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A transient three-dimensional heat transfer model of the human body [☆]

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ABSTRACT

The objective of this work is to develop an improved model of the human thermal system. The features included are important to solve real problems: 3D heat conduction, the use of elliptical cylinders to adequately approximate body geometry, the careful representation of tissues and important organs, and the flexibility of the computational implementation. Focus is on the passive system, which is composed by 15 cylindrical elements and it includes heat transfer between large arteries and veins. The results of thermal neutrality and transient simulations are in excellent agreement with experimental data, indicating that the model represents adequately the behavior of the human thermal system.

1. Introduction

The human thermal system is composed of the thermoregulatory and the passive system. The former is related to the physiological responses to changes in the thermal environment or activity level: vasodilatation or constriction, shivering, and sweating. The later includes heat conduction inside the body, heat transfer by convection because of flowing blood, and heat transfer between the body and the environment.

Several models of the human thermal system have been developed. One cylinder models — Fanger [1], Gagge et al. [2], Ferreira and Yanagihara [3] — can be used to predict global thermal comfort conditions, to investigate the sensitivity of a simulation to some parameters, and to test temperature regulatory strategies. All of them incorporate basic features, such as heat conduction in tissues, heat transfer between blood and tissue, metabolic heat generation, and heat transfer by convection, radiation, evaporation of sweat, and through respiration. Multi-segmented models — Wissler [4,5], Gordon et al. [6], Tikuisis et al. [7], Werner [8], Takemori et al. [9], Fiala et al. [10,11], Huizenga et al. [12], Tanabe et al. [13], Salloum et al. [14], Wan and Fan [15], and Al-Othmani et al. [16] — have more advanced applications, including evaluation of local thermal comfort and simulation of human physiological responses to cold water immersion. Werner and Buse [17] and Takemori et al. [9] considered 3D heat conduction.

Thermal comfort evaluation requires the simulation of asymmetric boundary conditions, which occur when there are sources of thermal radiation, air currents, or contact between part of the human body and a solid object. The aforementioned boundary conditions require the use of a 3D model, i.e., to consider 3D heat conduction inside the human body. Body geometry is usually represented by circular cylinders, each one representing a segment of the body. The use of circular cylinders results in elements with unrealistic lengths, feature incompatible with a 3D model. In this study, cylinders with elliptical cross section were used in order to achieve a better geometric representation of the human body.

2. Model description

2.1. Geometric and anatomic model

The global data of the anatomic model used [17] are height 1.76 m, weight 67 kg, surface 1.8 m^2, and volume 6.27×10^{-2} m^3. The human body was divided in 15 cylinders representing the head, neck, trunk, arms, forearms, hands, thighs, legs, and feet. The comparison presented in Table 1 shows that the use of cylinders with elliptical cross sections generates a model with realistic dimensions. The hand and trunk lengths in the model of Takemori et al. [9] are exaggerated because of their extensive superficial area. In the present model, the ellipse eccentricity accounts for this large area. The height obtained is 1.77 m.

The tissues considered were: skin, fat, muscle, bone, brain, viscera, lung, and heart. The choice was not arbitrary: (a) the skin was considered because its blood flow is variable, and it is dictated by the thermoregulatory system; (b) the fat was considered because it has the smallest thermal conductivity among the human tissues, behaving as a thermal insulation; (c) the muscle, because its blood flow and metabolism vary according to the physical activity and shivering level; (d) the bone, because its thermal properties and blood flow are very different from other tissues. Its thermal conductivity is the biggest and its specific heat, the smallest; (e) the lung, because its blood flow is approximately equal to the cardiac output and it has a small density; (f) the heart, because it has a high metabolic heat generation; (g) the brain, because it has a high metabolic heat generation and blood flow. Besides that, its temperature is considered to be an input to the regulatory system (the temperature of the hypothalamus pre-optic area to be more specific); and finally (h) the viscera, a homogeneous mixture of the following tissues — liver, kidney, stomach, gut, pancreas, spleen, bladder, and connective tissue — were considered because of their high metabolic heat generation and blood

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Nomenclature

a	major ellipse semi-axis (cm)
b	minor ellipse semi-axis (cm)
c	specific heat (J kg^{-1} K^{-1})
f_{cl}	ratio between the surface area of the clothed segment and the nude one
h	combined heat transfer coefficient (W m^{-2} K^{-1})
h_{av}	heat transfer coefficient between one big artery and vein (W K^{-1} $pair^{-1}$)
h_c	convective heat transfer coefficient (W m^{-2} K^{-1})
h_e	evaporative heat transfer coefficient (W m^{-2} Pa^{-1})
h_r	radiative heat transfer coefficient (W m^{-2} K^{-1})
k	thermal conductivity (W m^{-1} K^{-1})
L	cylinder length (cm)
m	mass (kg)
t	time (s)
v	air speed (m s^{-1})
w	skin wettedness
x	spatial coordinate (m), is equal to $\xi \cdot a \cdot \cos\eta$
y	spatial coordinate (m), is equal to $\xi \cdot b \cdot \sin\eta$
z	spatial coordinate (m), is equal to γ
A_s	superficial area (m^2)
CR	heat transfer flux by convection and radiation (W m^{-2})
E	heat transfer flux by evaporation (W m^{-2})
H_{av}	heat transfer coefficient between artery and vein reservoirs (W K^{-1})
J	Jacobian (m^2), is given by $x_\xi \cdot y_\eta - y_\xi \cdot x_\eta$
K	thermoregulatory system constant
M	metabolic heat generation per unit volume (W m^{-3})
P_w	partial water vapor pressure at the environment temperature (Pa)
$P_{w,sk}$	water vapor pressure at the skin surface temperature (Pa)
Q	heat lost (W)
R_{cl}	thermal resistance of cloth (W^{-1} m^2 K)
$R_{e,cl}$	resistance to evaporation imposed by clothes (W^{-1} m^2 Pa)
T	temperature (°C)
W	blood flow rate (m^3 s^{-1})

Greek symbols

Δ	variation
γ	spatial coordinate in the transformed space
η	spatial coordinate in the transformed space
ξ	spatial coordinate in the transformed space
ρ	tissue density (kg m^{-3})
ϕ	relative humidity of the air
ω_{bl}	tissue blood perfusion rate (m^3 m^{-3} s^{-1})

Subscripts

0	reference or set-point
ar	arterial
bl	blood
hy	hypothalamus
i	ith segment
in	
o	operative
re	rectal
sk	skin
sh	shivering
sw	sweat
ty	tympanic
ve	venous
w	water vapor

flow. Mean viscera and brain temperatures can represent rectal and hypothalamic temperature, respectively. The tissues thermal properties and physiological parameters used are presented in Table 2. The data were taken from Werner and Buse [17]. The arrangement of layers (Figs. 1–4) was based on human body cross-section photos [18]. The distribution in the neck is similar to the arm, and it is not represented here.

2.2. Heat transfer by conduction inside the body

The heat conduction equation with constant density and specific heat is given by:

$$\rho \cdot c \cdot (T)_t = (k \cdot T_x)_x + \left(k \cdot T_y\right)_y + (k \cdot T_z)_z + M \tag{1}$$

where ρ is the tissue density, c is the specific heat, T is the temperature, k is the thermal conductivity; x, y, z, and t denote derivation with respect to x, y, z, and time; M is the internal heat generation.

The numerical solution of Eq. (1) can be achieved using a coordinate transformation [19], which transforms an elliptical cylinder in the Cartesian space into a parallelepiped in the new coordinate system, with axes ξ, η, and γ. Eq. (1), rewritten in the new coordinate system, is given by:

$$J \cdot \rho \cdot c \cdot T_t = \left[\frac{k \cdot \left(x_\eta^2 + y_\eta^2\right)}{J} \cdot T_\xi - \frac{k \cdot \left(x_\xi \cdot x_\eta + y_\xi \cdot y_\eta\right)}{J} \cdot T_\eta\right]_\xi + \left[\frac{k \cdot \left(x_\xi^2 + y_\xi^2\right)}{J} \cdot T_\xi - \frac{k \cdot \left(x_\xi \cdot x_\eta + y_\xi \cdot y_\eta\right)}{J} \cdot T_\xi\right]_\xi + J \cdot \left[k \cdot T_\gamma\right]_\gamma + J \cdot M \tag{2}$$

where J is the Jacobian of the transformation.

Assuming symmetrical and uniform environments the heat transfer by convection and radiation in each element can be calculated by:

$$CR = \frac{T_{sk} - T_o}{R_{cl} + \frac{1}{f_{cl} \cdot h}} \tag{3}$$

where CR is the heat transfer by convection and radiation, T_{sk} and T_o are the superficial skin temperature and the operative temperature, R_{cl} is the thermal resistance of the cloth, f_{cl} is the ratio between the surface area of the clothed segment and the nude one, and h is the combined heat transfer (convection + radiation) coefficient in the element. The heat transfer coefficients were taken from the experiments of Dear et al. [20]. The evaporative coefficient (Eq. (7)) was calculated from the convective coefficient using the analogy between heat and mass transfer. The coefficients are presented in Table 3 and compared with experimental data. The cloth was modeled as an additional heat and mass transfer resistance [21].

The heat transfer by evaporation at the surface of each element can be calculated by:

$$E = w \cdot \frac{P_{w,sk} - \phi_a . P_{w,a}}{R_{e,cl} + \frac{1}{f_{cl} \cdot h_e}} \tag{4}$$

where E is the heat transferred by evaporation, $P_{w,sk}$ is the water vapor pressure at the skin surface temperature, w is the skin wettedness (varies from 0.06, when there is only water diffusion, to 1.0, when the skin is completely wetted by sweat), ϕ is the relative humidity of the air;