related differences in cutaneous warm sensation thresholds of human males in thermoneutral and cool environments *Journal of Thermal Biology* **36** 105-11

Tsuzuki-Hayakawa K, Tochihara Y and Ohnaka T 1995 Thermoregulation during heat exposure of young children compared to their mothers *European Journal of Applied Physiology and Occupational Physiology* **72** 12-7

van Marken Lichtenbelt W, Frijns A, van Ooijen M, Fiala D, Kester A and van Steenhoven A 2007 Validation of an individualised model of human thermoregulation for predicting responses to cold air *Int. J. of Biometeorology* **51** 169-79