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An extended multi-segmented human bioheat model for high temperature environments

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ABSTRACT

This paper proposes an extended multi-segmented human bioheat model for high temperature environments considering the effects of high temperature on the metabolic rate and the cardiovascular system. This extended model is modified from an original model for normal temperature environments based on the energy balance equations from Salloum' model, and the human thermal regulation equations from Stolwijk and Fiala's work. The original model for normal temperature environments and the extended model for high temperature environments are validated with the existing experimental data. The results show that there are good agreements between the simulation results and the experimental data in both environments. Through the comparison of the simulated results with the original model and the extended model, it is shown that the original model would underestimate the skin and core temperatures, and underrate the impact on the human body from high temperature environments, e.g. underestimate the time to reach the utmost heat tolerance and skin burn.

1. Introduction

Mathematical modeling of the human thermal response is one of the most valuable and effective tools [1], to simulate human physiological and thermoregulatory responses under different environment conditions and activity levels. Many human bioheat models have been used in thermal comfort research aimed for energy efficiency, human thermal discomfort under exposure to extreme hot or cold conditions, assessment of indoor air quality, and clothing test [2,3]. Since the first one was built in 1930s [4], the model development went into stages by two-layer models developed by Gagge [5,6], to multi-layer single-segment and multi-segment models initially developed by Stolwijk [7,8], Wissler [9], and Wyndham and Atkins [10]. Stolwijk's model used five cylindrical segments to describe the human body, and each segment was divided into four concentric lumped layers, among which the blood flow was used to connect. His model of thermal control was described as the functions of two tissue temperature signals as in Gagge's control system signals and the other was related to the rate of change of tissue temperatures.

All subsequent contemporary multi-segment multi-layer bioheat models are modifications and improvements on Stowijk model parameters and thermal control equations. The typical models include the models of Huizega and Hui [11] (known as the Berkeley model), Tanabe and Kobayashi [12], Fiala et al. [13,14], and Salloum et al. [3,15] (known as the AUB model). More recent works also contribute much to the models of human heat transfer and thermal response. Al-Othmani et al. [16], Ferreira and Yanagihara [17], and Zolfaghari and Maerefat [18] paid attention to human body transfer under transient environment, and developed the transient bioheat models with improvement of Gagge [6] and Stowijk's models [7,8]. Prek [19], and Prek and Butala [20] provided exergy analysis of human heat and mass exchange with the indoor environment. Takada developed a human thermal model based on Gagge's model [6] to consider the individual characteristics of body temperature regulation, and validated the model with his experimental data [21].

However, the above human bioheat models focus on the heat transfer process between the human and environment in normal temperature range, in which in general, the upper limit does not exceed 40 °C. These models are not suitable for the high-temperature condition by lack of considering the characteristics of human harsh situations that bring significantly differences in physiological responses and human thermal parameters, e.g. effects of high temperature on the metabolism rate, cardiovascular system, and blood flow rate, etc. Firefighters and other personnel working in steel and construction industry are usually exposed to hot environment,

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Nomenclature

BW	body weight (kg)
BWL	percentage of the body water loss and body weight
C	heat capacitance (J/K)
CON	convection heat transfer (W)
c	specific heat (J/kg K)
FBF	measurable forearm blood flow (ml/100 ml min)
EVA	evaporation heat transfer (W)
HR	heart rate (beats/min)
$h(t)$	pulsating heat convection coefficient (W/m^2 K)
h_c	heat convection coefficient (W/m^2 K)
h_M	proportionality coefficient of human metabolic rate
h_e	heat evaporation coefficient (W/m^2 Pa)
h_{mean}	mean non-pulsating convection coefficient (W/m^2 K)
h_r	heat radiation coefficient (W/m^2 K)
K	ratio of the variable quantities of the measurable forearm blood flow and the skin temperature (ml/100 ml min K)
k	heat conduction coefficient (W/K)
k_e	effective thermal conductivity (W/m K)
M	metabolic rate (W)
$\dot{m}$	mass flow rate (kg/s)
P	skin vapor pressure (Pa)
Q	heat transfer (W)
$SkBF$	human skin blood flow (l/min)
T	temperature (K)
t	time (s)
th	thickness (m)
W	mechanical work (W)
x	variable

Greek symbols

α	distribution coefficient
β	constant of the mechanical work
Δ	error signal

Subscripts

0	reference point
a	artery
adj, a	adjacent element of artery
adj, v	adjacent element of vein
air	ambient air
bl	blood
$bl\text{-}a$	artery blood
$bl\text{-}v$	vein blood
bl, a, adj	adjacent element of artery blood
bl, v, adj	adjacent element of vein blood
cr	core
$cr\text{-}artery$	exchange between core and artery
$cr\text{-}res$	respiration in core
$cr\text{-}sk$	exchange between core and skin
$cr\text{-}vein$	exchange between core and vein
cs	vasoconstriction
dl	vasodilatation
hy	hypothalamus
mrt	mean radiant temperature
$per, total$	total blood perfusion
sh	shiver
sk	skin
$sk\text{-}per$	skin perfusion blood flow
sw	sweat
$sweat$	sweating threshold
v	vein

which would lead to irrevocable burn injuries or life-threatening damages for human body if there are no appropriate protective measures. Jiang et al. [22] reported an integrated numerical simulator for thermal performance assessments of firefighters' protective clothing. The simulator included a CFD program to compute fire environment, and a one-dimensional model to compute the radiative and conductive heat transfer through the clothing and human skin, in which human was mainly treated as the heat receiving object, and it did not consider the human's self-adjustment functions under high temperature environments. Raimundo and Figueiredo [23] extended Stolwijk's thermoregulatory model to study personal protective clothing and safety of firefighters near a high intensity fire front. The model considered the human body divided into 22 segments, 4 layers (core, muscle, fat and skin), and the central blood compartment. But the model did not consider the relationship between the temperature rising in environments, and the human thermophysiological response. Therefore, it is necessary and important to develop the human bioheat model for high temperature environments to study human thermal response.

This paper presents a multi-segment human bioheat model extended from the model fitted for normal temperature to high temperature environments. This extended human bioheat model is built to simulate the human body thermal response under environments of temperature up to 48 °C. Higher temperature is not considered because there is a lack of information in the literature about the relationship between the temperature and the human thermophysiological response. Section 2 presents the human bioheat model details, and results and discussion are given in Section 3, followed by the forth section of conclusions.

2. An extended human bioheat model

A human bioheat model (named as the original model) based on Salloum's model [3] for normal temperature environments is firstly established, and then extended to high temperature environments considering the differences of the physiological responses and human thermal parameters [24]. In this model developed here, the human body with 170 cm height and 1.8305 m^2 surface of skin, is divided into 16 segments, i.e. head, chest, abdomen, pelvis, left and right upper arms, left and right forearms, left and right hands, left and right thighs, left and right calves, and left and right feet. Within each segment, the human body was separated into four layers: core, skin, artery and vein. The detailed parameters of each segment are shown in Table 1.

The physiological system of human body is divided into two parts according to Salloum's model [3]: one is "passive system" which describes the internal heat transfer and heat transfer between the human body and the environment. Another one is "active system" which describes the control and regulation of human body temperature by adjusting the heat exchange with the environment. It should be noted that the original model is the transient nude human body model to simulate the thermal behavior of the naked human body in normal temperature environments, and do not include a clothing model.

2.1. Passive system: energy balance equations

For each segment, the energy balance equation is written for each of the four layers (core, skin, artery and vein) after modification of Salloum's model [3] with the assumptions, shown in Fig. 1