Title
A model of human physiology and comfort for assessing complex thermal environments

Authors
Huizenga, Charlie
Zhang, Hui, Ph.D
Arens, Edward A

Publication Date
2001

DOI
DOI: 10.1016/S0360-1323(00)00061-5

PERGAMON

Building and Environment 36 (2001) 691–699

BUILDING AND ENVIRONMENT

www.elsevier.com/locate/buildenv

A model of human physiology and comfort for assessing complex thermal environments

Charlie Huizenga *, Zhang Hui, Edward Arens

Center for Environmental Design Research, University of California, Berkeley, CA 94720-1839, USA

Abstract

The Berkeley Comfort Model is based on the Stolwijk model of human thermal regulation but includes several significant improvements. Our new model allows an unlimited body segments (compared to six in the Stolwijk model). Each segment is modeled as four body layers (core, muscle, fat, and skin tissues) and a clothing layer. Physiological mechanisms such as vasodilation, vasoconstriction, sweating, and metabolic heat production are explicitly considered. Convection, conduction (such as to a car seat or other surface in contact with any part of the body) and radiation between the body and the environment are treated independently. The model is capable of predicting human physiological response to transient, non-uniform thermal environments. This paper describes the physiological algorithms as well as the implementation of the model.

Keywords: Thermal comfort; Thermoregulation; Human physiology; Computer simulation

1. Introduction

Stolwijk's 25-node model of thermoregulation [1] set out the fundamental concept, algorithm, physical constants and physiological control subsystems for many contemporary multinode models [2]. The Berkeley Comfort Model is based on the Stolwijk model as well as on work by Tanabe in Japan [3], but includes several significant improvements over the Stolwijk model. The Stolwijk model is based on six body segments: head, torso, arms, hands, legs, and feet. The Berkeley model can simulate an arbitrary number of segments. In most applications, we use 16 body segments corresponding to the Berkeley segmented thermal manikin [4]. Each of these segments consists of four body layers (core, muscle, fat, and skin tissues) and a clothing layer. A separate series of nodes represent blood and provide for convective heat transfer between segments and tissue nodes. The model computes heat transfer between each node using a standard finite-differencing algorithm with variable time-stepping to optimize computational resources while preserving numerical stability.

We use a series of discrete "phases" of variable length to simulate almost any sequential combination of environmental, clothing and metabolic conditions. Effects of transient and spatially asymmetric conditions that are completely lost in whole-body models such as the two-node PMV model can be predicted by the model. An example simulation might be a person walking from an air-conditioned building to hot summer outdoor conditions and then getting into a car that has been sitting in the sun, turning on the air-conditioning and driving as the car begins to cool off. Applications include evaluating thermal comfort in spaces with asymmetric or transient thermal environments, including buildings, automobiles, or outdoors.

2. Model improvements

The following improvements have been made over the Stolwijk model:

- Increase in number of body segments from six to unlimited.
- Improved blood flow model, including counter flow heat exchange in the limbs, and modified blood perfusion from vessels to tissues.
- Addition of a clothing node to model both heat and moisture capacitance.
- Addition of heat transfer by conduction to surfaces in contact with the body.

* Corresponding author.
E-mail address: huizenga@uclink.berkeley.edu (C. Huizenga).

0360-1323/01/$ - see front matter
PII: S0360-1323(00)00061-5

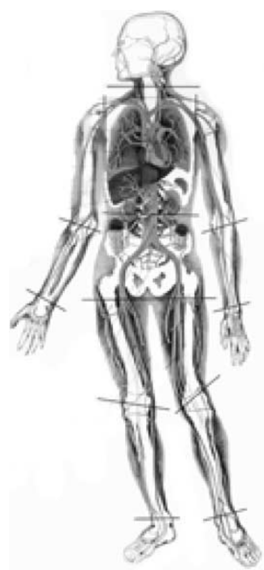

Fig. 1. Typical segmentation used in the model are: head, chest, back, pelvis, right and left upper arms, right and left lower arms, right and left hands, right and left thighs, right and left lower legs, and right and left feet.

- Improved convection and radiation heat transfer coefficients.
- Explicit radiation heat transfer calculation using angle factors.
- Addition of a radiation heat flux model (e.g. sunlight striking the body).

Segmentation: The model structure can accommodate an arbitrary number of body segments. In environments where there are large local variations in temperature or heat flux, a very fine segmentation can be used. For developing the model, we used 16 segments (Fig. 1) corresponding directly to those of the UC Berkeley segmented thermal manikin. The manikin can accurately measure heat transfer coefficients and clothing insulation values for individual body parts, and we can then use these data directly in our comfort model. The manikin measures heat flux to the environment for each segment, providing valuable data for validating the model.

Improved blood flow model: Human body thermal regulation is mainly achieved by regulating blood flow, so a realistic blood flow model is important for any dynamic model of human thermal comfort. It is by vasoconstriction and vasodilation that the body regulates blood distribution in order to control skin temperature and increase or decrease heat loss to the environment. During exercise or work, blood carries the extra heat produced to the body surface where higher skin temperatures increase heat loss through convection and radiation. Skin temperatures and, more importantly, hypothalamus temperature control this regulation as well as the opening of sweat glands to remove additional heat by evaporation. During cold stress, cutaneous vasoconstriction shunts blood from arteries to veins at a deeper level. Veins and arteries are paired, even down to very small vessels, and veins carry heat from the arteries back to the core. This counter-current heat exchange is a major process in decreasing heat loss and maintaining core temperature in cold environments.

The original Stolwijk model assumes the arterial blood temperature to be the same throughout the body. The heat exchanges between local tissues and local blood are thus simplified to heat exchanges between local tissues and blood at this core temperature. This assumption is basically sound for modeling the head and trunk. In the head, the brain receives a relatively large and constant blood flow that accounts for about 15% of the total blood flow of the body. With the high blood flow rate and relatively short vessel length, the heat exchange effectiveness is small and the blood temperature entering the brain is effectively the same as the core blood temperature. Similarly, large blood vessels in the trunk have relatively little heat transfer with surrounding tissues due to the high blood flow rates and incomplete contact with tissues [5,6].

In the limbs, Stolwijk's assumption is less valid. Based on Chato's data [5] we calculate that arterial blood flowing to the hands will reach a temperature about halfway between the temperature of the blood entering the upper arm and the temperature of the arm tissue. In a cool environment, this can result in 2°C or greater drop in arterial blood temperature from the upper arm to the wrist. For this reason, we decided that we could improve on Stolwijk's model by including the change in blood temperature as it flows through limbs to the extremities.

We made two significant changes to the Stolwijk blood flow model by adding: (1) central artery/vein countercurrent heat exchange, and (2) an improved blood perfusion model to estimate blood flow to local tissue.

Fig. 2 shows the blood flow model for an arm (the leg has the same structure) indicating both heat and mass transfer. Blood flows out through the central artery and returns through the central vein. Countercurrent heat exchange between the artery and vein, as well as heat exchanges between the blood vessels and the contacting tissue, is modeled as described by Mitchell and Myers [7]. Simultaneously, mass transfer occurs in the radial blood flow that leaves the central artery, goes through the transverse terminal arteries, to the capillary beds to distribute blood to core, muscle, fat, and skin tissues. It is then taken up by the transverse terminal veins and returns to the central vein. We use Pennes' blood flow perfusion term [8] to model mass and heat transfer at this level. Blood enters the local tissue at the average artery temperature for the segment and returns to the central vein at the tissue temperature from whence it came.

In the extremities (i.e. arms and legs) the entering artery blood temperature of one segment is the leaving artery blood temperature of the preceding segment. All blood returning from the veins mixes together to determine the returning core blood temperature.

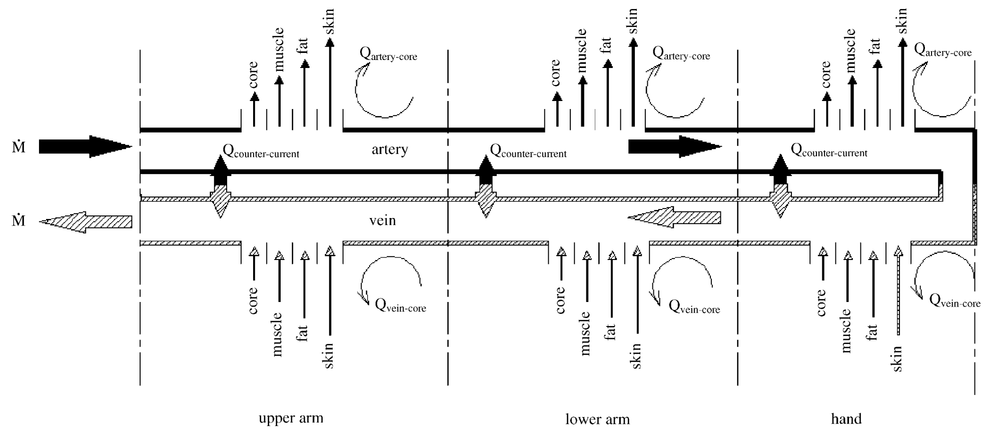

Fig. 2. Extremity blood flow model.

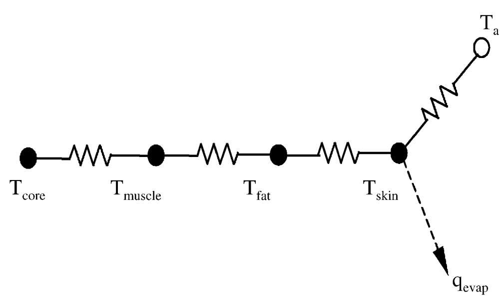

Fig. 3. Stolwijk model node structure.

Clothing model: Stolwijk considered clothing as insulation without mass (Fig. 3). We have included a clothing node to model both heat and moisture capacitance of clothing (Fig. 4). Heat capacity of the clothing has been demonstrated to be important when considering transient effects [9]. Moisture capacitance is important to correctly model evaporative heat loss from the body through clothing. The moisture model uses the regain approach [10] to calculate the amount of moisture that a specific fabric will absorb at a given relative humidity.

Contact surfaces: In almost any environment, the body is in contact with solid surfaces and loses heat via conduction. The most common contact surface for the body is a chair. Under steady-state conditions, this can be treated as increased insulation and modeled as clothing. Under transient conditions, this approach does not work well since the chair can have significant thermal mass. The Berkeley model includes a contact surface for each segment. This surface has an initial temperature, thermal conductivity, specific heat and thickness. A far-field temperature and heat transfer coefficient are used as a boundary condition. Each body segment includes the fraction of exposed skin and clothed skin in contact with the surface.

Convection and radiation heat transfer: Stolwijk used a combined convection and radiation heat transfer coefficient for each of the six segments in his model. The Berkeley model separates convection and radiation heat transfer. Convection heat transfer is calculated based on the air temperature and velocity supplied for each segment. Convective heat transfer coefficients for 16 body segments are based on test results from the Berkeley manikin in both seated and standing posture [11].

Radiation heat transfer can be calculated using a linearized model based on mean radiant temperature (MRT) specified for each body segment or using an explicit model using the Stefan–Boltzmann law. Using a realistic 3-D model of the body (Fig. 5), we calculate shape factors between each body segment and any arbitrary set of environmental surfaces. Each of these environmental surfaces is described by its position, surface area, temperature and emittance. This method is significantly more accurate than the MRT approach for non-uniform environments [12].

Radiation heat sources: In addition to long-wave radiation heat transfer with surrounding surfaces, the body is often exposed to radiation from the sun, heat lamps or other sources. We have included a two-band radiation heat flux model that separates this heat flux into short-wave and long-wave components. Short-wave radiation is absorbed based on skin or clothing absorptance and long-wave radiation is absorbed based on the skin or clothing emittance.

Physiological variation: Human physiology varies significantly among individuals, and these differences can affect perceptions of thermal comfort; e.g., higher metabolic rate or increased body fat can cause people to feel warmer. Remarkably, comfort models have not generally considered such variation. We have developed a pre-processor to our model which we call "body builder". The body builder model maps six descriptive characteristics of the human body (height, weight, age, gender, skin color, and body fat) to the physiological data used by the comfort model. Table 1 describes the physiological data that we modify and the basis for the relationships we use. We intend to use the body builder model to explore the extent to which physiological variation

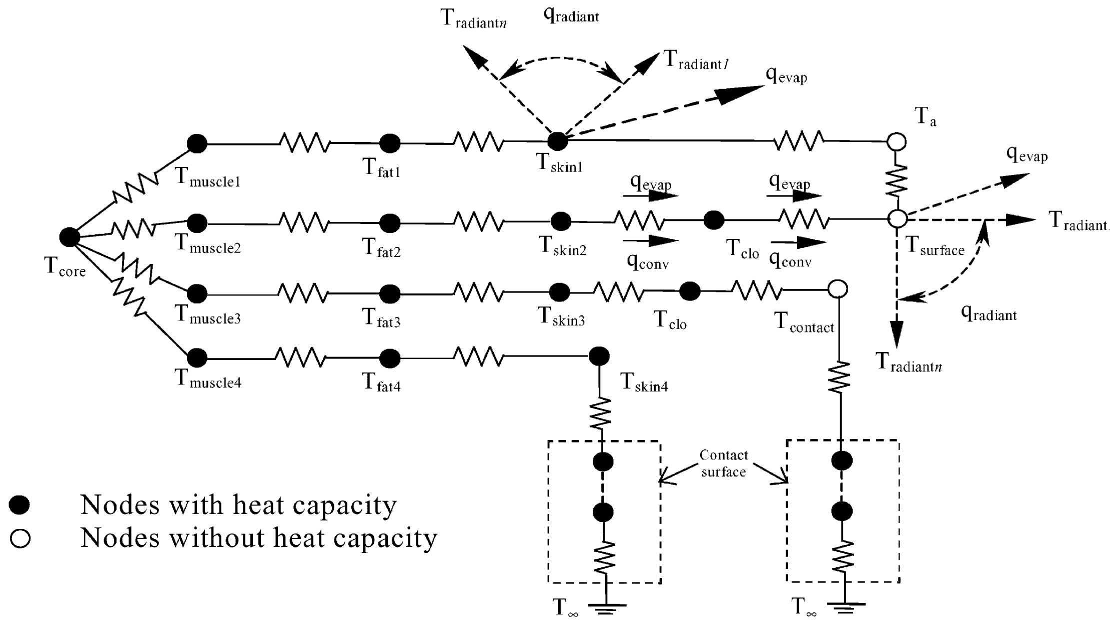

Fig. 4. Typical segment node structure showing four parallel heat paths: top, exposed skin with convective and radiant heat loss, second from top, clothed skin with convection and radiant heat loss; third, clothed skin with conductive loss to contact surface; bottom, bare skin.

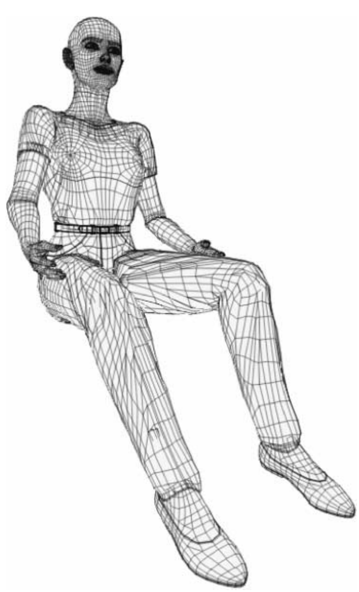

Fig. 5. A realistic three-dimensional model of the body is used to calculate radiation view factors between the body and surrounding surfaces.

influences perception of thermal comfort. Initial simulations show that a change in body fat from 14 to 28% can result in a skin temperature change of nearly 1°C.

3. Implementation

The Berkeley Comfort Model uses an unlimited number of sequential sets of environmental and physiological input conditions, called phases. The phases are specified either interactively or through text files to facilitate use of the model with other software (Figs. 6 and 7). Each phase consists of the following data [1]:

- Duration
- Metabolic rate
- Physiological constants*
- Clothing* (insulation level and moisture permeability)
- Air temperature*
- Mean radiant temperature* (or a list of surface temperatures, emissivities and angle factors)
- Air velocity*
- Relative humidity*
- Contact surface thermal properties*

Phases are most commonly used to represent segments of time where environmental conditions are constant or vary linearly with time. Since the length of the phase is arbitrary, non-linear transients can be simulated by short, linear approximations. All of the physiological constants embedded in the model can also be changed through the input data. This allows the user to change not only obvious physical data such as height, weight, basal metabolic rate, and heat transfer coefficients, but also more detailed physiological data such as tissue properties, thermal conductivities, hot/cold receptor properties, vasoconstriction and vasodilation coefficients. These properties can even be changed during the simulation to correct for changing conditions such as posture (e.g. seated vs. standing).

The model has been implemented in C++ using an object-oriented (OO) approach. The data structure and

[1] The data marked by an asterik are specified for each body segment.

Table 1
Physiological data modified by "body builder"

Physiological data	Parameters used	Basis for relationship
Surface area	Height, weight	Dubois (1927) [13]
Basal metabolic heat production	Height, weight, gender, age	Harris and Benedict (1958) [14]
Basal cardiac output	Height, weight, body fat	Gregersen (1950) [15], Allen et al. (1956) [16]
Thermal resistance	Body fat amount	Stolwijk (1970) [17]
Thermal capacitance	Height, weight	Stolwijk (1970) [17]
Countercurrent heat exchange	Height (extremity length)	Mitchell and Myers (1968) [7]
Skin solar absorption	Skin color	Houdas and Ring (1982) [18]
Clothing solar absorption	Fabric type and color	Blum (1945) [19]

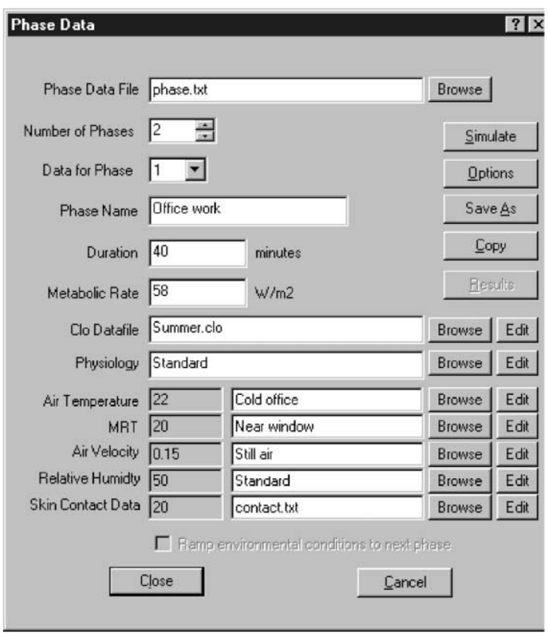

Fig. 6. The Phase Data dialog box. In this example screen there are four phases, the first of which lasts 40 min, with a metabolic rate of 58 W-m^2 (1 met) and a clothing ensemble as described in an external file called summer.clo.

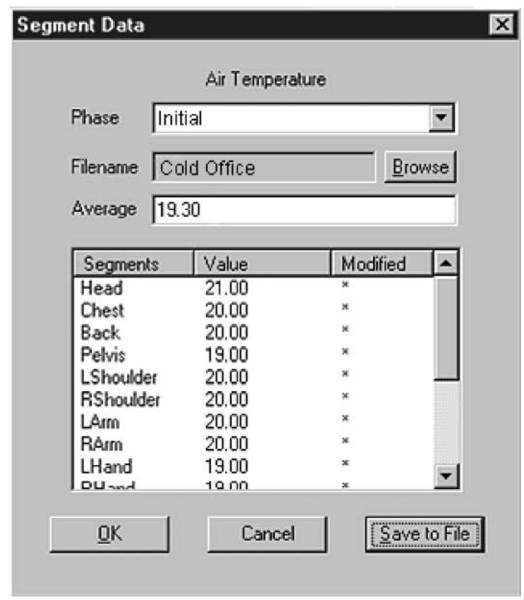

Fig. 7. The Edit dialog box for air temperature. Each body segment can be exposed to different environmental conditions.

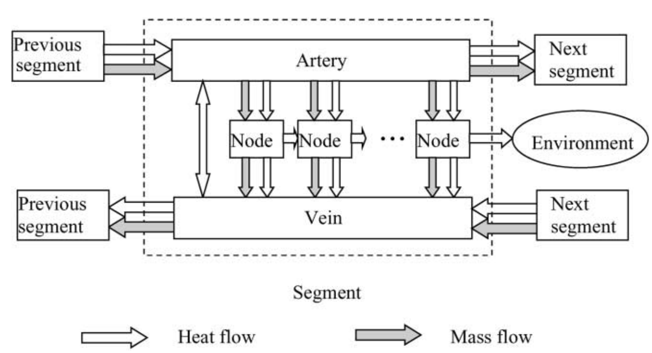

Fig. 8. Segment object schema.

simulation procedure resemble the physical model closely. We have kept the internal model structure very flexible, so that changes to the model can be implemented easily, often without recompiling the code. For example, the node structure is read from text input files so that adding a body segment only requires modifying program input. The choice of an object-oriented language has greatly simplified this approach.

Several objects are defined to represent each element of the physical model. The *node* object is the basic unit in this object structure. All the actual simulation procedures — heat production, heat transfer and regulating control mechanism — are done within node objects. Multiple nodes are organized into a tree-like structure that is maintained by a higher level object, the *segment* object. A segment also has a *blood* object which contains an *artery* and a *vein*. Fig. 8 shows the relationship of these objects. The *body* consists of several *segments* that are connected with each other via blood. Nodes exchange heat with their adjacent nodes via conduction as well as with blood.

Nodes in each segment form a linked tree. Multiple parallel branches may be included in each segment to simulate different heat flow paths. The structure of each segment does not need to be identical. This provides the capability to model different body parts having quite different physical structures and/or non-identical environmental conditions. For example, if the subject is wearing shorts, the model will generate both a clothed and a bare-skin path for the thigh segment. If the subject is wearing long pants, only the clothed path will be generated.

4. Validation

As an initial validation of the model, we compared simulated skin temperatures with a number of physiological studies reported by other researchers. These studies include several steady-state conditions and three transient environmental conditions.

Steady-state conditions. Werner performed 86 climatic chamber experiments with air temperatures ranging from 10 to 50°C at 40% relative humidity (RH). The test subjects wore only shorts and lay at rest on a hammock [20]. Skin temperatures by segments, rectal, and tympanic temperatures were measured.

Cold-exposure transients. Raven et al. [21] exposed 11 male subjects to a downward step change from 28.5°C at 45% RH to 4.7°C at 70% RH, in still air. Subjects wore only shorts, and rested in a supine position on a nylon-strip bed mounted that was wheeled from one chamber to another to achieve the change in environmental conditions. Rectal and skin temperatures on segments were measured.

Hardy and Stolwijk present data for three male subjects exposed to a step change from 43°C at 30% RH to 17°C at 40% RH. The human subjects walked quickly from one chamber to another which took less than 1 min. The rectal and the average of 10 areas of skin temperatures as well as evaporative heat loss are presented in [22].

Hot-exposure transient. Stolwijk and Hardy performed similar tests using an upward step change from 30°C at 40% RH to 48°C at 30% RH. The rectal and the average of 10 locations of skin temperatures and total evaporative heat loss are presented in [23].

Comparison of the measured data from the above experiments and the simulated results from our model are presented in Figs. 9–11. Under steady-state conditions, the core temperature prediction is very close to the measured values (within 0.5°C) (Fig. 9a). For most segments (Figs. 9b and 9c), the skin temperature simulation is within 1°C. For transient conditions, the measured toe temperature by Raven during transient is lower than the foot temperature from simulation (Fig. 10c). This is not unexpected since the toe is most distal part of the foot and responds more quickly to the transient than the entire foot. The measured arm temperature is higher than the simulated arm temperature during the transient, however, the final stable temperatures are very close. The measured arm temperature was obtained from Gordon and the specific location of the measurement was not stated. The rectal temperatures measured by Hardy and

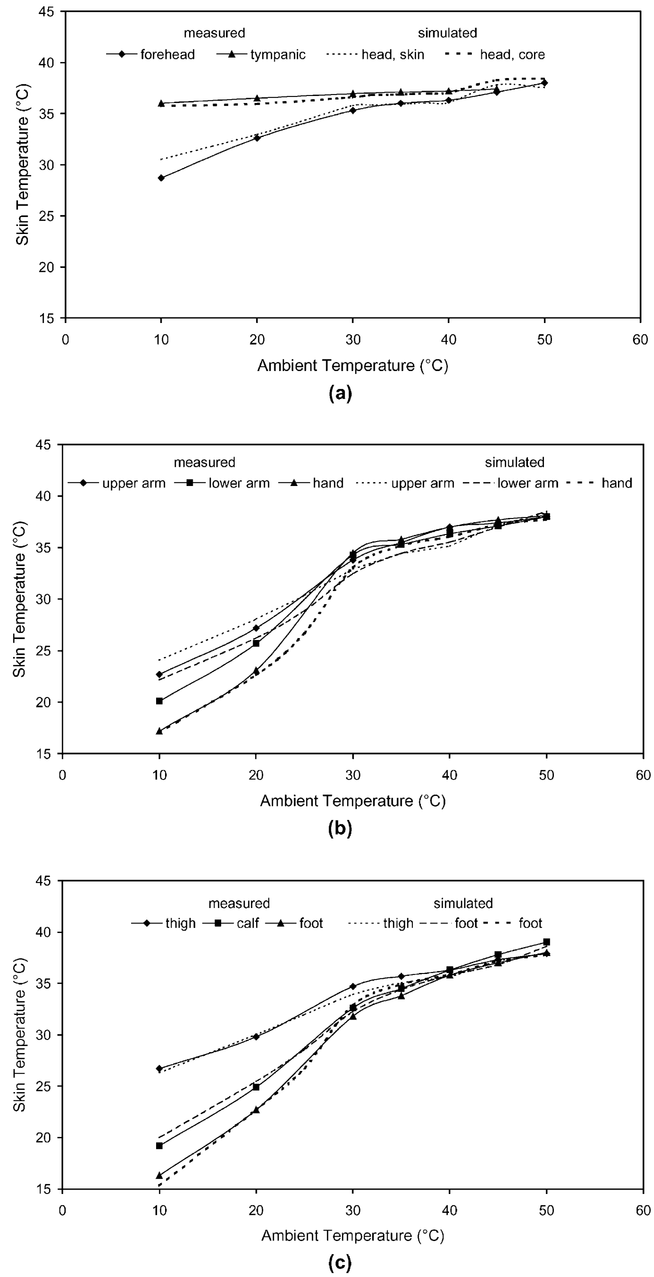

Fig. 9. Comparison of measured [20] and simulated temperatures during steady-state conditions ranging from 10 to 50°C. (a) head skin and core; (b) upper arm, lower arm and hand; (c) thigh, calf and foot.

Stolwijk are slightly higher than the those predicted by the model.

Fig. 11c shows measured and predicted evaporative heat loss during two step changes, to a hot condition and back. As Fu observed [24], Stolwijk's original model tends to predict higher skin temperatures than experimental data in cold environments. This is because the central blood model used by Stolwijk assumes that any node of a segment receives blood at the same temperature as the core. In fact artery blood temperature decreases because of countercurrent heat exchange, lowering extremity skin

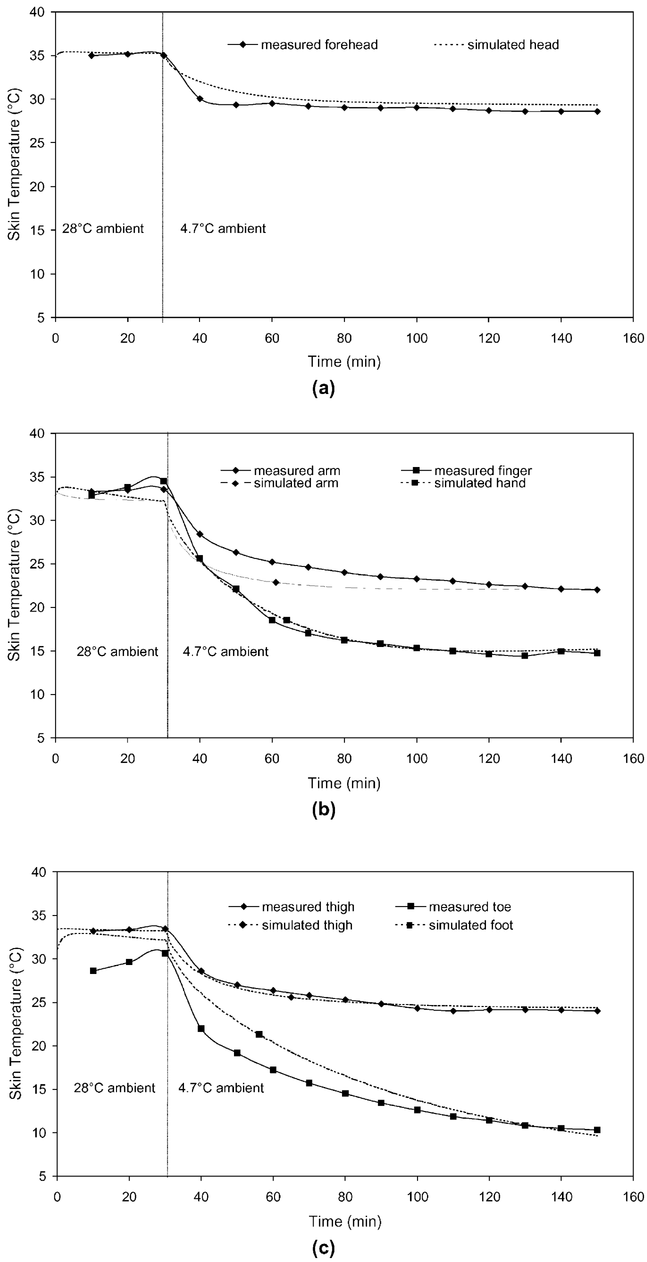

Fig. 10. Comparison of measured [21] and simulated temperatures during a step-change from 28 to 4.7°C. (a) head; (b) upper arm and hand; (c) thigh and foot.

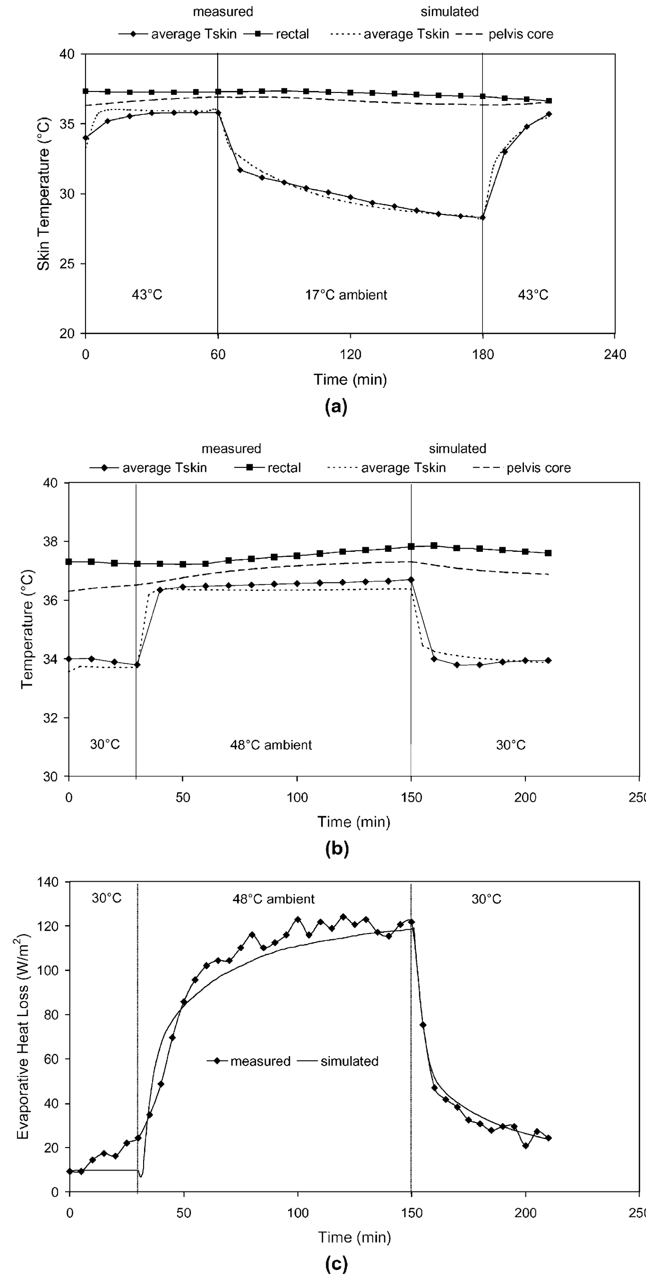

Fig. 11. Comparison of measured [1] and simulated temperatures and evaporative heat loss during temperature step-changes. (a) skin and core temperatures during cold step-change from 43°C, 30% RH to 17°C, 40% RH; (b) skin and core temperatures during hot step-change from 30°C, 40% RH to 48°C, 30% RH; (c) evaporative heat loss during the same hot step-change conditions.

temperature. Adding the countercurrent blood flow model greatly improved the agreement between our model and the experimental data in limbs and extremities. The above model validations show that the model is able to predict both core and extremity skin temperatures with reasonably accuracy under a range of environmental conditions.

5. Comfort prediction

Predicting the physiological response of the body to an environment is an interesting endeavor, but often we would like to predict the psychological or subjective response as well. Most well-validated models of predicted subjective response [25,26] are limited to uniform thermal environments. Bohm accepted 'Equivalent Homogenous Temperature' (EHT) proposed by Wyon [27] for assessing non-uniform environments and developed limits [28]. We calculate EHT for each body segment and generate a diagram plotting these within limits established for segments by Bohm as shown in Fig. 12. More

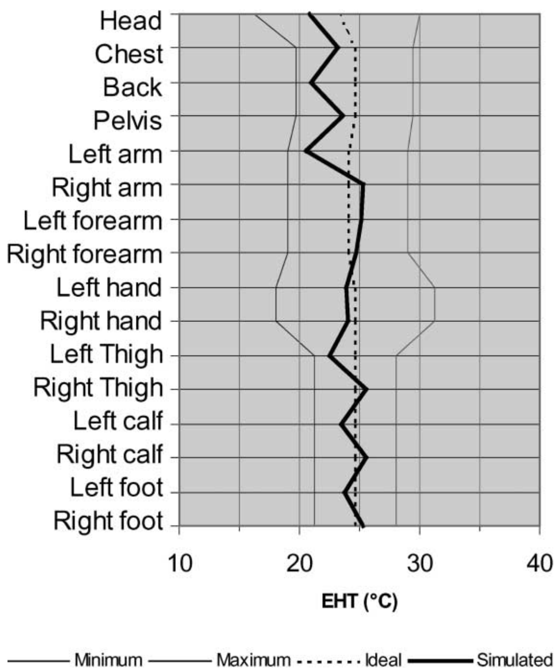

Fig. 12. Comfort prediction diagram for a person sitting near a cold window using EHT. Note that the left side of the body is colder than the right side.

research is required to develop a whole-body comfort index for non-uniform environments in transient conditions.

6. Applications

Its flexible input structure and its ability to evaluate transient, non-uniform thermal environments make the Berkeley Comfort Model useful for a wide range of applications. Examples include evaluation of innovative HVAC approaches for buildings such as task/ambient systems or displacement ventilation that provide non-uniform or stratified environments. Another example is evaluation of occupant comfort in automobiles, where the environment may be very transient and have highly non-uniform radiant loads. The input structure of the Berkeley model allows it to be connected to building simulation programs and to evaluate thermal comfort in a much more rigorous manner than is currently being done.

7. Future work

Our next step is to improve our ability to predict human subjective responses to non-uniform thermal environments during transient processes. We are considering including the detailed skin thermoreceptor model proposed by Ring and de Dear [29] and more detailed blood flow model for the whole limb proposed by Song et al. [30].

Acknowledgements

This work was sponsored in part by the following organizations: Delphi Harrison Thermal Systems, US Army Research Institute for Environmental Medicine, National Renewable Energy Laboratory. Taeyoung Han, Shin-ichi Tanabe and Richard de Dear provided valuable technical input.

References

[1] Stolwijk JAJ, Hardy JD. Temperature regulation in man — a theoretical study. Pflugers Archiv Ges. Physiol 1966;291:129–62.
[2] Hwang C, Konz SA. Engineering models of the human thermoregulatory system — a review. IEEE Transactions on Biomedical Engineering 1977;24(4):309–25.
[3] Tanabe S, Tsuzuki T, Kimura K, Horikawa S. Numerical Simulation Model of Thermal Regulation of Man with 16 Body Parts of Evaluating Thermal Environment (Part 1 Heat Transfer at Skin Surface and Comparison with SET* and Stolwijk Model). Summaries of Technical Papers of Annual Meeting, Architectural Institute of Japan, 1995.
[4] Tanabe S, Arens E, Bauman F, Zhang H, Madsen T. Evaluating thermal environments by using a thermal manikin with controlled skin surface temperature. ASHRAE Transactions 1994;100(Pt. 1):39–48.
[5] Chato JC. Heat transfer to blood vessels. ASME Journal of Biomechanical Engineering 1980;102:110–18.
[6] Chen MM, Homes KR. Microvascular contribution in tissue heat transfer. Annals of the New York Academy of Science 1980;335:137–50.
[7] Mitchell JW, Myers GE. An analytical model of the countercurrent heat exchange phenomena. Biophysical Journal 1968;8:897–911.
[8] Pennes HH. Analysis of tissue and arterial blood temperatures in the resting human forearm. Journal of Applied Physiology 1948;1(2):93–122.
[9] Burch SD, Ramadhyani S, Pearson JT. Analysis of passenger thermal comfort in an automobile under severe winter conditions. ASHRAE Transactions 1991;97(pt. 1).
[10] Morton WE, Hearle JWS. Physical properties of textile fibres. Manchester, UK: The Textile Institute, 1993.
[11] de Dear RJ, Arens E, Zhang H, Oguro M. Convective and radiative heat transfer coefficients for individual human body segments. International Journal of Bio-Meteorology 1997;40(3):145–56.
[12] Corrado JV, Pretti M, Sacchi A. Routine for the calculation of angle factors between human body and car drivers' cabin. SAE Technical Paper Series 95A1054 1995. 421–29.
[13] Dubois E. Height–Weight–Surface area. Philadelphia: Lea and Feibiger, 1927.
[14] Harris JA, Benedict FG. A biometric study of basal metabolism in man. Washington: Carnegie Institute of Washington, 1919.
[15] Gregersen MI, Nickerson JL. Relation of blood volume and cardiac output to body type. Journal of Applied Physiology 1950;3:329–41.
[16] Allen TH, Peng MT, Chen KP, Huang TF, Chang C, Fang HS. Prediction of blood volume and adiposity in man from body weight and cube of height. Metabolism 1956;5:328–45.
[17] Stolwijk JAJ. A Mathematical Model of Physiological Temperature Regulation in Man. NASA Report, 1970.
[18] Houdas Y, Ring EFJ. Human body temperature: its measurement and regulation. New York, London: Plenum Press, 1982.
[19] Blum HF. The solar heat load: its relationship to total heat load and its relative importance in the design of clothing. Journal of Clinical Investigation 1945;24:712–21.
[20] Werner J, Reents T. A contribution to the topography of temperature regulation in man. European Journal of Applied Physiology 1980;45:87–94.

[21] Raven PR, Horvath SM. Variability of physiological parameters of unacclimatized males during a two-hour cold stress of 5°C. International Journal of Biometeorology 1970;14(3):309–20.
[22] Hardy JD, Stolwijk JAJ. Partitional calorimetric studies of responses man during exposures to thermal transients. Journal of Applied Physiology 1966;21:967–77.
[23] Stolwijk JAJ, Hardy JD. Partitional calorimetric studies of responses of man to thermal transients. Journal of Applied Physiology 1966;21:1799–806.
[24] Fu G. A transient, 3-D mathematical thermal model for clothed human. Dissertation. Mechanical Engineering, Kansas State University, 1995.
[25] Fanger PO. Thermal comfort. New York: McGraw-Hill, 1970.
[26] Gagge AP, Stolwijk JAJ, Nishi Y. An effective temperature scale based on a simple model of human physiological regulatory response. ASHRAE Transactions 1971;77(1):247–62.
[27] Wyon DP, Larsson S, Forsgren B, Lundgren I. Standard procedures for assessing vehicle climate with a thermal manikin. SAE Technical Paper Series 890049 1989. p. 1–11.
[28] Bohm M, Browen A, Holmer I, Nilsson H, Noren O. Evaluation of Vehicle Climate with a Thermal Manikin – The Relationship between Human Temperature Experience and Local Heat Loss. Swedish Institute of Agricultural Engineering. JTI-Report 123, 1990.
[29] Ring JW, de Dear RJ. Temperature transients: A model for heat diffusion through the skin, thermoreceptor response and thermal sensation. Indoor Air 1991;1(4):448–56.
[30] Song WJ, Weinbaum S, Jiji LM, Lemons D. A combined macro and microvascular model for whole limb heat transfer. Journal of Biomechanical Engineering – Transactions of ASME 1988;110:259–68.