

A NEW HUMAN THERMAL MODEL

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INTRODUCTION

Mathematical human thermal models serve important functions, both theoretical and practical. They allow one to describe complex interactions between basic physiological functions, such as vasomotor responses to thermal stress and exercise, sweating, and shivering. They also allow one to evaluate in a rational manner the effect of clothing properties, exercise, and ambient conditions on human performance.

The purpose of this paper is to describe a model developed recently by the author. Although it is similar to previously developed models, it differs in several important ways. It probably resembles most closely the model developed in 1999 by Fiala, et al. (3, 4), in that both models represent the human form as a set of right-circular cylinders in which physical properties and temperature vary as functions of radial and angular position and time. Both models take as their starting points the heat conduction equation proposed by Pennes in 1948 (8). Since longitudinal conduction of heat is neglected in both models, transport of heat between major elements is effected only by arterial and venous blood flow. The two models differ in the way they treat heat conduction in the θ -direction, which is probably not significant, and in the way they define physiological functions, which could be significant. The models also differ in the way clothing and ambient conditions are described.

Human thermal models like those developed by Fiala, et al. and the author are complex computer programs that typically involve over 4,000 lines of code. While that number is small compared to the millions of lines of code involved in computer games and Windows, it is still large enough to permit significant differences between programs. Since various aspects of human thermal models may interact in ways that are not intuitively obvious, it can be worthwhile to compare the properties of independently constructed models.

METHODS

Human geometry is represented by the set of 21 right-circular shown in Fig. 1 – two for the head, three for the torso, and four for each arm and leg. Superimposed on each element is a two-dimensional (r,θ) grid with 15 radial nodes and 12 angular nodes as represented in Fig. 2. Six additional cylindrical shells external to the body are available

to model clothing. An alternating direction implicit method is used to generate numerical solutions for the transient heat conduction equation.

Associated with each node are the tissue temperature, density, specific heat, thermal conductivity, metabolic rate, and blood perfusion rate. Mass and energy balances for arterial and venous streams are defined for each element. Environmental conditions are specified at each skin node in terms of the thickness, thermal conductivity and water permeability of the garment covering clothed areas, and the temperature and heat transfer coefficient of ambient air. This approach allows one to describe human anatomical and physiological features with reasonable accuracy while still computing with good speed. A six-hour real-time simulation requires less than two minutes on a 1.8 GHz processor.

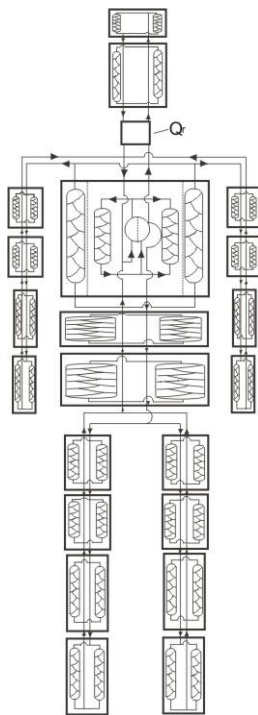


Figure 1. Twenty-one element human thermal model.

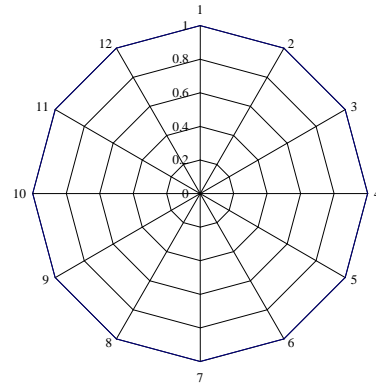


Figure 2. Twelve angular positions at which temperatures are computed. Not shown some of the 15 radial nodes located along the radius vectors.

An important difference between this model and other models is that physiological control functions (for example, control of skin blood flow) are defined in terms of the results of stand-alone physiological studies, and not simply to achieve good agreement between computed and measured responses to exercise and thermal stress. For example, one of the more complex aspects of human thermal regulation is control of skin blood flow, which has been studied extensively by physiologists for at least 70 years. A comprehensive review of those studies yielded a control algorithm that defines local skin blood flow in terms of central blood temperature, local and mean skin temperature, posture, and intensity of exercise (11). A similar approach was used to define control functions for sweating and shivering, although, unfortunately, the amount of empirical

information available is not as extensive as for skin blood flow. The perfusion rate of active muscle is defined in terms of metabolic requirements; vasoconstriction is assumed to occur in resting muscle during exposure to cold.

A somewhat unique aspect of the model is that assignment of regional subcutaneous fat thickness is based on NMR data for men and women reported by Hayes, et al. (5), instead of on thicknesses measured with calipers. Several studies have shown that caliper measurements typically underestimate the true fat thickness by as much as 50 percent (6). That difference can be significant when the model is used to analyze human behavior in the cold.

Clothing properties defined individually for the 12 angular sectors on each major element change as sweat accumulates in the garment. In addition, the model accounts for enhanced heat loss owing to condensation within a garment that has a relatively impervious outer shell, when the ambient temperature is low (12).

A new algorithm has been developed for computing regional heat transfer coefficients during exercise. That algorithm defines a characteristic velocity for free walking, treadmill walking, and cycling, and then defines regional velocities (for example, the velocity of the thigh or upper arm) in terms of the characteristic velocity. Those relationships were derived primarily from the data of Nishi and Gagge (7) who computed velocities from the rate of sublimation of naphthalene spheres. Relationships between regional velocities and convective heat transfer coefficients were based on the manikin studies of deDear, et al. (1), and Qian and Fan (2, 9).

RESULTS

The model has been validated by comparing computed results with experimental data reported by various investigators. Observations made in the Pierce Foundation chamber at Yale University are particularly valuable because continuous measurement of subject weight provided a complete record of the whole-body evaporative cooling rate (10). Shown in Figs.3 and 4 are esophageal and mean skin temperatures during cycling at 25, 50, and 75 percent of the subjects' maximal rate of oxygen consumption. Results for two ambient temperatures, 10 and 30 °C, are shown. Computed temperatures for 20 °C (not shown) and 30 °C were in good agreement with measured values. Computed mean skin temperatures for 10 °C were significantly lower than measured values during the two higher intensities of exercise. An analysis of computed results indicates that the discrepancy is attributable to strong evaporative cooling driven by elevated central temperature, even though the skin temperature is low. The fact that computed and measured rates of whole-body evaporative cooling are comparable suggests that the problem is excessive cutaneous vasoconstriction, not excessive sweating. However, that is an open question to be investigated further.

CONCLUSIONS

Like any human thermal model, the model described in this paper needs to be validated for specific applications by comparing computed values with corresponding

measured values before it is used analyze new conditions. Nevertheless, when used properly, our new model can be used to analyze human response to exercise and thermal stress under various conditions.

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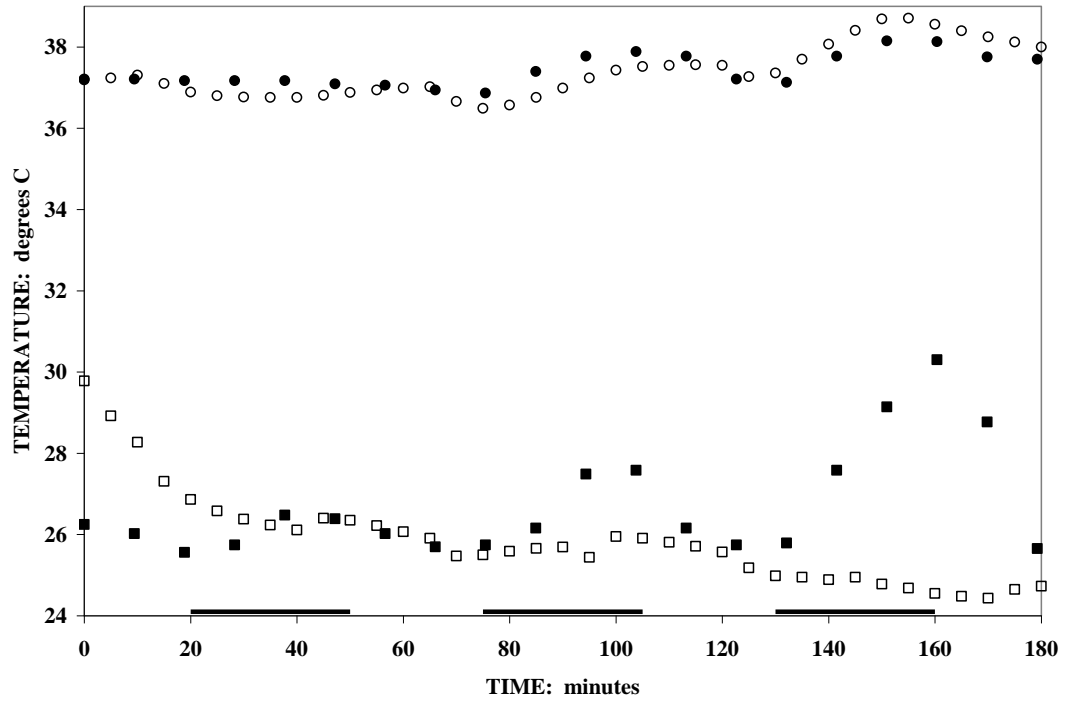


Figure 3. Measured (●, ■) and computed (○, □) esophageal and mean skin temperatures for a lightly clothed subject during cycling exercise in 10 °C ambient air. Horizontal bars indicate periods of exercise.

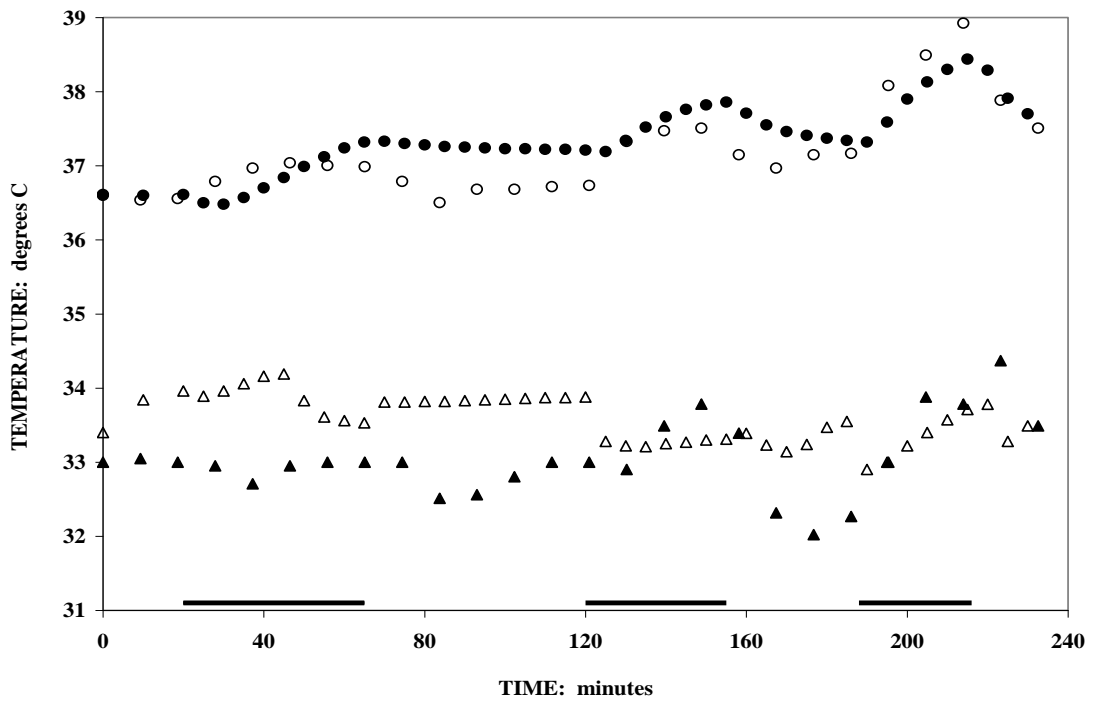


Figure 4. Measured (●, ■) and computed (○, □) esophageal and mean skin temperatures for a lightly clothed subject during cycling exercise in 30 °C ambient air.

