



Bioheat modeling of elderly and young for prediction of physiological and thermal responses in heat-stressful conditions

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ABSTRACT

Exposure to hot and humid conditions results in physiological changes in metabolism, cardiac output and thermoregulation of the young adult and these changes deviate with elderly due to aging. The elderly population is more vulnerable than the healthy and young population due to age-weakened physiology and thermoregulatory functions. There are, however, limited bioheat models addressing such changes due to hot exposure in the young and the elderly. This paper develops robust bioheat models for young and elderly while incorporating the physiological changes under exposure to heat-stressful conditions for both age groups the age-related changes in physiology and thermoregulation to an elderly human. However, due to a large variability of thermoregulation among the elderly population, a sensitivity analysis revealed that the average elderly is characterized by metabolic rate and cardiac output, which are lower than those of the young by 21% and 14.4%, respectively. Moreover, the thresholds of the onset of vasodilation and sweating are delayed from those of young adults by 0.5 °C and 0.21 °C, respectively.

The elderly and young bioheat models were validated with number of independent published experimental studies under hot exposures in steady and transient conditions. Model predictions of core and mean skin temperatures showed good agreement with published experimental data with a discrepancy of 0.1 °C and 0.5 °C, respectively.

1. Introduction

The past decades have witnessed increasing heat waves along with significant temperature variability in various regions of the globe which has resulted in substantial effect on mortality, especially among the elderly population (Cheng et al., 2018, 2019). It is anticipated that the projected climate change and global warming in the twenty-first century would intensify the exposure to deadly ambient conditions (temperature and relative humidity, *RH*) (Mora et al., 2017). Mora et al. (2017) found that about 30% of the world's population is currently exposed, for at least 20 days annually, to climatic conditions that exceed global thresholds of daily mean temperature and *RH* beyond which mortality appears. Moreover, Mora et al. (2017) projected that by 2100, the percentage of people exposed to deadly thresholds would increase by at least 48% and it was also expected that three out of four people could be subjected to this same threat. Human subjects exposed to hot conditions would be under a health risk if they were unable to adapt to release the

accumulated heat, either by sweating or increasing blood flow to skin surface and extremities. Under such hot conditions, the elderly population (>60 years old) is more vulnerable than the healthy and young population due to age-related changes in physiology and thermoregulatory functions (Van Hoof et al., 2017; Roelofsen, 2017; Rida et al., 2014; Ma et al., 2017; Kenny et al., 2019; Kjellstrom et al., 2009). Although the elderly population has been increasing in both developed and developing countries (Li et al., 2016), there is a limited number of experimental studies on the thermal response of elderly people under long exposure to hot conditions. Klenk et al. (2010) examined the relationship between maximum outdoor temperature and mortality rates in residents of 95,808 elderly nursing homes in southwest Germany between 2001 and 2005. They concluded that mortality risk increased by 26% and 62% at days of maximum outdoor temperature of 32.0–33.9 °C and 34 °C and more, respectively. Furthermore, there is a limited number of modeling studies to predict the elderly thermal response, particularly under high heat stress conditions (Novieto and Zhang, 2010; Rida et al., 2014; Hirata et al., 2015; Ma et al., 2017; and Coccarelli

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Nomenclature

A_{artery}	surface area of the artery (m^2)	M_{sk}	metabolic rate in the skin (W)
$A_{sk,exp}$	surface area of the exposed skin (m^2)	MET	metabolic equivalent of task
A_{vein}	surface area of the vein (m^2)	MET_{basal}	basal metabolic rate (Met)
$A_{vein,s}$	cross-sectional area of the superficial vein (m^2)	MRT	mean radiant temperature ($^{\circ}C$)
AVA	arterio-venous anastomoses	P_{amb}	ambient vapor pressure (kPa)
C_{bl}	specific heat of the blood (J/kg·K)	P_{fat}	percentage increase of abdomen fat thickness compared to young (%)
$C_{bl,v,s}$	superficial vein blood capacitance (J/kg·K)	P_{sk}	skin vapor pressure (kPa)
C_{cr}	thermal capacitance of the segment core (J/K)	Q_{res}	heat dissipated by respiration (W)
C_{sk}	thermal capacitance of the segment skin node (J/K)	Q_{cr-sk}	heat exchanged between the skin and the core (W)
CO	cardiac output (cm^3/hr)	$R_{d,air}$	dry thermal resistance of the air layer near the skin ($m^2 \cdot K/W$)
CO_{basal}	basal cardiac output (cm^3/hr)	$R_{d,clo}$	dry thermal resistance of the clothing layer ($m^2 \cdot K/W$)
CO_{con}	constricted cardiac output (cm^3/hr)	$R_{e,air}$	evaporative resistance of the air layer near the skin ($m^2 \cdot kPa/W$)
$CO_{con,min}$	constricted minimum cardiac output (cm^3/hr)	$R_{e,clo}$	evaporative resistance of the clothing layer ($m^2 \cdot kPa/W$)
CO_{dil}	dilated cardiac output (cm^3/hr)	RH	relative humidity (%)
$CO_{dil,max}$	dilated maximum cardiac output (cm^3/hr)	t	time (s)
h_{artery}	convective heat transfer coefficient of blood in the artery ($W/m^2 \cdot K$)	T_{amb}	ambient air temperature ($^{\circ}C$)
h_c	external convective heat transfer coefficient between skin and surrounding ($W/m^2 \cdot K$)	$T_{bl,a}$	artery blood temperature ($^{\circ}C$)
h_e	evaporative heat transfer coefficient between skin and surrounding ($W/m^2 \cdot kPa$)	$T_{bl,a,adjacent}$	temperature of blood in adjacent artery of previous body segment ($^{\circ}C$)
h_r	radiative heat transfer coefficient ($W/m^2 \cdot K$)	$T_{bl,v}$	vein blood temperature ($^{\circ}C$)
h_{vein}	convective heat transfer coefficient of blood in the core vein ($W/m^2 \cdot K$)	$T_{bl,v,adjacent}$	temperature of blood in adjacent core vein of previous body segment ($^{\circ}C$)
$h_{vein,s}$	convective heat transfer coefficient of blood in the superficial vein ($W/m^2 \cdot K$)	$T_{bl,v,s}$	superficial vein blood temperature ($^{\circ}C$)
i	index indicating the number of the body segment	T_{clo}	clothing temperature ($^{\circ}C$)
\dot{m}_a	blood flow rate through the artery (kg/s)	T_{cr}	core temperature ($^{\circ}C$)
\dot{m}_{AVA}	blood flow due to AVA (kg/s)	$T_{cr,basal}$	basal core temperature ($^{\circ}C$)
$\dot{m}_{perf,cr}$	total perfusion rate of blood entering the core (kg/s)	$T_{cr,max}$	maximum core temperature ($^{\circ}C$)
$\dot{m}_{perf,sk}$	skin perfusion blood flow rate without AVA (kg/s)	$T_{cr,sweat}$	threshold core temperature for onset of sweating ($^{\circ}C$)
$\dot{m}_{perf,sk,basal}$	basal skin perfusion blood flow rate (kg/s)	T_{sk}	mean skin temperature of body segment ($^{\circ}C$)
$\dot{m}_{perf,sk,con}$	constricted skin perfusion blood flow rate (kg/s)	V_a	air velocity (m/s)
$\dot{m}_{perf,sk,dil}$	dilated skin perfusion blood flow rate (kg/s)	w	skin wettedness
$\dot{m}_{perf,sk,max}$	maximum skin perfusion blood flow rate (kg/s)	W	mechanical power, muscular activity (W)
$\dot{m}_{perf,sk,min}$	minimum skin perfusion blood flow rate (kg/s)		
\dot{m}_v	blood flow rate through the vein (kg/s)		
M_{cr}	basal metabolic heat generated in each segment (W)	Greek symbols	
M_{shiv}	segmental thermoregulatory metabolic rate generated by shivering (W)	α	coefficient equal to unity for the upper chest and zero for other segments
		ΔT	temperature change from elderly reference case in $^{\circ}C$
		η_{evap}	sweating evaporation efficiency

et al., 2018). Developing such bioheat models under high heat stress levels is practically important to set safe exposure thresholds to hot and humid conditions. In order to accurately model the elderly thermal state under exposure to high heat-stress conditions, it is important to first identify the changes in physiology and thermoregulation of young in hot exposure and how these changes deviate with elderly due to aging.

With aging, elderly people undergo reductions in their basal metabolic rate and cardiac output (CO) compared to young adults. However, a large variability in these changes has been reported among the elderly population in several studies (Novieto and Zhang, 2010; Tsuzuki and Ohfuku, 2002; and Ma et al., 2017). The variability in the reduction in basal metabolism compared to young ranged from a minimum of 5.3% to a maximum of 30%. Moreover, the distribution of body fat in the elderly was found to differ from the young, with the elderly having higher fat thickness in the abdomen. This increase in fat thickness was found to be positively correlated with the resting metabolic rate (Herbert and Neuh, 2001). According to Novieto and Zhang (2010), Rida et al. (2014) and Ma et al. (2017), the reduction in CO varied between a minimum of 3.4% to a maximum of 40% compared to young adults depending on the physical fitness of the elderly subjects. Moreover,

Hirata et al. (2012) and Sagawa et al. (1988) reported that the thresholds for the onset of vasodilation and sweating varied among elderly at values ranging from 0.05 $^{\circ}C$ to 1.5 $^{\circ}C$. The observed variability in physiological changes among the elderly brings up the need to conduct a sensitivity analysis to check the influential parameters and establish reference values for a representative elderly age group.

Whether young or old, human exposure to high temperatures and humid conditions results in physiological changes in metabolism, CO and thermoregulation, which negatively affect the elderly health in a more noticeable way than the young (Sawka and Coyle, 1999; Chevront et al., 2004; Kosaka et al., 2004; Parsons, 2014). For young adults, several studies observed that an increase in body core temperature resulted in an increase in the metabolic rate (Kosaka et al., 2004; Parsons, 2014). The same observation was found at resting metabolic rates with increasing temperature, where this elevation in metabolism was attributed to the higher oxygen consumption with the increase in the kinetic energy of the cells and the cellular chemical reactions (Clarke and Fraser, 2004). The increase in metabolic rate due to elevated core temperature was also reported to result in an increase in the heart rate due to heat accumulation (Dubé et al., 2019). Moreover, the human

body was observed to depend on sweat evaporation to cool and maintain its core temperature around 37 °C when the ambient conditions became hotter and more humid or when human activity level increased. It is well known that humid conditions restrict sweat evaporation, which would result in accumulation of the sweat secreted by the human body on the skin, hence increasing the skin wettedness (w ; defined as the ratio of evaporative heat flux to maximum evaporative heat flux) and causing sweat to start dripping rather than evaporating. This was reported to result in a decrease in the sweat evaporation efficiency (Candas et al., 1979). The decrease in sweat efficiency has higher importance at hot and humid conditions where sweat secretion is high but sweat evaporation is limited. Furthermore, studies observed that as the human body loses water, the rates of sweating and the skin blood flow decreased (Sawka and Coyle, 1999; Chevront et al., 2004). In addition, as the body loses water, the threshold for the onsets of sweating and skin blood flow were reported to increase (Sawka and Coyle, 1999; Chevront et al., 2004). This would result in accumulation of the heat stored in the body and thus would increase the core temperature (Sawka and Coyle, 1999). These impairments on the human body occur for both young adults and elders and thus it is of great importance to incorporate these changes in bioheat models that can predict thermal responses of subjects under such hot and humid conditions.

Previously developed bioheat models for the elderly accounted for the change in metabolism, CO and body weight due to age (Novieto and Zhang (2010), Rida et al. (2014), Hirata et al. (2015), Ma et al. (2017) and Coccarelli et al., 2018). In addition, Hirata et al. (2015) developed a bioheat model that took into consideration the maximum possible evaporative body heat loss when subjected to hot conditions. Ma et al. (2017) developed a human thermoregulation model for the Chinese elderly based on experimental data on Chinese subjects. Rida et al. (2014) developed an elderly segmental bioheat model based on modifying the young bioheat model of Karaki et al. (2013) to account for physiological changes associated with age as well as accurate prediction of blood flow in the extremities including the fingers. I Vanggaard et al. (2011) reported that the arterio-venous anastomoses (AVA) play a major role in the blood circulation in the peripheral body parts. When subjected to hot conditions, the presence of AVA function is very important in causing heat induced vasoconstriction so that the warm blood cannot reach the human core easily as reported by Daanen (1991) modeled by Karaki et al. (2013). Published elderly and young bioheat models were mainly validated against cold to moderate conditions and did not take into consideration the changes in physiology and thermoregulation upon exposure to hot conditions. For accurately predicting the elderly thermal responses in heat stressed conditions, the bioheat model needs to account for the changes in physiology and thermoregulation due both age as well as exposure to hot conditions. In hot conditions, the limbs play an important role in removing the body heat, so these segments need to be well represented. Hence, the elderly bioheat model should accurately predict the CO , metabolism as well as heart rate through modeling the arterial network for blood flow circulation and skin blood flow of the different body segments. The body fat as well as the sweat glands are not uniformly distributed in the human body, which highlights the need for a segmental bioheat model to accurately predict sweat secretion and evaporation as well as thermoregulatory changes for clothed and nude segments. While the young adult bioheat model of Karaki et al. (2013) is a segmental multi-node bioheat model, it did not account for physiological changes associated with long exposure to heat-stressful conditions. Such changes need to be incorporated in the young bioheat model to better predict the thermal state under hot conditions and understand how these changes affect the elderly bioheat model.

The aim of this paper is to develop bioheat models that can predict the thermal state of elderly and young people under high heat exposure by incorporating the reported changes in physiology and thermoregulation. In particular, the elderly bioheat model takes into consideration the reported wide variability in physiological parameters affecting the

thermoregulation and thermal response of the elderly group. The model predictions of core and mean skin temperatures in steady and transient hot exposure for both elderly and young are validated with a number of published experimental data.

2. Model development

Following the model of Rida et al. (2014), the proposed elderly and young bioheat models divide the human body into 25 segments, which include the head, upper and lower trunk, upper and lower arms, palms, fingers, thighs, calves, and feet. Fig. 1 (a) shows a schematic description of the segmented human body and its interaction with surrounding environment through convection, radiation, respiration and sweat evaporation. Each segment is represented by a cylinder with or without clothing, and is composed of a core node, skin node, artery node, vein node, and, when applicable, a superficial vein node, as shown in section A-A of Fig. 1 (b). The modeling of blood flow is based on a modified multi-branched arterial tree model of Avolio (1980) to include the five fingers for each hand, as adopted in the bioheat models of Karaki et al. (2013) and Rida et al. (2014). In addition, the model implements the AVA mechanism in the peripheral body segments: forearms, palms, fingers, calves, and feet. Karaki et al. (2013) reported the temperature thresholds for vasodilation, vasoconstriction, shivering, and sweating for the young.

In the following subsections, the adopted changes in physiology with age reported in literature are discussed. Since there is a large variability in physiology and thermoregulation among the elderly population, the adopted model values of various physiological parameters and thermoregulatory thresholds are derived from sensitivity tests in which the model predictions are compared with the published experimental data of Sagawa et al. (1988) at moderate and hot conditions. This is followed

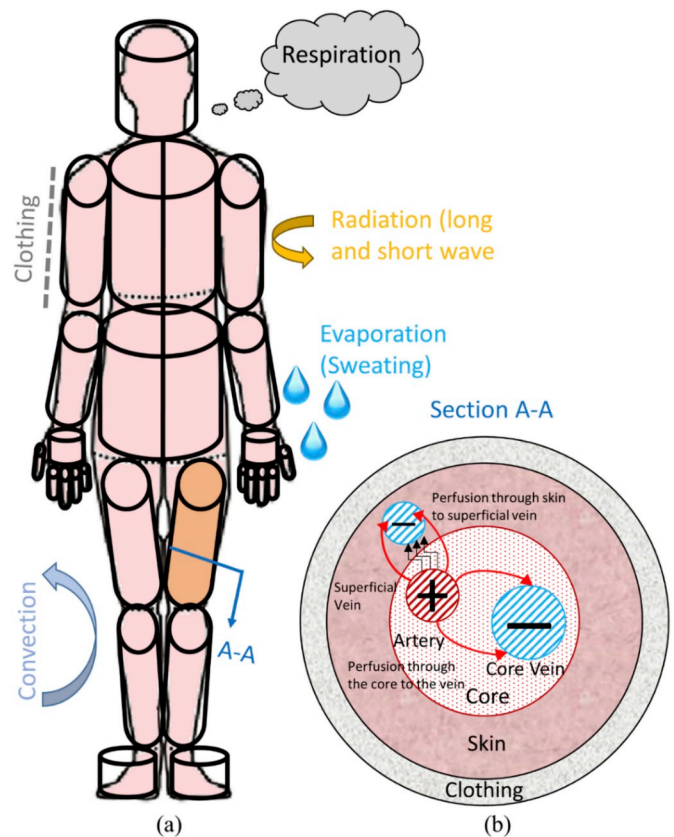


Fig. 1. Schematic description of (a) the segmented human body and its interaction with the surrounding and (b) the cross-section of a cylindrical segment showing the main nodes.

by the adopted changes in physiology and thermoregulation with significant sweating due to exposure to heat stressful conditions for both young and elderly models. Then the bioheat model general heat balance nodal (core, skin, artery, vein) equations for clothed or nude segment that apply to the young or elderly and associated thermoregulatory equations are presented followed by the numerical solution method.

2.1. Changes in physiology due to age and sensitivity analysis

With aging, elderly people undergo reductions in their basal metabolic rate and CO, and delays in their onset of vasodilation and sweating. However, a large variability in these changes has been reported among the elderly population in several studies (Novieto and Zhang, 2010; Tsuzuki and Ohfuku, 2002; and Ma et al., 2017). Due to the established variability among the elderly population, a sensitivity analysis on the different parameters would need to be performed to generate representative average input data to the elderly bioheat model. In the sensitivity analysis, one parameter would be changed at a time while the other parameters remain fixed. This would allow checking which parameter has the most significant effect on the predicted core and skin temperatures compared to a reference case. Table 1 summarizes the parameters considered in the elderly sensitivity analysis, along with the published values adopted in the young bioheat models (Salloum et al., 2007; Karaki et al., 2013).

A reference case for the sensitivity analysis was selected based on published experimental studies in which physiological parameters were reported with corresponding skin and core temperatures in moderate and hot conditions. One of the notable experimental studies is that of Sagawa et al. (1988). This experiment included a preconditioning period of 1 h at 26 °C temperature and 40% RH, where the subjects dressed in cotton underwear (shorts), and sat resting in a controlled room. After that, the room temperature was raised to 40 °C at a constant rate of 1 °C/min and RH was kept constant at 40%, while the subjects sat resting on a wide-meshed chair for 90 min. After the transient period of raising

Table 1
Parameters of the sensitivity analysis and their selected values for elderly along with the reference young values.

Parameter	Symbol	Reference Values of Young Adult	Selected Values for Elderly
Basal metabolic rate	MET_{basal}	58.15 W/m ²	Either 70% ^{a,b} or 79% of that of the young adult.
Basal CO	CO_{basal}	290,000 ^{c,d} cm ³ /hr	Reduced from those of young by either 3.4% ^b or 14.4%.
Minimum constricted CO	$CO_{con, min}$	270,000 ^{c,d} cm ³ /hr	
Maximum dilated CO	$CO_{dil, max}$	427,500 ^{c,d} cm ³ /hr	
Threshold core temperature for onset of sweating	$T_{cr, sweat}$	36.85 °C ^e	Varied between 36.9 °C and 37.06 °C.
Percentage increase of abdomen fat thickness compared to young	P_{fat}	19.12 mm ^{c,f}	Either same as young ^c or 60%.
Threshold core temperature for onset of vasodilation	$T_{cr, basal}$	36.8 °C ^e	Increased either by 0.05 °C or by 0.5 °C compared to those adopted in young adult models ^{c,d}
Threshold core temperature calculating skin blood perfusion	$T_{cr, max}$	37.2 °C ^e	

^a Tsuzuki and Ohfuku (2002).

^b Rida et al. (2014).

^c Salloum et al. (2007).

^d Karaki et al. (2013).

^e Smith (1991).

^f Gordon et al. (1976).

the room temperature, the temperature was kept constant at 40 °C. Based on the results of the sensitivity analysis, the changes on the different parameters related to the physiology and thermoregulation were implemented in the bioheat model.

2.2. Changes in physiology in heat-stressed conditions for elderly and young

The human body at different ambient conditions and metabolic rates (activity level) regulates its core temperature to stay around its neutral value of 37 °C. As the ambient conditions become hotter and/or more humid with increased level of activity, the human body tends to depend on sweat evaporation from skin surface to cool and maintain its core temperature. Studies have shown that as the human body loses water mainly due to sweating, the rate of sweating decreases (Sawka and Coyle, 1999; Chevront et al., 2004). In addition, the threshold for the onset of sweating increases as the body loses water (Sawka and Coyle, 1999; Chevront et al., 2004). This would increase the amount of heat stored in the body and thus increase the core temperature, particularly in hot and/or humid climates (Sawka and Coyle, 1999). To account for this effect, a decrease in sweating rate by a factor of 0.111 was adopted for every 1% of elderly body net water loss (sweating water loss minus any rehydration) as per the experimental data of Chevront et al. (2004). A further limitation on the amount of sweat secretion was imposed in the young bioheat model by setting a maximum possible amount of sweat rate equivalent to 1000 g/h (ISO, 2004). However, this amount was further reduced by 20% to account for the decrease in elderly sweating compared to young adults (Hirata et al., 2012).

In humid conditions where sweat evaporation becomes restricted, the sweat secreted by the human body would accumulate on the skin surface, thus raising the skin wettedness (w) and causing sweat to start dripping instead of evaporating. This leads to a decrease in the sweat evaporation efficiency, η_{evap} , defined by Candas et al. (1979) as the ratio of sweat evaporated to total secreted sweat rate. This was implemented in the bioheat model, in the energy balance of the skin node, as a factor that reduces the amount of sweat evaporation as a function of w as it varies and approaches a maximum value of 1.0. The variation of $\eta_{evaporation}$ with w was taken from the published experimental data of Candas et al. (1979) as given in Equation (1). This factor has higher importance at hot humid conditions where sweat secretion is high but sweat evaporation is limited.

$$\begin{cases} \eta_{evap} = -4.8076 \times w^3 + 8.3638 \times w^2 - 5.0536 \times w + 2; & \text{if } 0.4143 \leq w \leq 1 \\ \eta_{evap} = 1; & \text{if } w < 0.4143 \end{cases} \quad (1)$$

Studies have also shown that as the human body loses water the skin blood flow rate decreases (Sawka and Coyle, 1999; Chevront et al., 2004). The change in skin blood flow rate is proportional to the percentage of body water loss (Chevront et al., 2004). To account for this effect, a decrease of skin blood flow rate by a factor of 0.4 is adopted for every 1% of elderly body water loss as per the experimental data of Chevront et al. (2004). It should be noted that the decrease in water content of blood would decrease its specific heat capacity, which is close to that of water in neutral conditions (Blake et al., 2000).

Furthermore, several studies reported that an increase in body core temperature resulted in an increase in the metabolic rate (Kosaka et al., 2004; Parsons, 2014). This elevation in metabolism was contributed to a higher oxygen consumption with the increase in the kinetic energy of the cells and the cellular chemical reactions (Clarke and Fraser, 2004). These observations were also found at resting metabolic rates with increasing temperature (Clarke and Fraser, 2004). To account for this effect, a correlation between the core temperature and the metabolic rate (or oxygen consumption) derived from the experimental data of Thauer and Wezler (1943) was implemented in the proposed elderly and young bioheat models:

$$MET = MET_{basal}(1+f); f = 0.283T_{cr} - 10.471 \text{ for } T_{cr} > 37^\circ C \quad (2)$$

It should be noted that the increase in the metabolic rate due to elevated core temperature was also reported to result in an increase in the heart rate and CO due to heat accumulation (Dubé et al., 2019; ASHRAE, 2009; Fu, 1995; Salloum et al., 2007). The actual CO and heart rate due to the excess metabolic rate are expressed as follows:

$$CO = \frac{MET}{MET_{basal}} \times \frac{CO_{dil} \times CO_{con}}{CO_{basal}} \quad (3)$$

$$\text{Heart rate (beats / min)} = 3.4 \times (0.0476 \times MET - 7) + 75 \quad (4)$$

The above equations are common for elderly and young people. However, the values of the input parameters would vary according to the age-related physiological changes as determined by the sensitivity analysis.

2.3. Nodal energy balances and thermoregulatory equations

The two main systems that play a role in the predictions of the elderly and young thermal responses are the passive and active systems. The passive system is associated with the heat transfer between the human body and the surroundings and is modeled through energy balance equations. The energy balance equations are written for the nodes of the

$$C_{sk} \frac{dT_{sk}}{dt} = M_{sk} + Q_{cr-sk} - A_{sk,exp} \left[\frac{1}{R_{d,air} + R_{d,clo}} (T_{sk,surf} - T_{amb}) + h_r \cdot (T_{clo} - MRT) \right] + \frac{\eta_{evap}}{R_{e,air} + R_{e,clo}} (P_{sk} - P_{amb}) + \dot{m}_{perf,sk} C_{bl} (T_{cr} - T_{sk}) + \sum_{veins} h_{vein,s} A_{vein,s} (T_{bl,v,s} - T_{sk}) \quad (6a)$$

core, skin, artery, vein and superficial vein for the 25 body segments following the formulation of Karaki et al. (2013). Each energy balance equation corresponds to a body segment i , where i is an index indicating the number of the body segment. Proper changes in the circulatory system of elderly are introduced in those equations. These changes include reduced metabolic rate for each segment and the change in physiology for the AVA blood flow for the diminished vasoconstriction in extremities. The body segments are connected through blood flow in the arteries and veins offering an improved representation of the circulatory system and the distribution of heat within the body. Thus, the nodal energy balances for a body segment i take into consideration the heat transported by the blood from the adjacent segment. Using the lumped capacitance method, there are five nodes for the energy balance in each peripheral segment as provided in equations (5)–(9) for each segment i . For clothed segments, the third term on the right-hand side of equation (6a) will be modified to account for the added resistance of the clothing, as reported in the study of Salloum et al. (2007) and shown in equation (6b). The model will check if a segment i is clothed or not and accordingly solve for the segmental skin temperature using equation (6a) or (6b). In addition, the factor η_{evap} , that reduces the amount of sweat evaporation as a function of w , is introduced in equation (6).

The core node energy balance in each segment i , is given by

$$C_{cr} \frac{dT_{cr}}{dt} = M_{cr} + M_{shiv} - W - \alpha Q_{res} - Q_{cr-sk} - \sum_{arteries} h_{artery} A_{artery} (T_{cr} - T_{bl,a}) - \sum_{veins} h_{vein} A_{vein} (T_{cr} - T_{bl,v}) + (\dot{m}_{perf,cr} - \dot{m}_{perf,sk}) C_{bl} (T_{bl,a} - T_{cr}) \quad (5)$$

where C_{cr} is the thermal capacitance of the segment core, T_{cr} is the segmental core temperature, M_{cr} is the basal metabolic heat generated in each segment, M_{shiv} is the segmental thermoregulatory metabolic rate generated by shivering as a function of skin and core temperature

(Smith, 1991), W is the mechanical work generated by the body, α is equal to unity for the upper chest and zero for all other segments, Q_{res} is the heat dissipated by respiration, Q_{cr-sk} is the heat exchanged between the skin and the core. h_{artery} or h_{vein} is the heat transfer coefficient calculated from the Nusselt number for laminar pulsating flows (turbulent only in major arteries) in circular pipes (Craciunescu and Clegg, 2001; Habib et al., 2004). A_{artery} or A_{vein} is the surface area of the blood vessels. $T_{bl,a}$ and $T_{bl,v}$ are the artery and vein blood temperatures, respectively. C_{bl} is the blood specific heat, $\dot{m}_{perf,cr}$ is the total perfusion rate of blood entering the core and $\dot{m}_{perf,sk}$ is the skin perfusion blood flow rate. The blood circulation in the arteries and veins, and blood perfusion to the skin were modeled using the nonlinear formulation of the Avolio multi-branched model of the human arterial system (Avolio, 1980), as implemented by Salloum et al. (2007) and Karaki et al. (2013).

The skin node energy balance in each nude segment i , is given by

$$C_{sk} \frac{dT_{sk}}{dt} = M_{sk} + Q_{cr-sk} - A_{sk,exp} [h_c \cdot (T_{sk,surf} - T_{amb}) + h_r \cdot (T_{sk,surf} - MRT) + \eta_{evap} \cdot h_e (P_{sk} - P_{amb})] + \dot{m}_{perf,sk} C_{bl} (T_{cr} - T_{sk}) + \sum_{veins} h_{vein,s} A_{vein,s} (T_{bl,v,s} - T_{sk}) \quad (6a)$$

The skin node energy balance in each clothed segment i , is given by

where C_{sk} is the thermal capacitance of the segment skin node and T_{sk} is the segmental skin temperature. The skin node lumped capacitance model adopted by Karaki et al. (2013) is also used in this study, which introduces a correction that assumes a linear temperature profile in the thin skin layer to allow for the prediction of the skin surface temperature ($T_{sk,surf}$). The exposed segmental skin surface temperature, $T_{sk,surf}$, is then equal to $(2T_{sk} - T_{cr})$. This assumption increased accuracy of the predicted skin temperature in comparison to experiments as reported by previous researchers (Karaki et al., 2013; Xu et al., 2009). The symbol h_c is the external convective heat transfer coefficient between the skin and the surrounding calculated using the formula and data of Fiala et al. (2012), h_r is the linearized radiative heat transfer coefficient as reported in ASHRAE (2009) assuming MRT is equal to the ambient temperature (T_{amb}), h_e is the evaporation coefficient derived from h_c by the Lewis formula; $h_e = 16.5 \times h_c$ (Jones, 1999), P_{sk} is the skin saturated vapor pressure calculated using the formulation of Jones (1999), and P_{amb} is the ambient vapor pressure. $h_{vein,s}$ is the convective heat transfer coefficient of blood flow in the superficial vein and $A_{vein,s}$ is the cross-sectional area of the superficial vein. The symbols $R_{d,air}$ and $R_{d,clo}$ represent the dry thermal resistance of the air layer near the skin and the clothing layer, respectively (Salloum et al., 2007). The symbols $R_{e,air}$ and $R_{e,clo}$ represent the evaporative resistance of the air layer near the skin and the clothing layer, respectively (Salloum et al., 2007).

The artery node energy balance in each segment i , is given by

$$C_{bl,a} \frac{dT_{bl,a}}{dt} = - \sum_{arteries} h_{artery} A_{artery} (T_{bl,a} - T_{cr}) + \dot{m}_a C_{bl} (T_{bl,a,adjacent} - T_{bl,a}) \quad (7)$$

where \dot{m}_a is the blood flow rate through the artery and $T_{bl,a,adjacent}$ is the temperature of the blood in the adjacent artery of the previous body segment.

The vein node energy balance in each segment i , is given by

$$C_{bl,v} \frac{dT_{bl,v}}{dt} = - \sum_{veins} h_{vein} A_{vein} (T_{bl,v} - T_{cr}) + \dot{m}_v C_{bl} (T_{bl,v,adjacent} - T_{bl,v}) + \dot{m}_{perf,cr} C_{bl} (T_{cr} - T_{bl,v}) \quad (8)$$

where \dot{m}_v is the blood flow rate through the vein and $T_{bl,v,adjacent}$ is the temperature of the blood in the adjacent core vein of the previous body segment.

The superficial vein node energy balance existing in distal limbs and fingers is given by:

$$C_{bl,v,s} \frac{dT_{bl,v,s}}{dt} = - \sum_{veins} h_{vein,s} A_{vein,s} (T_{bl,v,s} - T_{sk}) + \dot{m}_{v,s} C_{bl} (T_{bl,v,s,adjacent} - T_{bl,v,s}) + \dot{m}_{perf,sk} C_{bl} (T_{sk} - T_{bl,v,s}) + \dot{m}_{AVA} C_{bl} (T_{bl,a} - T_{bl,v,s}) \quad (9)$$

where $\dot{m}_{perf,sk}$ is the blood perfusion in the skin layer without AVA, $C_{bl,v,s}$ is the superficial vein blood capacitance, and \dot{m}_{AVA} is the AVA blood flow.

The active system is triggered when the human body is under cold/heat stress. Depending on whether the trigger is due to a warm or cold signal, the four thermoregulatory functions are activated accordingly.

$$\dot{m}_{perf,sk,dil} = \begin{cases} \dot{m}_{perf,sk,basal} & \text{for } T_{cr} \leq T_{cr,basal} \\ \frac{T_{cr} - T_{cr,basal}}{T_{cr,max} - T_{cr,basal}} (\dot{m}_{perf,sk,max} - \dot{m}_{perf,sk,basal}) + \dot{m}_{perf,sk,basal} & \text{for } T_{cr,basal} \leq T_{cr} \leq T_{cr,max} \\ \dot{m}_{perf,sk,max} & \text{for } T_{cr} \geq T_{cr,max} \end{cases} \quad (11)$$

$$\dot{m}_{perf,sk,con} = \begin{cases} \dot{m}_{perf,sk,min} & \text{for } T_{sk} \leq 10.2^\circ C \\ \frac{T_{sk} - 10.2}{33.2 - 10.2} (\dot{m}_{perf,sk,basal} - \dot{m}_{perf,sk,min}) + \dot{m}_{perf,sk,min} & \text{for } 10.2^\circ C \leq T_{sk} \leq 33.2^\circ C \\ \dot{m}_{perf,sk,basal} & \text{for } T_{sk} \geq 33.2^\circ C \end{cases} \quad (12)$$

These functions include vasodilation, vasoconstriction, shivering and sweating. The total sweating rate of the body is found as a function of the core temperature as it rises above the threshold core temperature for the onset of sweating following the formulation of Smith (1991) for young and then adapted to elderly due to the delay in sweating response. Then the segmental sweating rate is found by multiplying the total sweating rate with a sweating factor corresponding to the body segment i . The segmental sweating factors are reported in the study of Salloum et al. (2007) for young adults and Rida et al. (2014) for elderly. The shivering is triggered once T_{cr} falls below $35.8^\circ C$, at which the shivering threshold value is $35.5^\circ C$, but shivering does not occur if T_{cr} is above $37.1^\circ C$ (Smith, 1991). However, between $35.8^\circ C$ and $37.1^\circ C$, the shivering threshold decreases in a parabolic manner with the variation of T_{cr} . Moreover, as the mean T_{sk} decreases the intensity of shivering increases,

reaching its maximum value at T_{sk} of $20^\circ C$. Thus, Smith (1991) found M_{shiv} as a function of mean T_{sk} and the shivering threshold value. This M_{shiv} is the total shivering metabolic rate of the body, while the segmental M_{shiv} is found by multiplying the total rate with a cold shivering factor corresponding to the body segment i . The segmental cold shivering factors were reported in the study of Salloum et al. (2007) for young adults and Rida et al. (2014) for elderly. During vasoconstriction or vasodilation, $\dot{m}_{perf,sk}$ varies between a minimum ($\dot{m}_{perf,sk,con}$) and a maximum ($\dot{m}_{perf,sk,dil}$) based on threshold values of local core and skin temperatures as given by Smith (1991), Karaki et al. (2013) and Rida et al. (2014) and shown in equations (10)–(12). The adopted threshold values for $\dot{m}_{perf,sk}$ during vasoconstriction were similar to those reported in the model of Karaki et al. (2013) for young adults and Rida et al. (2014) for elderly. During vasodilation the elderly thresholds for $\dot{m}_{perf,sk}$ ($T_{cr,basal}$ and $T_{cr,max}$) were based on the sensitivity tests conducted in this study.

$$\dot{m}_{perf,sk} = \frac{\dot{m}_{perf,sk,dil} \times \dot{m}_{perf,sk,con}}{\dot{m}_{perf,sk,basal}} \quad (10)$$

The CO equations are controlled by the skin and core temperatures (Fu, 1995). Fu (1995) reported values of the basal cardiac output, CO_{basal} , minimum constricted cardiac output, $CO_{con,min}$, and maximum dilated cardiac output, $CO_{dil,max}$, for young adults. As for the elderly CO, the values reported by Fu (1995) on young adults are reduced by a percentage determined from the sensitivity analysis and thus the new values of CO_{basal} , $CO_{con,min}$, and $CO_{dil,max}$ are deduced. The total CO is generally determined using the equation of Fu (1995) and Iyoho et al. (2009) as follows:

$$CO = \frac{CO_{dil} \times CO_{con}}{CO_{basal}} \quad (13)$$

The elderly CO_{con} and CO_{dil} were calculated, respectively, after adjusting the elderly thresholds as follows:

$$CO_{con} = \begin{cases} CO_{basal} & \text{for } T_{sk} \geq 33.2^\circ C \\ \frac{(T_{sk} - 10.2) \times (CO_{basal} - CO_{con,min})}{(33.2 - 10.2)} + CO_{con,min} & \text{for } 10.2^\circ C < T_{sk} < 33.2^\circ C \\ CO_{con,min} & \text{for } T_{sk} \leq 10.2^\circ C \end{cases} \quad (14)$$

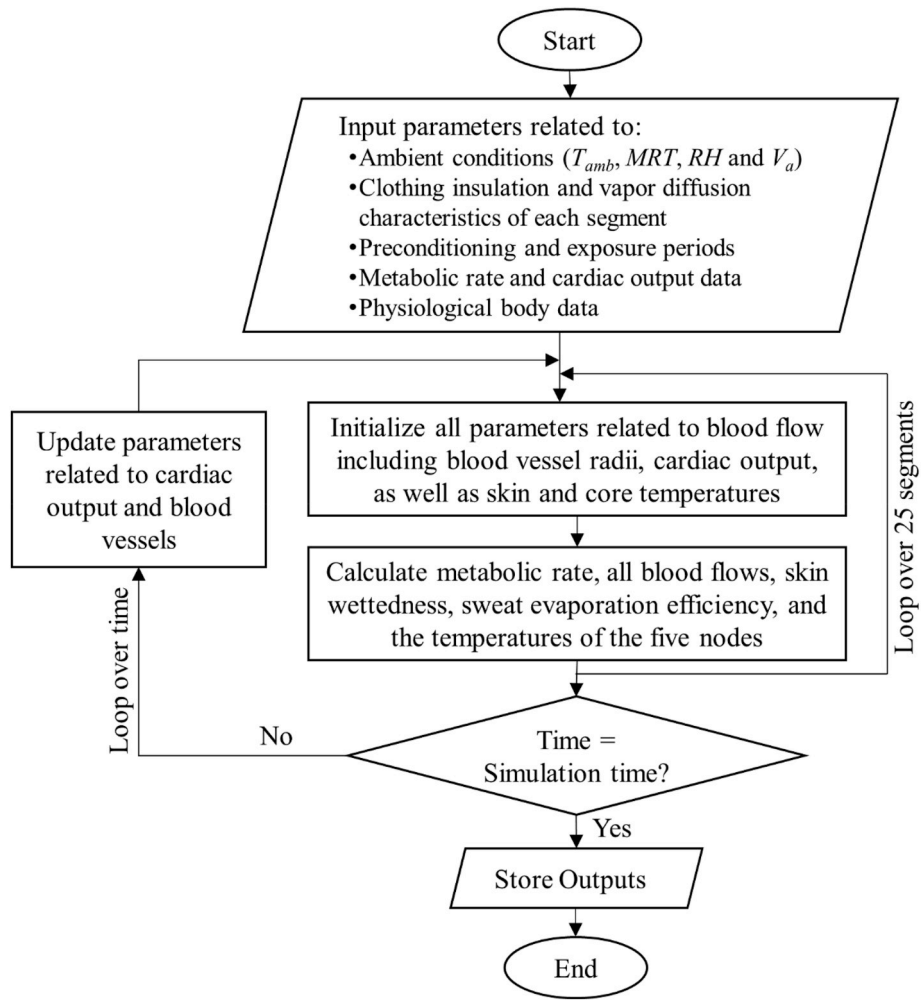


Fig. 2. Numerical procedure to solve the elderly or young model equations.

$$CO_{dil} = \begin{cases} CO_{dil,max} & \text{for } T_{cr} \geq T_{cr,max} \\ \frac{(T_{cr} - T_{cr,basal}) \times (CO_{dil,max} - CO_{basal})}{(T_{cr,max} - T_{cr,basal})} + CO_{basal} & \text{for } T_{cr,basal} < T_{cr} < T_{cr,max} \\ CO_{basal} & \text{for } T_{cr} \leq T_{cr,basal} \end{cases} \quad (15)$$

The above equations along with the thermoregulatory functions were used to predict the segmental core, skin, artery, vein, superficial vein temperatures, blood flow rates, heart rate, sweating rate, and cardiac output.

2.4. Numerical solution

Fig. 2 shows the numerical procedure to solve the young or elderly model equations. The models require the following input data:

- Ambient conditions (T_{amb} , MRT , RH and V_a) and exposure duration
- Metabolic rate that reflects the activity level
- Clothing insulation and vapor diffusion characteristics of each body segment

- Elderly or young physiological body data that include the basal metabolic rate, basal skin blood flow, minimum and maximum skin blood flow, sweating factor, cold shivering factor, surface area, and fat thickness of each body segment.
- CO for maximum vasoconstriction, basal conditions, and maximum vasodilation.

The elderly or young bioheat model was solved using a fully explicit first order Euler-Forward integration scheme with a time step of 0.05s over the desired simulation period. The energy balances were constrained by the modified thermoregulatory controls to predict segmental core and skin temperatures and arterial blood flows for given metabolic rate and environmental conditions. Initialization of the different parameters related to blood flows and skin and core temperatures was first done for a preconditioning period and then the steady state results are taken as initial values for the conditioning or exposure period. The

Table 2
Results of the sensitivity analysis for different parameters at $T_{amb} = 26\text{ }^{\circ}\text{C}$ and $40\text{ }^{\circ}\text{C}$.

Case No.	Parameter	$T_{amb} = 26\text{ }^{\circ}\text{C}$, RH = 40%		$T_{amb} = 40\text{ }^{\circ}\text{C}$, RH = 40%	
		T_{cr} ($^{\circ}\text{C}$) (ΔT_{cr})	T_{sk} ($^{\circ}\text{C}$) (ΔT_{sk})	T_{cr} ($^{\circ}\text{C}$) (ΔT_{cr})	T_{sk} ($^{\circ}\text{C}$) (ΔT_{sk})
$\Delta T = \text{increase from Elderly Reference Case in } ^{\circ}\text{C}$					
Ref. Case	Experimental data of Sagawa et al. (1988)	36.850 \pm 0.100	31.800 \pm 0.200	37.260 \pm 0.100	36.600 \pm 0.200
Case 1	$MET_{basal} = 70\%$ of young CO_{basal} , $CO_{con,min}$ & $CO_{dil,max}$ reduced by 3.4% $T_{cr,sweat} = 36.9\text{ }^{\circ}\text{C}$ $T_{cr,basal}$ & $T_{cr,max}$ delay by $0.05\text{ }^{\circ}\text{C}$ $P_{fat} = 0\%$	36.903 (0.053)	32.318 (0.518)	37.034 (0.226)	37.089 (0.489)
Case 2	$MET_{basal} = 79\%$ of young CO_{basal} , $CO_{con,min}$ & $CO_{dil,max}$ reduced by 3.4% $T_{cr,sweat} = 36.9\text{ }^{\circ}\text{C}$ $T_{cr,basal}$ & $T_{cr,max}$ delay by $0.05\text{ }^{\circ}\text{C}$ $P_{fat} = 0\%$	36.951 (0.101)	31.787 (0.013)	37.123 (0.137)	36.531 (0.069)
Case 3	$MET_{basal} = 70\%$ of young CO_{basal} , $CO_{con,min}$ & $CO_{dil,max}$ reduced by 14.4%, $T_{cr,sweat} = 36.9\text{ }^{\circ}\text{C}$, $T_{cr,basal}$ & $T_{cr,max}$ delay by $0.05\text{ }^{\circ}\text{C}$ $P_{fat} = 0\%$	36.861 (0.011)	32.155 (0.355)	37.008 (0.252)	37.033 (0.433)
Case 4	$MET_{basal} = 70\%$ of young, CO_{basal} , $CO_{con,min}$ & $CO_{dil,max}$ reduced by 3.4%, $T_{cr,sweat} = 37.06\text{ }^{\circ}\text{C}$, $T_{cr,basal}$ & $T_{cr,max}$ delay by $0.05\text{ }^{\circ}\text{C}$ $P_{fat} = 0\%$	36.866 (0.016)	32.182 (0.382)	37.036 (0.224)	37.769 (1.169)
Case 5	$MET_{basal} = 70\%$ of young, CO_{basal} , $CO_{con,min}$ & $CO_{dil,max}$ reduced by 3.4% $T_{cr,sweat} = 36.9\text{ }^{\circ}\text{C}$ $T_{cr,basal}$ & $T_{cr,max}$ delay by $0.05\text{ }^{\circ}\text{C}$ $P_{fat} = 60\%$	36.858 (0.008)	32.955 (1.155)	37.001 (0.259)	37.162 (0.562)
Case 6	$MET_{basal} = 70\%$ of young CO_{basal} , $CO_{con,min}$ & $CO_{dil,max}$ reduced by 3.4% $T_{cr,sweat} = 36.9\text{ }^{\circ}\text{C}$ $T_{cr,basal}$ & $T_{cr,max}$ delay $0.5\text{ }^{\circ}\text{C}$ $P_{fat} = 0\%$	36.865 (0.015)	32.157 (0.357)	37.018 (0.242)	36.992 (0.392)
Case 7	$MET_{basal} = 79\%$ of young CO_{basal} , $CO_{con,min}$ & $CO_{dil,max}$ reduced by 14.4% $T_{cr,sweat} = 37.06\text{ }^{\circ}\text{C}$, $T_{cr,basal}$ & $T_{cr,max}$ delay by $0.5\text{ }^{\circ}\text{C}$ $P_{fat} = 60\%$	37.000 (0.150)	31.820 (0.020)	37.210 (0.050)	36.760 (0.160)

Table 3
Values of parameters deduced from the sensitivity analysis for elderly.

Parameter	Value
MET_{basal}	79% ^a of young basal metabolism
CO_{basal}	248,240 cm^3/h
$CO_{con,min}$	231,120 cm^3/h
$CO_{dil,max}$	365,940 cm^3/h
$T_{cr,sweat}$	37.06 $^{\circ}\text{C}$
P_{fat}	60% ^a increase from young
$T_{cr,basal}$	37.3 $^{\circ}\text{C}$
$T_{cr,max}$	37.7 $^{\circ}\text{C}$

^a [Salloum et al. \(2007\)](#).

outputs of the bioheat models are summarized as follows:

- Skin and core temperature of each body segment
- Average values of skin and core temperatures. The average T_{sk} is calculated using the formula of [Hardy and Du Bois \(1938\)](#) and T_{cr}

Table 4
Comparison of elderly model predictions with measurement of [Yochihara et al. \(1993\)](#) for the core temperature at the start and end of exposure to ambient temperature of $35\text{ }^{\circ}\text{C}$ and RH of 60%.

Time (min) from the onset of exposure to hot environment at $35\text{ }^{\circ}\text{C}$	Reported experimental measurements of mean core temperature ($^{\circ}\text{C}$) \pm Standard Deviation ^a	Predicted core temperature ($^{\circ}\text{C}$) by the elderly bioheat model	Deviation between model and reported data ($^{\circ}\text{C}$)
0	37.05 \pm 0.05 $^{\circ}\text{C}$	37.09 $^{\circ}\text{C}$	0.040
49 min	37.25 \pm 0.05 $^{\circ}\text{C}$	37.19 $^{\circ}\text{C}$	0.060

^a [Yochihara et al. \(1993\)](#).

takes the value of the lower torso segment as it best reflects the measured experimental body core or rectal temperature.

- Sweat rate of each body segment
- Total body sweat rate
- Skin wettedness
- Total body water loss percentage
- Total skin and perfusion blood flow rates
- Total dry and latent heat loss or gains

3. Results and discussion

This section summarizes the results of the sensitivity analysis that lead to the definition of a reference elderly person. The characteristics of the reference elderly person were then used in the validation cases of the elderly model. Moreover, the young bioheat model predictions of core and mean skin temperatures under the same heat stressed conditions were also validated and compared with those of the elderly, where

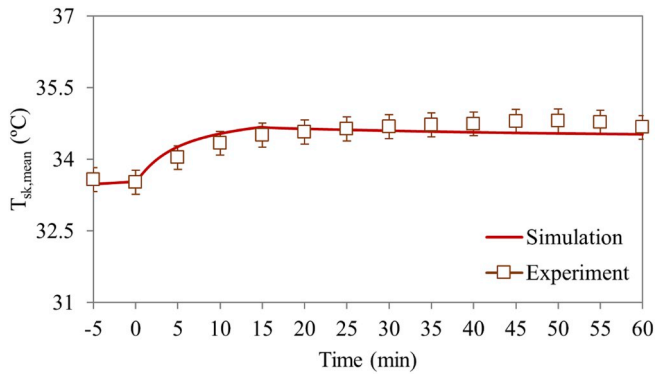


Fig. 3. Comparison of the elderly model predictions with the experimental data of Xiong et al. (2019) for the transient mean skin temperature.

applicable since not all experimental studies included young control group.

3.1. Sensitivity analysis and thermoregulatory controls of elderly

The experimental data of Sagawa et al. (1988) was used as a benchmark case for the sensitivity analysis. The experiments consisted of two periods, a preconditioning period at $T_{amb} = 26\text{ }^{\circ}\text{C}$ and $RH = 40\%$, followed by a hot exposure period at $T_{amb} = 40\text{ }^{\circ}\text{C}$ and $RH = 40\%$. Table 2 summarizes the results of the sensitivity analysis. The main parameter that affects the core temperature at both exposure conditions is the basal metabolism, where reducing it by 21% results in a lower core temperature by $0.137\text{ }^{\circ}\text{C}$ at $T_{amb} = 40\text{ }^{\circ}\text{C}$ than the measured temperature. The second influential parameter is the threshold temperature for the onset of sweating, where using $37.06\text{ }^{\circ}\text{C}$ leads to a $0.224\text{ }^{\circ}\text{C}$ lower core temperature than the measured temperature. The third influential parameter is the threshold temperature for the onset of vasodilation, where increasing it by $0.45\text{ }^{\circ}\text{C}$ leads to a $0.242\text{ }^{\circ}\text{C}$ lower core temperature. The fourth influential parameter is the CO, where decreasing it by 14.4% leads to a $0.252\text{ }^{\circ}\text{C}$ lower core temperature. Finally, the minimal effect on the predicted core and mean skin temperatures is associated with the increased abdomen fat thickness, where increasing it by 60% leads to a $0.259\text{ }^{\circ}\text{C}$ lower core temperature.

Adopting all the identified changes in the physiological parameters has led to better prediction of the core and mean skin temperatures as will be discussed in the next elderly model validation studies. Table 3 summarizes the values of the influential parameters.

Hence, the characteristics of a reference elderly person to be used in the elderly bioheat model are as follows:

Table 5

Comparison of elderly and young model predictions with experimental data of Sagawa et al. (1988) for: core and mean skin temperatures during gradual exposure to ambient temperature of $40\text{ }^{\circ}\text{C}$ and RH of 40%.

Time (min) from the onset of exposure to increasing temperature from $26\text{ }^{\circ}\text{C}$ to $40\text{ }^{\circ}\text{C}$ at a rate of $1\text{ }^{\circ}\text{C}/\text{min}$		At onset of exposure	90 min from exposure	At onset of exposure	90 min from exposure	Temperature difference between Elderly and Young ($^{\circ}\text{C}$)
		Elderly	Young	Young	Elderly	
Reported experimental measurements of temperature ^a	Core temperature ($^{\circ}\text{C}$)	36.85	37.26	36.86	37.06	0.2
Predicted temperature by the elderly bioheat model		37.00	37.21	36.91	37.001	0.21
Deviation between model and reported data ($^{\circ}\text{C}$)		0.15	0.05	0.05	0.06	
Reported experimental measurements of temperature ^a	Mean skin temperature ($^{\circ}\text{C}$)	31.8	36.6	31.44	36.33	0.27
Predicted temperature by the elderly bioheat model		31.82	36.76	31.42	36.35	0.41
Deviation between model and reported data ($^{\circ}\text{C}$)		0.02	0.16	0.02	0.02	

^a Sagawa et al. (1988).

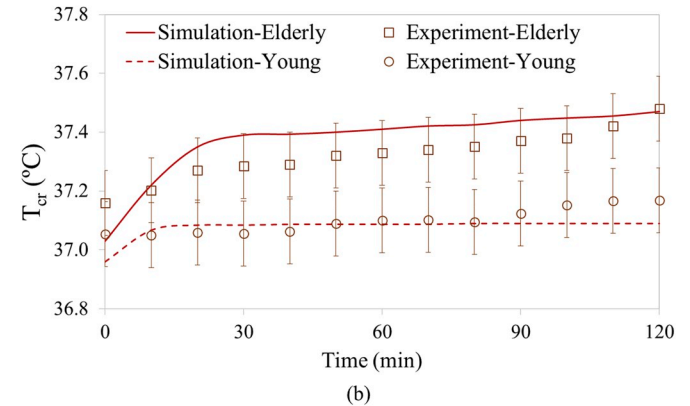
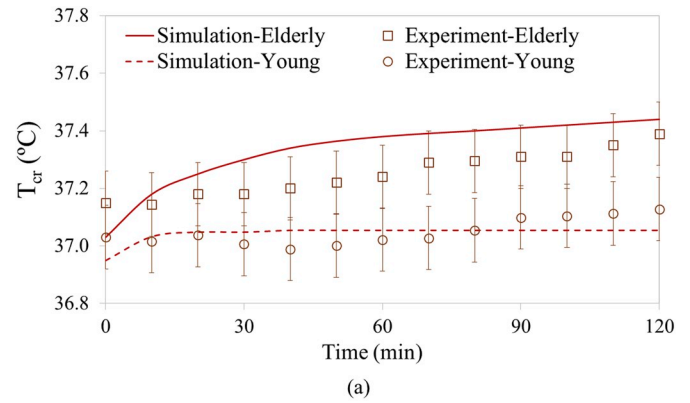


Fig. 4. Comparison of elderly and young models' predictions with experimental data of Stapleton et al. (2013) for: (a) transient core temperature during hot-dry condition, (b) and transient core temperature during hot-humid condition.

- Body mass of 72.335 kg and height of 180 cm (Rida et al., 2014)
- Age group of 65–70 years as obtained from the correlation of Harris and Benedict (1918).
- Body fat percentage of around 24%
- Reduced basal metabolism from the young adult by 21% (in the range adopted in the elderly bioheat model of Ma et al. (2017) and reported by Novieto and Zhang (2010)).
- Reduced CO from the young adult by 14.4% (similar to the reduction reported by Novieto and Zhang, 2010).
- Onset of sweating at $37.06\text{ }^{\circ}\text{C}$ (similar to the value reported by Sagawa et al. (1988)).

Table 6

Comparison of elderly and young models' predictions with experimental data of Stapleton et al. (2013) of the steady state mean skin temperature after 120 min of exposure at hot dry and hot humid conditions.

Condition		Steady-State T_{sk} , mean (°C)	
		Elderly	Young
Experimentally measured values ^a	Hot dry conditions at 36.5 °C and 20% RH	34.2	34.9
Predicted values by model		33.3	35.2
Experimentally measured values ^a	Hot humid conditions at 36.5 °C and 60% RH	34.6	35.0
Predicted values by model		34.1	35.47

^a Stapleton et al. (2013).

- Delay in onset of vasodilation by 0.5 °C from the young adult (in the range reported and adopted in the elderly bioheat model of Hirata et al., 2012).

3.2. Experimental validation of the elderly and young bioheat models

This section presents the validation of the developed elderly and young bioheat models' predictions of core and mean skin temperature against published experimental data conducted in hot and humid environments at steady and transient conditions. Five independent experimental studies on elderly human subjects have been used for validation of the elderly model in hot and humid exposure. Three of these studies included experimental data for a young control group and are used for validation of the young bioheat model with exposure to the same thermally stressful conditions of the elderly subjects.

The first validation compares the elderly model predictions with published experimental data under steady state conditions of Yochihara et al. (1993). Yochihara et al. (1993) conducted experiments on 9 elders, aged above 65 years, and recorded their oral temperature and sensations. The experiments involved a pre-conditioning period, where subjects wearing a cotton long sleeved shirt, long pants and socks (equivalent to 0.63 clo) sat resting in a room, at 25 °C and 60% RH for 23 min. Then, the subjects were exposed to 35 °C and 60% RH for a period of 49 min while the subjects sat resting. During the experiments, measurements of oral temperature were taken at the start and end of exposure. Table 4 presents the results for the model predictions and experimental data of Yochihara et al. (1993) for the core temperature T_{cr} at the start and end of exposure to ambient temperature of 35 °C. The predicted results show good agreement with the experimental data, where T_{cr} increases from 37.09 °C to 37.19 °C due to exposure to hotter ambient temperature of 35 °C. The maximum discrepancy between the predicted and measured data is 0.06 °C.

The second model comparison was performed with the transient measurement of the elderly mean T_{sk} of Xiong et al. (2019). Xiong et al. (2019) conducted experiments on 16 elders (males and females) aged above 65 years and wearing clothing equivalent to 0.55 clo. The elders were first exposed to preconditioning states for 30 min at 26 ± 0.5 °C and 75.5 ± 4.2% RH. Then the elders, while sitting and relaxed, were exposed to 30.9 ± 0.4 °C and 69.2 ± 3% RH at an air velocity below 0.1 m/s for 60 min. The comparison results for the transient mean T_{sk} are shown in Fig. 3. Upon exposure to moderately hot conditions of 30.9 ± 0.4 °C, the mean T_{sk} has a sharp increase during the first 15 min of exposure, after which almost stable conditions were attained. The model predictions show a good agreement with the experimental data with a maximum discrepancy of 0.3 °C.

The third comparison study is with the measurement data of Sagawa et al. (1988). Sagawa et al. (1988) conducted experiments on 6 healthy male elders aged above 61 years and 10 young males aged below 39 years. The experiments had a preconditioning period where subjects dressed in cotton underwear (shorts), sat resting in a room kept at 26 °C temperature and 40% RH for 60 min. After that, the room temperature

Table 7

Comparison of elderly and young model predictions with experimental data of Tsuzuki and Ohfuku (2002) and elderly predictions of Schellen et al. (2010).

	Group		Core Temperature (°C)
	Elderly	Young	
Exposure to 23 °C and 60% RH for 90 min ^a	Elderly	Experiment	37.00
		Simulation	36.91
	Young	Experiment	36.90
		Simulation	36.90
Exposure to 21.5 °C and 40% RH for 8 h ^b	Elderly	Experiment	36.60
		Simulation	36.87

^a Tsuzuki and Ohfuku (2002).

^b Schellen et al. (2010).

was raised to 40 °C at a constant rate of 1 °C/min and RH was kept constant at 40% while the subjects sat resting on a wide-meshed chair for 90 min. After the transient period of raising the room temperature, the temperature was kept constant at 40 °C. Table 5 presents a comparison between the elderly and young model predictions and measurement data of Sagawa et al. (1988) for the steady state (a) mean skin temperature (b) and core temperature under the ambient temperature of 40 °C and RH of 40%. The predicted results show a good agreement with the experimental data, where the mean T_{sk} and T_{cr} increase with ambient temperature from 26 °C to 40 °C. The predicted elderly T_{cr} at the end of the hot exposure was higher than that of the young by about 0.21 °C, which is an indication of the greater heat accumulation in the elderly human body. This implies that the elderly are under more risk than the young when exposed to heat-stressful conditions (Van Hoof et al., 2017; Roelofsens, 2017; Rida et al., 2014; Ma et al., 2017; Kenny et al., 2019). The discrepancy between the predictions and experimental data of Sagawa et al. (1988) was 0.16 °C in the mean T_{sk} and 0.05 °C in T_{cr} for the elderly and 0.02 °C in the mean T_{sk} and 0.06 °C in T_{cr} for the young.

The fourth comparison study is for the elderly and young transient T_{cr} and steady state mean T_{sk} of the experimental data of Stapleton et al. (2013). The latter conducted experiments on 12 elders (males and females) aged above 60 years and on 12 young adults (males and females) aged below 24 years while wearing light athletic shorts and sandals. The subjects, while seated, were exposed to 36.5 °C and 20% RH (hot-dry condition) or to 36.5 °C and 60% RH (hot-humid condition) for 120 min. Fig. 4 shows a comparison between the elderly and young model predictions and experimental data for the transient mean skin and core temperatures. The transient variation of the elderly T_{cr} had a higher slope than that of the young, which resulted in higher values of T_{cr} for the elderly by the end of both the hot-dry and hot-humid exposure periods. The higher elderly T_{cr} is attributed to the fact that elderly people do not sweat as efficiently as young adults do and thus heat is stored in their bodies rather than released to the surroundings (Stapleton et al., 2013). The steady-state model prediction of skin temperatures in both experiments of Stapleton et al. (2013) are summarized in Table 6. The model predictions have good agreement with the experimental data with a maximum discrepancy of 0.1 °C and 0.07 °C in T_{cr} and 0.5 °C and 0.5 °C in the mean T_{sk} of the elderly and young, respectively.

The fifth elderly and young model comparison is with the experimental data of Tsuzuki and Ohfuku (2002) and Schellen et al. (2010) for the steady-state T_{cr} . Tsuzuki and Ohfuku (2002) conducted experiments on elders and young adults at exposure to 23 °C and 60% RH for 90 min while they were seated and wearing clothing of 0.63 clo. Schellen et al. (2010) conducted experiments on elders with exposure to 21.5 °C and 40% RH for 8 h while they were seated and wearing clothing of 1 clo. Table 7 presents the comparison results, where the elderly and young model predictions are in good agreement with the experimental data. The predicted results under the relatively neutral ambient conditions of Tsuzuki and Ohfuku (2002) show that elderly people have similar T_{cr} as young adults and under no heat stress.

The changes that were applied to the elderly bioheat model resulted in improved predictions compared to the published experimental data

for the core and mean skin temperatures under high heat stress levels during exposure to hot and dry or humid conditions. The elderly model is applicable for the studied exposure ranges, but should not be applied to extreme exposure conditions when the thermoregulation starts to fail. Moreover, the changes applied to the young bioheat model showed results of good agreement when validated with published experimental data under heat-stressful conditions.

4. Conclusions

The elderly population (>60 years old) have age-weakened physiology and thermoregulation and are therefore subject to a higher heat-related health risks than young adults. Furthermore, exposure to high heat stress levels results in physiological changes in metabolism, cardiac output and thermoregulation. This paper addressed the development and validation of an elderly bioheat model that predicts the thermal response of elderly under exposure to high heat stress levels as well as the development and validation of a young bioheat model for better predictions in heat-stressful conditions. The developed elderly model incorporates changes in physiology and thermoregulation due to aging and exposure to hot and dry or humid conditions. Due to the large physiological variability among the elderly population, a sensitivity analysis was conducted to set the characteristics of an average representative elderly person. Consequently, the metabolic rate and cardiac output of elders were decreased from those of young adults by 21% and 14.4%, respectively. Furthermore, the thresholds of the onset of vasodilation and sweating were delayed from those of young adults by 0.5 °C and 0.21 °C, respectively. The elderly and young models were then validated by comparing their predictions with published experimental data for the transient and steady state mean skin and core temperatures under hot exposure conditions. The discrepancy between predictions and measurement data of core and mean skin temperatures was within 0.1 °C and 0.5 °C, respectively.

The developed elderly bioheat model, due to limited published experimental data for healthy elderly people, is applicable to the studied exposure ranges and should not be applied to extreme exposure conditions where the thermoregulation starts to fail or if an elderly person is ill or taking any medication. Further improvement of the model could be done by taking into consideration the variability among the elderly population due to age. In other words, the elderly population could be divided into different age groups and representative average elderly characteristics would be developed for each age group.

The developed models can be used for assessing the level of heat stress through thermal and physiological responses such as elevated core temperature, skin wettedness and percentage of net body water loss. Hence, they allow the determination of thresholds for safe exposure to elevated indoor environmental conditions of temperature and humidity that can pose a risk, especially to the health of the elderly. Moreover, the developed elderly model and predicted thermal stress and associated comfort/discomfort ranges would have important implications on the design and operations of the built environments for seniors and for mixed-occupants spaces (such as houses, apartments, hospitals, etc.), as well as on the current comfort standards which are suitable for young and healthy adults.

CRedit authorship contribution statement

Mariam Itani: Software, Validation, Investigation, Writing - original draft. **Nesreen Ghaddar:** Conceptualization, Supervision, Project administration, Writing - original draft. **Kamel Ghali:** Conceptualization, Methodology, Writing - review & editing. **Abdelaziz Laouadi:** Conceptualization, Formal analysis, Writing - review & editing, Resources, Funding acquisition.

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