Project Title:

Development of whole body vascular plexus simulator

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1 INTRODUCTION

The cardiovascular system (CVS) plays a crucial role in human thermoregulation. José [1] pointed out that vascular convective heat transfer is the most important heat-exchange pathway inside the body, and over 50% of the heat flow in body tissues is transferred via the flowing blood [2]. Cold stress or heat stress (caused by external thermal environment or exercise) would also result in cardiovascular strains, such as heat stress may result in significant cardiovascular adjustments that are necessary to maintain adequate cardiac output (CO) and skin blood flow through adjusting heart rate, cardiac contractility, and peripheral vascular resistance to maintain internal temperature within a narrow range under different heat-stressed conditions [3].

Over the past several decades, a large number of human thermoregulation models have been developed for different purposes [4-9]. To the best of our knowledge, however, there are no studies have taken into account a complete closed-loop CVS except the one developed by zhang et al. [10], in which the CVS is represented via an integrated closed-loop lumped-parameter cardiovascular model. The objective of this study is to evaluate the cardiovascular function in human thermoregulation. We incorporate a closed-loop multiscale cardiovascular model into a multi-segment integrated thermoregulation model to compute the convective heat exchange between the CVS and surrounding core tissues, and the blood perfusion within core tissues for the first time.

2 METHODOLOGY

The presented thermoregulation model consists of two parts: the controlled system and controlling system. The controlled system includes a multi-segment integrated thermal model of the human body and a closed-loop multi-scale thermo-fluid model of the CVS. The controlling system is the so-called physiological thermoregulatory system, which can regulate body temperature through sweating, shivering, peripheral vasomotion, and CVS adjustments.

2.1 Multi-segment integrated bio-heat model of the human body

A total of six cylindrical elements is used to represent the thermal characteristics of the whole human body, which include head, trunk, right/left upper extremity, and right/left lower extremity, as shown in figure 1a. And each element is subdivided into two layers (core and skin) with uniform thermal characteristic and temperature, the details of a two-layered model for one element and its interaction with surrounding environment are shown in figure 1b. The heat exchange between two adjacent two elements is via the flowing blood, and the conductive heat exchange is ignored.

The energy balance equation for core tissue is expressed as

$$\begin{aligned} C_{cr}\frac{dT_{cr}}{dt} &= M - W - \alpha Q_{res} - Q_{cr\_sk} + \dot{m}_{perfusion}\cdot c_b\cdot(T_{art}-T_{cr}) \\ &- \dot{m}_{sk}\cdot c_b\cdot(T_{cr}-T_{sk}) + \sum_{arteries}\left[h_{ves}\cdot A_{artery}\right]\cdot\left[T_{art}-T_{cr}\right] \\ &+ \sum_{veins}\left[h_{ves}\cdot A_{vein}\right]\cdot\left[T_{vein}-T_{cr}\right] \end{aligned} \quad (1)$$

where C_{cr} is the thermal capacity of the core tissue, T_{cr} is core temperature, M is core metabolic heat production, M is external work, Q_{res} is respiratory heat loss, $Q_{cr\text{-}sk}$ is conductive heat exchange between the core and skin, $\dot{m}_{perfusion}$ is the total perfusion rate of blood entering core tissue, c_b is blood specific heat, $\dot{m}_{sk}$ is skin blood flow, T_{sk} is skin temperature, h_{ves} is the pulsating heat convection coefficient of the blood flow, A_{artery}/A_{vein} is surface area of artery/vein vessel, T_{art}/T_{vein} is temperature of artery/vein blood.

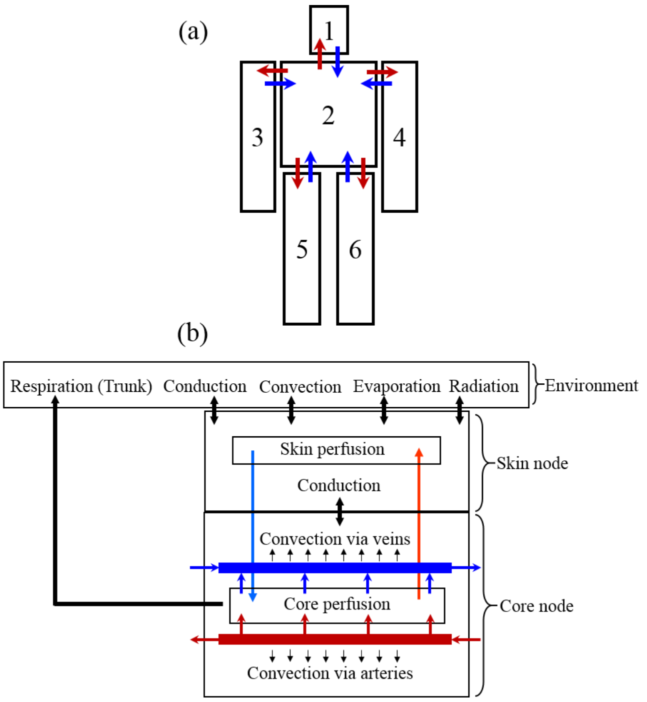

Figure 1. Schematic representations of (a) six-cylinder model of the human body (1, head; 2, trunk; 3, right upper extremity; 4, left upper extremity; 5, right lower extremity; 6, right lower extremity) and (b) the core and skin nodes and their interactions with CVS and external thermal environments.

Skin is the primary mode by which exchange heat with the environment via convection, evaporation and radiation. Therefore, the energy balance equation for skin can be expressed as

$$C_{sk}\frac{dT_{sk}}{dt} = Q_{cr\_sk} - Q_c - Q_r - Q_e + \dot{m}_{sk}\cdot c_b \cdot (T_{cr} - T_{sk}), \quad (2)$$

where C_{sk} is thermal capacity of skin, Q_c/Q_r is the convective/radiative heat exchange between skin and environment, and Q_e is the evaporative heat loss from skin.

2.2 Closed-loop multi-scale cardiovascular model

The cardiovascular model used in this study is composed of detailed 0D lumped-parameter descriptions of the four heart chambers and peripheral vascular beds, and 1D descriptions of the major systemic and pulmonary circulation, as shown in figure 2. The detailed geometrical data of 1D cardiovascular network and connections between terminal arteries and veins are given in Mynard and Smolich [11].

The 1D governing equations for blood flow in larger arteries and veins can be represented as follows [11]

$$\frac{\partial A}{\partial t} + \frac{\partial Au}{\partial x} = 0 \quad (3)$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + \frac{1}{\rho}\frac{\partial p}{\partial x} = -\frac{22\pi\mu}{\rho}\frac{u}{A} \quad (4)$$

where A is the cross-sectional area of the vessel, t is the time, x is the axial coordinate along the vessel, u is the average axial velocity, p the average internal pressure over the cross section, μ is the blood viscosity (0.035 poise), ρ is the density of blood (1050 Kg/m^3).

The constitutive equation used to describe pressure-area relation of the arteries and veins is

$$p - p_{ext} = \frac{2\rho c_0^2}{b}\left[\left(\frac{A}{A_0}\right)^{b/2} - 1\right] + P_0 \quad (5)$$

where p_{ext} is the external pressure, c_0 is the reference pulse wave velocity, b is a constant used to determine the shape of the pressure-area relationship, A_0 is the reference cross-sectional area at the reference pressure P_0. The detailed methods used to determine c_0 and b can be found in [5].

Here we assume that the entire CVS are all distributed within the core tissues, therefore the energy balance equation for 1D blood flow is expressed as

$$\frac{\partial T_b}{\partial t} + \frac{q}{A}\frac{\partial T_b}{\partial x} = -\frac{h_{ves}\cdot A_s}{c_b\cdot\rho\cdot A}(T_b - T_{cr}) \quad (6)$$

where T_b is the blood temperature, q is the blood flow rate, h_{ves} is the heat transfer coefficient of the blood vessel, A_s is surface area of the blood vessel per unit.

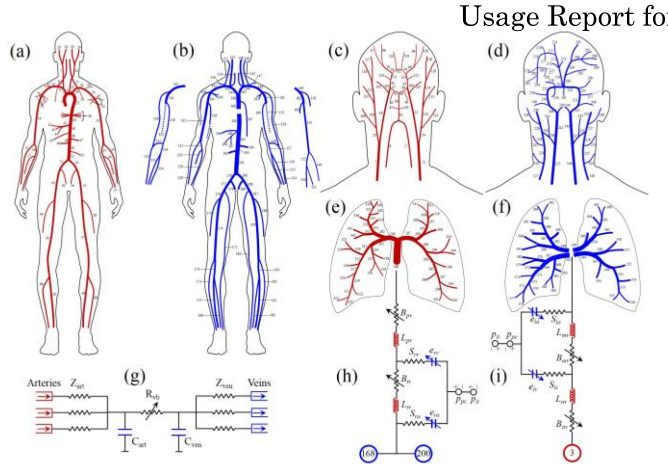

Figure 2. Schematic representation of the closed-loop multiscale cardiovascular model, which consists of 1D representations of (a) systemic arteries, (b) systemic veins, (c) cerebral arteries, (d) cerebral veins, (e) pulmonary arteries, (f) pulmonary veins, and 0D lumped-parameter representations of (g) peripheral vascular bed, (h) right heat, (i) left heart.

2.3 Physiological thermoregulatory system

The basic processes of thermoregulation can be summarized as follows: when body temperatures increase above the threshold settings (37℃), the temperature signals will initiate vasodilation and sweating to liberate heat from the body; When body temperatures fall below the threshold settings, the temperature difference will initiate vasoconstriction and shivering to constrain heat within body. The detailed description of the thermoregulatory mechanisms used in our model, such as shivering, sweating, vasomotion, heart rate, is given in zhang et al. [10].

The code of this multiscale thermoregulatory system is written in Fortran language and runs on the HOKUSAI GreatWave supercomputer of RIKEN.

3 RESULTS AND CONCLUSIONS

Figure 3 shows comparison of the mean body (core and skin) temperatures between model predictions and *in vivo* measurements. The results suggest that the predicted results agree well with the *in vivo* measured results from Munir et al. [12]. The simulation results show that the developed thermoregulation model is validated to be capable of predicting human transient thermal responses and cardiovascular function during varying thermal environments.

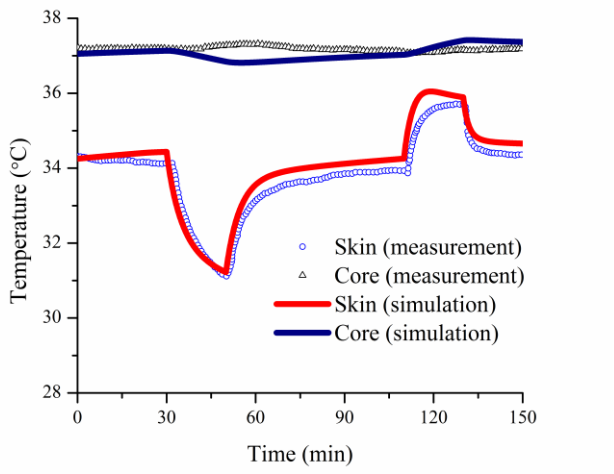

Figure 3. Comparisons between predicted and measured mean body temperatures (core and skin).

The future tasks will be focused on the following aspects:

1) Evaluation of the effects of cardiovascular parameters on human thermal response, such as heart rate, left ventricle contractility, and total peripheral vascular resistance.
2) Evaluation of the effects of cardiovascular aging on human hemodynamics and thermal responses
3) Evaluation of the effects of hypertension on human thermal responses.

As one of the ultimate clinical applications, we aim to provide a useful clinical tool, through incorporating a recently developed anesthesia model into the multi-scale CVS-thermoregulation model, to evaluate individualized human thermal responses for the anesthetized patients during surgery environment.

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Fiscal Year 2016 List of Publications Resulting from the Use of the supercomputer

[Publication]

Zhang, X., Noda, S., Himeno, R., & Liu, H.: Gravitational effects on global hemodynamics at different postures: A closed-loop multi-scale mathematical analysis, Acta Mechanica Sinica, 2016. DOI 10.1007/s10409-016-0621-z (accepted)