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A simplified thermoregulation model of the human body in warm conditions

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A B S T R A C T

Thermoregulation models of the human body have been widely used in thermal comfort studies. The existing models are complicated and not fully verified for application in China. This paper presents a simplified thermoregulation model which has been statistically validated by the predicted and measured mean skin temperature in warm environments, including 21 typical conditions with 400 Chinese subjects. This model comprises three parts: i) the physical model; ii) the controlled system; and iii) the controlling system, and considers three key questions formerly ignored by the existing models including: a) the evaporation efficiency of regulatory sweat; b) the proportional relation of total skin blood flow and total heat loss by regulatory sweating against body surface area; and c) discrepancies in the mean skin temperatures by gender. The developed model has been validated to be within the 95% confidence interval of the population mean skin temperature in three cases.

1. Introduction

The thermal interaction of the human body with the environment involves two processes: i) the heat transfer between the human body and the thermal environment, simultaneously including radiation, convection, conduction, evaporation and respiration; and ii) the self-regulation function of the human body which responds to varied thermal environments, such as vasoconstriction, vasodilation, shivering and sweating (Cheng et al., 2012). Thermoregulation models of the human body are developed to simulate these two processes of interaction and predict the human thermal response under different thermal conditions and have been widely used in the field of physiology or thermal comfort studies (Parsons, 2014). An accurate thermoregulation model will help improve the accuracy of the current thermal comfort prediction models, and provide a basic theoretical analysis of the accuracy of the various models in application (De Giuli et al., 2014; Holopainen et al., 2014).

The simplified Gagge's 2-node model of thermoregulation (Gagge et al., 1971) is one of the most popular models in the field of thermal comfort study. Moreover, various complex thermoregulation models have been further developed by improving the modelling of body segmentation, particularly for heat insulation (Arezes et al., 2013), thermoregulatory systems and heat transfer (Fiala et al., 2001; Munir et al., 2009; Stolwijk, 1971; Werner and Webb, 1993; Xu and Werner, 1997), considering individual body characteristics (Takada et al., 2009; Zhang et al., 2001), and increasing the number of body segments to obtain a higher resolution temperature distribution on the skin surface (Huizenga et al., 2001; Tanabe et al., 2002).

These models are mostly developed based on European or American populations; however, their accuracy lacks effective validation (Yang et al., 2015a). There is little strong evidence in the existing research to show that existing models are applicable to the Chinese population. Thermal comfort prediction for the Chinese people still remains in an early research stage which is largely based on the modification of the traditional models but is still lacking systematic analysis (Zhou et al., 2013, 2014). In this context, this paper aims to i) validate the predictive accuracy of the classic Two-Node model for the Chinese population; and ii) develop and validate a new simplified model based on the laboratory

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experiments.

The mean skin temperature was used for the validation of the developed model. In the existing studies, skin temperature has been demonstrated to be strongly related to the thermal interaction between the human body and the thermal environment, which is also an important indicator of thermal comfort (Parsons, 2014). It has been successfully used to validate increasingly complex and sophisticated predictive models for thermoregulatory responses, and to build thermal sensation models.

The systems predicting the interaction between people and their environment are complex (Andrew Thatcher, 2016). Here, the developed model shows advantages over many other existing models. The individual differences in human thermal responses are caused by some characteristics which can be quantitatively defined (age, height, weight, etc.), but may also contains some of the potential differences which are not so easily described such as the property of each layer of the body including core composition, muscle composition, fat composition and skin composition respectively. The mean basal metabolic rate of the Chinese population is re-measured in this study. It has allowed the simplification of the human body abstraction as a cylinder with its specific geometric dimensions and heat transfer direction, which cannot be provided by simply adjusting the parameters of existing models for the Chinese population. Meanwhile, the introduction of a cylinder model and the development of control plates make it more convenient and accurate in application compared to other models (Yang et al., 2015b).

2. Description of the new model

The proposed model consists of three parts: the physical model of the human body, the controlled system and the controlling system.

2.1. Physical model of the human body

In this physical model, the human body is abstracted as a cylinder consisting of four concentric layers: the core, muscle, fat and skin. A central pool of blood delivers the arterial blood to the capillaries and tissues in each layer, and meantime the blood flows back to the central pool through the veins. The schematic diagram of this physical model is shown in Fig. 1. Assuming that the physical characteristics in each layer are uniform, the physical parameters of each layer are recalculated from the data of reference (Gordon et al., 1976; Stolwijk, 1971) and listed in Table 1.

Considering the size of the physical model, the height dimension is far greater than the radius dimension. In the simulation, heat is only supposed to be transferred in a radial direction. Radial dependency of temperature is calculated in the model. In this paper, abbreviations with subscripts of $i = 1,2,3,4$ represent the layers of core, muscle, fat and skin respectively. The subscripts b and cl represent the central blood and clothing nodes respectively.

The geometric characteristics of the physical model can be calculated from the basic information of the human body (gender, height, weight and body fat percentage). The surface area A (m^2) of a Chinese human body can be obtained by Equations (1) and (2) for male and female subjects (Wang, 1994). The length of the cylinder L (m) and the external radius of layer i (which is denoted by $r_{s,i}$(m)) can be calculated by Equations (5) and (6) respectively.

$$A = 0.0057H + 0.0121W + 0.0882 \text{ (for males)} \quad (1)$$

$$A = 0.0073H + 0.0127W - 0.2106 \text{ (for females)} \quad (2)$$

$$m_i = \alpha_{m,i} W \quad (3)$$

$$V_i = m_i / \rho_i \quad (4)$$

$$L = A^2 \bigg/ \left(4\pi \sum_{i=1}^{4} V_i\right) \quad (5)$$

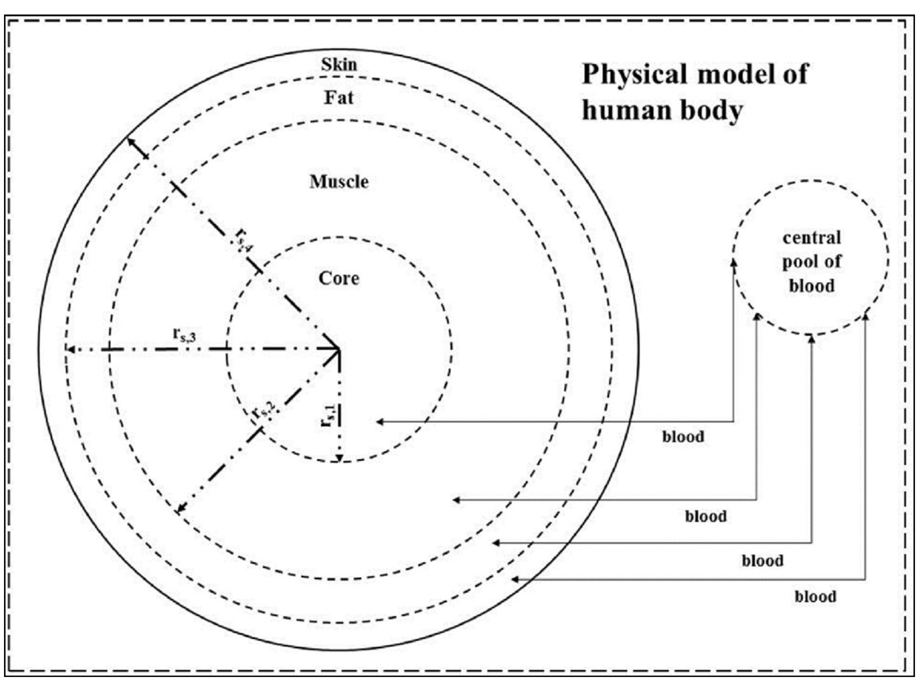

Fig. 1. The schematic diagram of the physical model of the human body.