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An individualized human thermoregulation model for Chinese adults

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ABSTRACT

An individualized human thermoregulation model for the prediction of skin temperature was established for Chinese adults. Considering the differences in body size and composition between western and Chinese people, a standard Chinese model was built based on the anthropometric and physiological data of Chinese people, and then it was individualized with four parameters including height, weight, age and sex. Sensitivity analysis revealed that the difference in height and weight could result in a variance of 1.2 °C in calculated mean skin temperature. Both the standard and the individualized Chinese model were tested with the experimental data of Chinese adults under different ambient conditions. Significant improvements were found in mean and local skin temperatures predicted by the standard Chinese model compared to the standard Fiala model. The maximum bias of the predicted mean skin temperature decreased from 0.79 °C to 0.48 °C, and that of local skin temperature changed from 2.11 °C to 1.46 °C. Further significant improvements were found when comparing the individualized Chinese model with the standard Chinese model. For the individualized model, the mean bias of mean skin temperature between prediction and measurement ranged from 0.20 °C to 0.38 °C, and the mean bias as well as its standard deviation of most local skin temperature was less than 1 °C. Prediction accuracy was also validated in the extensive comparison with other researchers' experiments on Chinese subjects. Prediction accuracy of Chinese adults' skin temperature could be improved via the modification and individualization of thermoregulation model with Chinese physiological characteristics.

1. Introduction

Thermal comfort, associated with thermal sensation is one of the most important performance indicators for Heating, Ventilation and Air Conditioning (HVAC) systems. Currently thermal comfort criteria imbedded in standards ASHRAE Standard 55 and ISO Standard 7730 are based on the predicted mean vote (PMV) model [1], focusing on minimizing the percentage of people dissatisfied [2]. However, good agreement between PMV model and experiment was particularly found for uniform and steady-state environmental conditions [3]. On the other hand, thermal comfort may be achieved more energy-efficiently in non-uniform thermal environments. The distributions of skin temperature in such environments are different according to the region of human body, so developing a model to evaluate thermal comfort in asymmetrical environments or transient conditions has being a hotspot of recent study [4]. Furthermore, accurate models for predicting thermal comfort not only can be beneficial in avoiding malperformance in the use phase of a building [5], but also especially valuable for predicting responses under conditions that cannot be tested ethically using human volunteers [6].

Thermal comfort model consist of physiological (thermoregulation in human body) and psychological model. Thermoregulation model, for the purpose of calculating skin temperature, is the first step of developing thermal comfort model. For practical utilization in design and evaluation of building environment, the calculated results of the model must agree well with the experimental measurements on human body. However, the thermoregulatory responses of different individuals are different, which makes the comparison impossible without a methodology to express individual difference in the model itself [7]. There were two approaches to deal with the problem of individual differences in thermoregulation model; one is from the passive systems of the body [8], such as thermal capacitance, thermal resistance, or surface area related to heat transfer, and the other is from the controlling systems of the body, such as regulatory sweating or skin blood flow. A population-based dynamic human thermoregulation model built by Havenith [9] expanded with control equations incorporating several individual characteristics such as body surface area, mass, and body fat percentage. Although the prediction of individual heat strain had been improved by the model, a substantial part of differences in individual responses remain unexplained. Zhang et al. [10]

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developed a model called "body builder" to translate descriptive data of an individual into a set of physiological parameters, which were then incorporated into a human thermoregulation model. Their simulated result only showed that the normal body fat group had lower skin temperature but higher rectal temperature than the lean group, yet a future work including more validations with experiments needs to be done. Study carried out by van Marken Lichtenbelt et al. [11] shows that on a group level predictions of skin temperatures can be improved when adopting individualized body characteristics and measured metabolic rate, but the predictions on an individual level were not improved. Fiala model [12] was individualized by Lichtenbelt et al. with respect to anthropometrics, body fat, and metabolic rate using the physiological data of Dutchman [13]; predictions of the individualized model were improved but a significant error remained. Furthermore this adapted model was used to predict thermal sensation and comfort in building environment [5].

Individual difference has been considered in human thermoregulation models, but ethnic difference which is closely related to the establishment of domestic building standard has received few concerns, although study indicates there are significant differences in body size between western and eastern people [14]. In China building energy consumption that largely depends on the operation of HVAC system is increasing rapidly [15,16], to balance energy consuming and thermal comfort of Chinese people, a precise model capable to predict thermal response of Chinese people is in urgent need. Thus in this study, a thermoregulation model was established for Chinese people and then individualized with four descriptive parameters of human body: height, weight, sex and age.

2. Establishment of Chinese model

2.1. Standard Chinese model

Fiala thermoregulation model [12], which has been proved to be reasonable accurate [17,18], was adopted in this study after extensive evaluation. Fiala model consists of two interacting systems: the controlled passive system and the controlling active system. In the passive system, as shown in Fig. 1 [12], the human body was subdivided into 14 segments, using cylinders stand for the trunk and extremities and a cylinder combined with sphere to represent for the face and head. Most of the body elements were divided into four layers (core, muscle, fat and skin from the inside to outside) with three sectors (anterior, posterior and inferior). Convection, radiation (long-wave and short-wave) and evaporation were considered in the heat exchange between human and environment, and heat changes via respiration was also included [20]. In the active system, central nervous system (CNS) accounts for overall changes in muscle metabolism by shivering, skin blood flow by vasodilatation and vasoconstriction, and skin moisture excretion by sweating. Local autonomic regulation was employed to modify local sweat rates, local blood flows, and tissue metabolic rates [21]. Former studies indicated that major physiological difference between ethnicity and individuals lies in the passive system [11,22].

A standard Chinese model was established based on the Fiala model with modifications in body size and composition. Human dimension of Chinese adults specified in the national standard of China [19] were employed for the establishment of the standard Chinese model. Considering the difference on body size between sex, independent model for man and woman were developed. Skin surface area (A_{sk}) of standard Chinese model was derived from former experiment researches [23,24]. Thermophysiological parameters such as body fat percent (BF%) value for the standard Chinese model were obtained from the research of Deurenberg [14], basal metabolic rate (BMR) value from the research of Liu [25] and cardiac output (CO) was from the physiological research on Chinese [26]. Comparison on human dimension and thermophysiological parameters between Chinese and Fiala model were shown in Table 1. The weight of standard Chinese model was 19.1% lower than standard Fiala model, which leads to relatively lower value in A_{sk} and BMR of a standard Chinese man. Body size of Chinese woman was even smaller than that specified in the

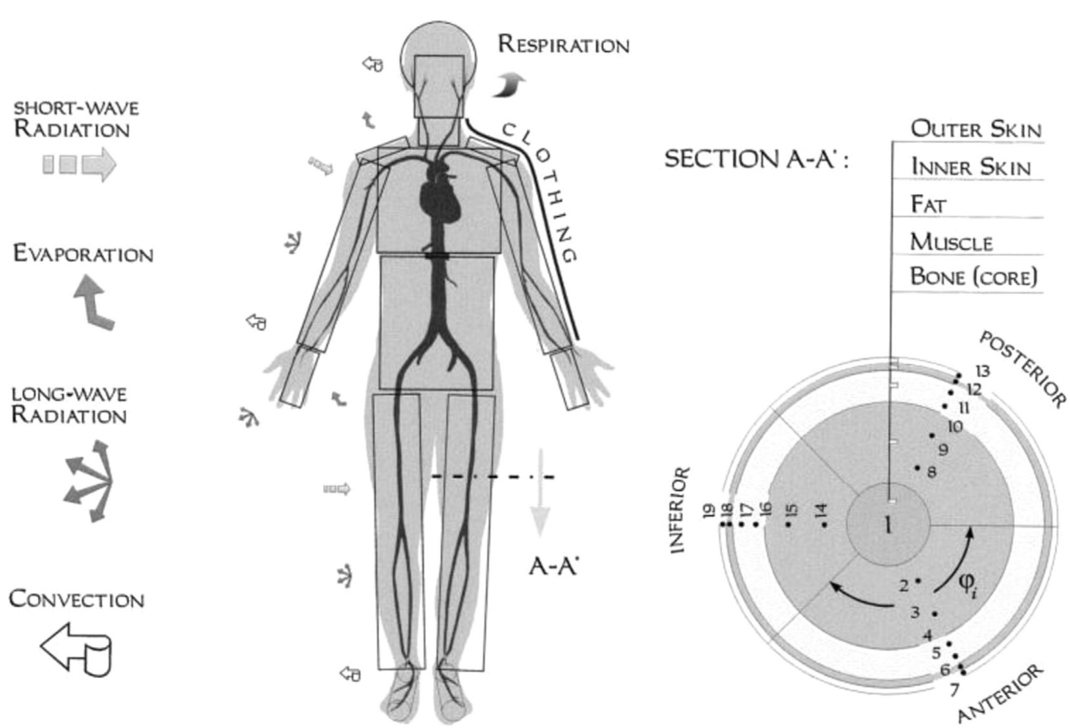

Fig. 1. Schematic diagram of the passive system in Fiala model.