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# THERMAL MODEL OF HUMAN BODY FITTED WITH INDIVIDUAL CHARACTERISTICS OF BODY TEMPERATURE REGULATION

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ABSTRACT

To develop a thermal model that can predict the thermal responses of the human body under given environmental conditions, it is necessary for the model to be fitted with the individual characteristics of human body temperature regulation. As the basis for this, in this paper, it is shown that the coefficients that represent the thermoregulatory responses in the two-node model (thermal model of human body) can be identified for individuals. Six coefficients related to the regulation of sweating and skin blood flow in the two-node model are tuned for the individuals involved in the experiments: the core and skin temperatures calculated by the model are fitted with the measured results for the entire thermal transient processes, including exposures to heat and cold.

KEYWORDS

Thermal model of human body, Two-node model, Individual difference, Subject experiment, Transient state, Thermoregulatory response

## 1. INTRODUCTION

The thermal model of the human body (TMHB) consists of equations that describe the heat transfer in the body and regulatory responses such as sweating and blood flow rate control. If it were possible to predict the thermal responses of the human body under a given environmental condition, the TMHB would be useful in the design and evaluation of architectural environments. A large number of TMHBs have been developed for more than fifty decades. Most of them are numerical models in which the temperature distribution in the body is expressed in a discrete manner. The originality of each model lies in the manner in which the body is divided into nodes, and also in the form of the equations describing regulatory responses such as sweating and blood flow rate control. Recent models have tended to divide the body into many nodes. The evaluation of nonhomogeneous environments is generally performed numerically by using models with many nodes [1][2][3][4]. In the case that many nodes are considered, it is necessary to input detailed local information (for example, blood flow rate between nodes, distribution of thermal properties, heat production, and sweat secretion) to the model; however, such physiological data are limited. Thus, the precision in the prediction of the body temperature distribution is not still sufficient although a higher resolution of the temperature distribution can be obtained in the calculated results.

For practical utilization in the design and evaluation of environments, the calculated results based on the TMHB must agree with the actual responses of the human body. The calculated results in the transient state [5] have been compared with experimental values for stepwise thermal transients [6][7]. However, it should be emphasized that the comparison between the results calculated by the TMHB and those measured in human subject experiments is not sufficient with regard to both quantity and quality, and therefore, the reliability of these models is still not sufficient.

In order to raise the reliability of the models, it is necessary to show that the model describes the real thermal responses of human body well enough through a comparison between experimental and calculated results; however in such a procedure, another problem arises: the thermoregulatory responses of different individuals are different, even under the same environmental conditions, which makes comparison impossible without a methodology to express individual difference in the model itself. This paper proposes a methodology to consider individual characteristics in thermoregulatory responses in the TMHB.

There are a few studies that take into account individual differences: Havenith [7] expressed the individual differences in the thermal resistance and capacitance of body components and in the sweating and skin blood flow rate on the basis of several individual characteristics such as body surface area, mass, and body fat percentage, and incorporated them into the model. Zhang et al. [8] used the "body builder model," which expresses individual differences by inputting elements similar to those expressed by Havenith. In these studies, the results simulated by considering the differences between individual body builds were compared with the results for which the differences were not considered; however, the results considering the differences were not clearly superior for transient states, leaving room for further study on individual differences in the thermoregulatory control system such as in regulatory sweating and skin blood flow control. There are two approaches to deal with the problem of individual differences: One is from the passive systems [9] of the body, such as thermal capacitance, thermal resistance, or surface area related to heat transfer. The other is from the controlling systems [9] of the body, such as regulatory sweating or skin blood flow. This study focuses on the latter.

The simplest model is used in this study: the two-node model proposed by Gagge et al. in 1971 [9]. In this model, regulatory sweating and skin blood flow rate are expressed as functions of the core and skin temperatures. In this study, keeping the shape of the equations as they are, the possibility of tuning the coefficients in the equations is examined based on the experimental results. First, experiments involving four subjects (naked, sedentary) are conducted. In the experiments, the subjects are exposed to a neutral temperature, which is then varied in a stepwise manner to a low temperature, high temperature, and finally neutral temperature. Second, based on the experimental data on the core and skin temperatures, the physiological constants (set point temperature of core and skin, coefficients in the dynamic model of regulatory sweating and skin blood flow rate) included in the two-node model [9] are optimized so that the difference between the experimental and calculated values of the core and skin temperatures reduce to the minimum values throughout the transient process.

## 2. SUBJECT EXPERIMENT

### 2.1 Method

Four healthy male students (Table 1) seated back-to-back were exposed to transient thermal conditions: nearly (thermally) neutral conditions, followed by a low air temperature, a second neutral condition, a high air temperature, and finally, a third neutral condition. The experiments were conducted in two climate chambers. The settings of the climate chambers are shown in Figure 1 along with the schedule of the experiment. All the subjects wore only trunks (undershorts) and remained sedentary in the thermally neutral condition (29.4°C, 47%rh) for 1 hour before the experiment began. During the experiments, the core and skin temperatures, heart rate, and environmental conditions (air temperature, humidity, globe temperature, and wind velocity) were measured continuously at intervals of 10 s. For the skin temperature measurements, the Hardy and DuBois seven-point method was employed. In addition, the body weight loss during the experiment was measured. The measured data are shown in detail in Table 2. The body surface area was calculated from the height and weight [10].

2.2 Result of subject experiment

As shown in Figure 2, the difference between the rectal temperatures of the subjects reached a maximum value of 1 [K]. This is a significant difference from the viewpoint of a numerical model of thermoregulation in the human body because a 1 [K] difference in the core temperature translates into a significant difference in the thermoregulatory responses such as the skin blood flow rate and sweat rate. As shown in Figure 3, similar differences between the individuals were found in the tympanic temperature. In Figure 4, the averaged skin temperature (Hardy and DuBois seven-point method) is shown. The differences between the temperatures of the subjects reached 1 [K]. The heart rate is shown in Figure 5. The differences in the heart rate were significant, indicating the individual differences in the characteristics of the regulation of the blood flow regulation. Table 3 shows the body weight loss averaged for the whole process of the experiment. The weight losses of subjects B and D were greater than those of the others, indicating the individual differences in regulatory sweating responses. Table 4 shows the data on the environmental conditions such as the room air temperature, humidity, globe temperature, and wind velocity. The temperature and humidity were controlled in a manner such that they were maintained constant during each step of the transient process. The movements of the subjects from one room to another (at the $30^{th}$, $50^{th}$, $80^{th}$, and $100^{th}$ min) began at the scheduled times; it took c.a. 1 min to exit the previous room. The time required for the movements were recorded and considered in the following analysis.

## 3. IDENTIFICATION OF TWO-NODE MODEL FITTED TO INDIVIDUALS

### 3.1 Basic equations of two-node model

In the two-node model [9], the heat balance equations for the core and skin nodes are expressed as follows:

$$\frac{c_{cr} \cdot W_{cr}}{S} \frac{dT_{cr}}{dt} = (1-\eta) \cdot M - q_{res} - (c_{bl} \cdot v_{bl} + K_{\min}) \cdot (T_{cr} - T_{sk}) \tag{1}$$

$$\frac{c_{sk} \cdot W_{sk}}{S} \frac{dT_{sk}}{dt} = (T_{cr} - T_{sk}) \cdot (K_{\min} + c_{bl} \cdot v_{bl}) - (\alpha_c + \alpha_r) \cdot (T_{sk} - T_o) \cdot F_{cl} - (q_{diff} + q_{rsw}) \tag{2}$$

The elements in equations (1) and (2) are described as follows:

Heat loss due to respiration

$$q_{res} = 0.0023 \cdot M \cdot (44 - \phi_a \cdot P_a) \tag{3}$$

Heat loss due to sweating

$$q_{rsw} = r \cdot m_{sw} \cdot 2.0^{\frac{T_{sk} - T_{sk,set}}{3.0}} \tag{4}$$

Heat loss due to skin diffusion

$$q_{diff} = p_{wet} \cdot q_{\max} - q_{rsw} \tag{5}$$

where

$$q_{\max} = r \cdot \alpha' \cdot (P_{sk} - \phi_a \cdot P_a) \cdot F_{pcl} \tag{6}$$

$$p_{rsw} = q_{rsw} / q_{\max} \tag{7}$$

$$p_{wet} = 0.06 + 0.94 \cdot p_{rsw} \tag{8}$$

$$F_{cl} = \frac{1}{1 + 0.155 \cdot (\alpha_c + \alpha_r) \cdot clo} \tag{9}$$

The thermoregulatory responses are expressed as functions of the core and skin temperatures as follows:

For the sweating rate,

$$m_{sw} = k_{sw} \cdot \left(T_{cr} - T_{cr,set}\right) \cdot \left(T_{sk} - T_{sk,set}\right) \cdot \frac{1}{3600} \cdot \frac{1}{1000} \tag{10}$$

If any value in parentheses is negative, it should be replaced with a zero.

For the skin blood flow rate,

$$v_{bl} = \frac{k_{basal} + k_{dil} \cdot \left(T_{cr} - T_{cr,set}\right)}{1 + k_{con} \cdot \left(T_{sk,set} - T_{sk}\right)} \cdot \frac{1}{3600} \tag{11}$$

If any value in parentheses is negative, it should be replaced with a zero.

In these equations, six coefficients are included, and the values of these coefficients are provided in the original paper [9]. Some of the coefficients were determined based on a thermophysiological experiment, but for the other coefficients, the process of determination is not clear. The above model could have been fitted with the measured results for several particular subjects. However, the differences in individual characteristics are not taken into account in the original two-node model.

3.2 Method for identifying coefficients for individuals

Six coefficients related to sweating and skin blood flow rate control models were identified for each subject; these six coefficients are regarded as the parameters as follows:

$$m_{sw} = pr3 \cdot (T_{cr} - pr1) \cdot (T_{sk} - pr2) \cdot \frac{1}{3600} \cdot \frac{1}{1000} \tag{10'}$$

$$v_{bl} = \frac{pr4 + pr5 \cdot (T_{cr} - pr1)}{1 + pr6 \cdot (pr2 - T_{sk})} \cdot \frac{1}{3600} \tag{11'}$$

These six coefficients included in the two-node model were determined for each subject so that the differences between the calculated and experimental core and skin temperatures throughout the thermal transient process decreased to the minimum values.

For the six parameters, candidate solutions from the assumed domain were selected, as shown in Table 5. And the combination of parameters that minimized the objective function $J$ in equation (12) was searched from all the combinations. (The total number of possible combinations of parameters is 1,260,000.)

$$J = \sum_{i=1}^{N} \left\{ (T_{cr,i} - T_{cr,i}')^2 \right\} + \sum_{i=1}^{N} \left\{ (T_{sk,i} - T_{sk,i}')^2 \right\} \tag{12}$$

For the experimental data, the mean skin temperature (Hardy and DuBois seven-point method) and rectal temperature were used to represent the skin and core temperatures, respectively. The data acquisition was conducted at intervals of 10 s. Therefore, the total number of the time series data for the 2-h experiment was 721.

The experimental values were used as the initial conditions of the core and skin temperatures in the calculation. For the boundary conditions, the room air temperature and humidity data measured during the experiment were inputted into the calculation program. For the mean radiant temperature, the air temperature was provided because the difference between the globe temperature and air temperature was sufficiently small, as shown in Table 4. The conditions under which the calculations were performed are listed in detail in Table 6. The masses and the surface areas of the subjects are provided in Table 1. The mass ratio of core and skin was set to 95:5 [9].

### 3.3 Result of identifying coefficients for individuals

The coefficients identified are shown in Table 7. The experimental results, the results calculated with the determined coefficients, and the results calculated with the default coefficients (proposed by Gagge et al., the original authors) are compared in Figures 6–9 for both the core and skin temperatures, for each subject. For all the subjects, the results calculated with the identified combinations of coefficients agree well with the experimental results as compared to those obtained with the default coefficients. The value of $J$ in equation (12), the sum of the squared difference between the experimental and calculated core and skin temperatures, is about 60 for all the subjects. This means that the error is about 0.2 [K] when the difference is averaged for the core and skin temperatures over the whole transient process. Therefore, it can be concluded that the parameters were tuned well to describe the individual characteristics of each subject.

## 4. VALIDATION OF DETERMINATION

### 4.1 Method (Analysis of another type of transient thermal condition)

It was shown that by tuning the combination of the six coefficients related to the body temperature regulation in the two-node model, the solution of the two-node model agrees well with the experimental results for one set of transient thermal conditions. In order to ensure that the determined coefficients describe the characteristics of the body temperature regulation of each subject well, a test was conducted to determine whether the combination of parameters determined based on the experiment under the stepwise variation in temperature shown in Figure 1 is valid for the other type of temperature change shown in Figure 10.

The experiment on the other type of transient thermal condition was conducted on the same four subjects in a similar manner and in the same week during which the first experiment was conducted. Only the room air temperature conditions were varied, as shown in Figure 10. The environmental conditions measured in the experiment are shown in Table 8 as the averaged values for each process. The calculations are performed in the same manner as that described in the previous section, with the combination of parameters (already identified as shown in Table 7) provided for each subject.

### 4.2 Result of validation

The results of the comparison between the experimental and calculated results are shown in Figures 11–14. For all the subjects, the calculated results agree well with the experimental results. With the combination of coefficients optimized using one series of thermal transients, the experimental results for another series of thermal transients are explained well. This suggests that the identified combination of coefficients in the two-node model appropriately describes the individual body temperature regulation system of the each subject.

## 5. DISCUSSION

### 5.1 Application Range of Results

In this paper, the tuning of the two-node model to individuals is based on an experiment in which sedentary subjects who wore only trunks were exposed to temperature ranges from 20.0 °C to 40.9 °C, under the relative humidity around 50% (details are shown in Table 4). This would cover indoor environments, from the static viewpoint. At the same time, from the dynamic viewpoint, it is important to cover the temperature changes often experienced in architectural environments. The step changes in temperature used in the experiment reached ca. 10 [K] (29.4 °C – 20.0 °C – 29.4 °C – 40.9 °C – 29.4 °C), and these changes would be large enough to cover ordinary indoor conditions. However, further study would be required to validate the proposed method for conditions of high metabolic rate, such as during exercise.

In this paper, the possibility of identifying the coefficients in the two-node model for individuals was confirmed from the analysis of the data for the four healthy male subjects involved in the experiments. This possibility would also be true for many types of individuals, although the values of the coefficients, themselves, would be different. A method for such an application will be described at the end of this section.

## 5.2 Differences between new and old versions of two-node model

As is known widely, there are several versions of the two-node model published by the original authors. The current version (called the "new version" in this paper) was published in 1986 [11] and is used in the calculation of the standard effective temperature (SET*). In this paper, the version published in 1971 [9] (called the "old version") is used in the analysis because of the following reasons. There are three main differences between them.

The first is the difference in the mass ratio of core and skin. In the new version, it is variable depending on the skin blood flow rate: the ratio of skin becomes larger in low-temperature conditions, and smaller in high-temperature conditions. On the other hand, in the old version, the ratio of the skin is constant and set to about 5%. No quantitative experimental data for the mass ratio of core and skin is shown in the references in the original paper [11], and this should be clarified in some way. From the viewpoint of simplicity, the old version is adopted in this paper.

The second is the difference in the type of equation for regulatory sweating. In the new version, sweating rate is expressed by an exponential function of the body temperature. The authors [11] would have tried to improve the behavior of the model to fit some experimental data. However the experimental data or the process of the improvement is not explicitly shown. On the other hand, the source of the equation in the old version (equation (10) in this paper) is shown in the paper [9]. This is also the reason why the old model is adopted in this paper.

The third one is the shivering model. In the old version, the shivering model is not included. During the time period from 30 min to 50 min in the first experiment shown (Figure 1), the air temperature was 20.0 °C and shivering was observed for some subjects. Nevertheless, by adding the shivering model of the new version [11] to this calculation, it was found that the determined coefficients did not vary significantly because the level of shivering was not very significant under these conditions.

5.3 Form of objective function in tuning parameters

In this study, in the definition of the objective function (the difference between the experimental and calculated temperatures of core and skin), the rectal and mean skin temperatures are summed up with an equal weight ratio of 1:1, as shown in equation (12). However, another ratio of weighting can be selected. For example, by weighting more on the core temperature, the difference between the calculated and experimental temperatures is reduced for the core temperature, but increased for the skin temperature. In this study, the change in the core temperature (experimental results) was only 0.4 [K] through the thermal transient. Therefore, the improvement afforded by weighting more on the core temperature in the objective function is not significant: and on the other hand, the predicted skin temperatures become significantly worse. Thus, the weighting ratio for a specific case could be selected according to the importance of either the core or skin temperatures in that specific case.

Moreover, there are several other methods that use alternate data such as blood flow rate, sweating rate, or skin temperature measured at a specific part of the body (not averaged) as an element of the objective function for optimizing the parameters.

## 5.4 Meaning of each optimized parameter

The combination of six parameters in the two-node model shown in Table 7 describes the changes in the core and skin temperatures during the two types of thermal transient conditions for the four subjects. In this methodology, the *combination* is determined for individuals and the meaning of *each parameter* is discussed.

For the set point of the core temperature (*pr1*), the identified values appear to represent the individual differences. The identified set point of the core temperature for subject A is the lowest among those of the four subjects, and the rectal temperature of subject A varied at the lowest level. For subjects B and D, the measured rectal temperatures were at a higher level and the identified set points were also at a higher level.

However, the identified parameters related to the skin blood flow rate are not easy to interpret. In the original skin blood flow rate model, the following five parameters are related: set points of core and skin temperatures (*pr1* and *pr2*), basal skin blood flow rate (skin blood flow rate under thermally neutral conditions, *pr4*), vasodilation (*pr5*), and vasoconstriction (*pr6*). The identified parameter of vasoconstriction (*pr6*) is almost zero. This means that the vasoconstriction is expressed as a decrease in vasodilation in the model with the identified parameters. Moreover, the identified value of the basal skin blood flow rate (*pr4*) for subject B is small. It is probable that from the viewpoint of physiology, this small value is not the *basal* skin blood flow rate. In this methodology, the skin blood flow rate, in combination of the five parameters in equation (11), is identified to explain the experimental data for each subject.

Apparently, it is ideal that each identified parameter has a physiological meaning provided in the original model; however, *each parameter* identified in this study does not necessarily have the physiological implications. In this study, the *combination* of parameters was identified and thermophysiological characteristics of the individuals were successfully described. This suggests that there is room for simplification of the original model of thermoregulatory responses such as the skin blood flow rate and sweating rate.

## 5.5 Selection of parameters for describing individual differences

In this study, the individual differences in the characteristics of the thermophysiological regulatory responses were focused upon, and the elements related to the differences between body builds were regarded as common constants (only the total mass and skin surface difference were taken into account in the calculation based on the measurements for each subject). The metabolic rate and thermal conductance between the core and skin nodes would have some influence on the results by affecting the values of thermal production and resistance, respectively; and these elements should be studied quantitatively in studies conducted in the future.

## 5.6 Application of this methodology to other thermal models of the human body

The two-node model is one of the simplest thermal models of the human body. There exist a large number of higher-complexity models that possess more nodes, and the methodology proposed in this study can be adapted to any type of model.

In this study, it was shown that the physiological variables included in the two-node model can be tuned for individuals. This is not a trivial result but an important one, because the combination of parameters that fits individual characteristics cannot be identified if the model is improper. The results provided in this paper indicate an aspect of the validity of the two-node model; furthermore, these results indicate the possibilities for tuning the thermal models of the human body for individuals or for describing the differences between individual characteristics by using TMHB.

## 5.7 Application to architectural environments

For successful application to the design or evaluation of architectural environments, there are several steps to be studied.

In the procedures for fitting the model to the individual characteristics of different types of individuals, an easier method of determining the characteristics of the individual should be developed. The method described in this paper involves a complex experiment in a climate chamber with heat and cold exposure in order to obtain necessary data to identify the coefficients in the model fitted to individual characteristics. By taking more data based on the methodology proposed in this paper, there is a possibility to identify some empirical relationship between the characteristics of the thermoregulatory responses and other individual data that may be acquired easily, such as body mass or height of the body, percentage of fat, and skin temperature of a certain segment of the body.

An alternative to the methodology proposed in this paper is to constitute a *learning* system for the individual whose thermal responses are to be predicted. With a help of the advanced technology for sensing the body temperature or regulatory responses, the thermal model of human body could evolve so that the coefficients included are fitted with the person's characteristics in a step-by-step manner.

As a basis for application to architectural environments, it is shown in this paper that the two-node model can be fitted to individual thermoregulatory responses by determining the coefficients of the regulatory control equations.

## 6. CONCLUSION

To develop a thermal model in which the individual characteristics of human body temperature regulation are taken into account, the coefficients in the two-node model were identified for individuals based on the data obtained in experiments on four subjects who were exposed to a series of transient thermal conditions (a type of stepwise variation in air temperature). It was shown that the combination of six coefficients related to sweating and skin blood flow rate regulation in the two-node model can be tuned for individuals. By using the combination of coefficients determined for each subject, the measured results for another type of transient thermal condition were predicted with good precision. These results simultaneously support the validity of the determined coefficients and the methodology of considering the individual characteristics of the thermoregulatory responses into the TMHB.

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## NOMENCLATURE

$c$: Specific heat [J/(kg·K)]

$clo$: Thermal resistance of clothing [clo]

$k_{basal}$: Skin blood flow rate under thermally neutral conditions [L/(m$^2$·h)]

$k_{con}$: Coefficients of vasoconstriction [1/K].

$k_{dil}$: Coefficients of vasodilation [L/(m$^2$·h·K)]

$k_{sw}$: Coefficient of sweating rate model [g/(m$^2$·h·K$^2$)]

$m_{sw}$: Regulatory sweating rate [kg/(m$^2$·s)]

$p_{rsw}$: Skin wetness due to regulatory sweating [n.d.]

$p_{wet}$: Skin wetness [n.d.]

$q_{diff}$: Heat loss by skin diffusion [W/m$^2$]

$q_{max}$: Maximum heat loss by evaporation [W/m$^2$]

$q_{res}$: Heat loss by respiration [W/m$^2$]

$q_{rsw}$: Heat loss by regulatory sweating [W/m$^2$]

$r$: Evaporative heat of water [J/kg]

$t$: Time [s]

$v_{bl}$: Skin blood flow rate [kg/(m$^2$·s)]

$F_{cl}$: Heat transfer efficiency of clothing [n.d.]

$F_{pcl}$: Vapor transfer efficiency of clothing [n.d.]

$K_{min}$: Minimum heat conductance by skin tissue [W/(m$^2$·K)].

$M$: Metabolic rate [W/m$^2$]

$N$: Number of data obtained in a series of transient state [n.d.]

$P_a$: Saturated vapor pressure of ambient air [mmHg]

$P_{sk}$: Saturated vapor pressure due to skin temperature [mmHg]

$S$: Body surface area [m$^2$]

$T$: Calculated temperature [°C]

$T'$: Measured temperature [°C]

$W$: Mass [kg]

$\alpha$: Heat transfer coefficient [W/(m$^2$·K)]

$\alpha'$: Moisture transfer coefficient [kg/(m$^2$·s·mmHg)]

$\phi_a$: Relative humidity (fraction) [n.d.]

$\eta$: Working efficiency [n.d.]

SUFFIX

*bl*: blood

*c*: convective

*cr*: core

*o*: ambient

*r*: radiative

*set*: set point

*sk*: skin

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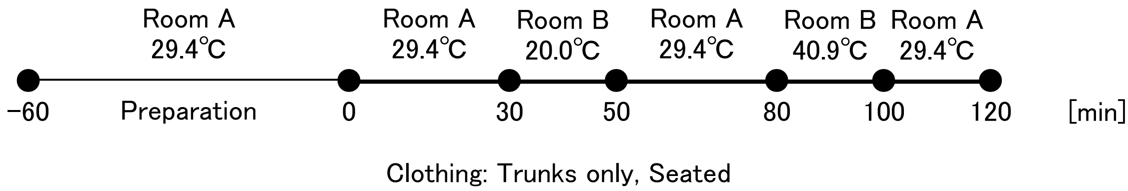


*Figure 1 Schedule of experiment*

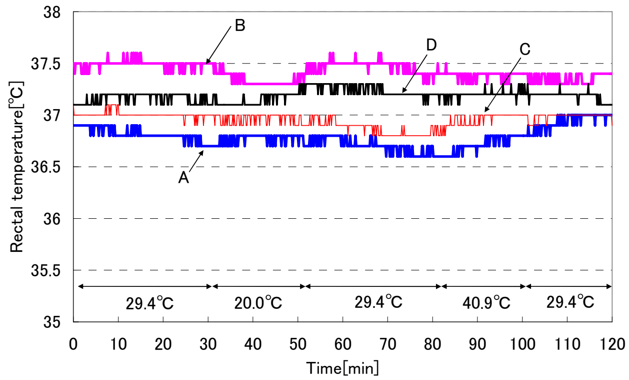


*Figure 2 Rectal temperature (Experiment)*

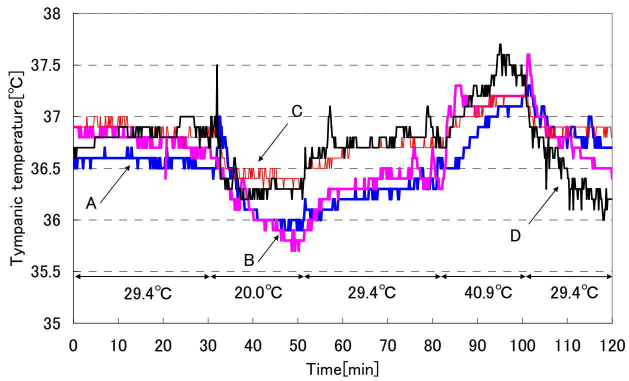


*Figure 3 Tympanic temperature (Experiment)*

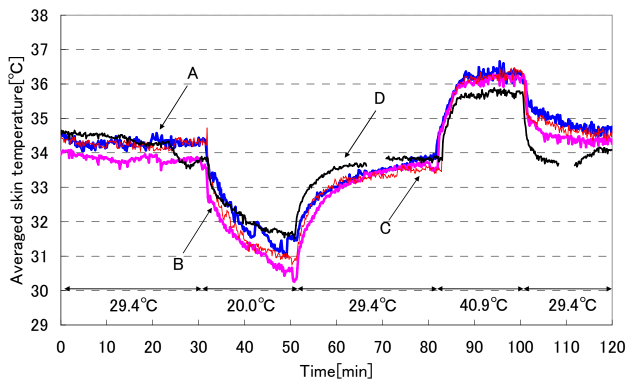


*Figure 4 Averaged skin temperature (Experiment)*

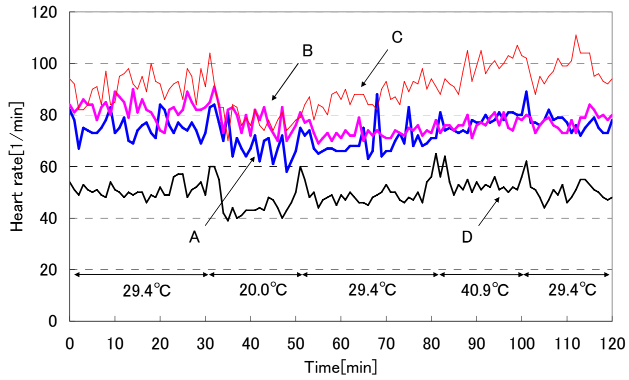


*Figure 5 Heart rate (Experiment)*

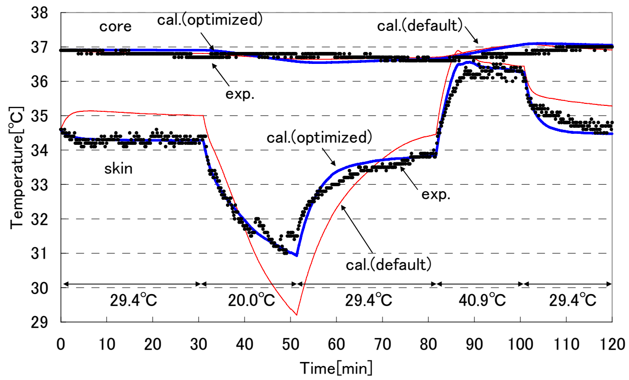


*Figure 6 Calculated and measured results of subject A (Core and skin temperatures)*

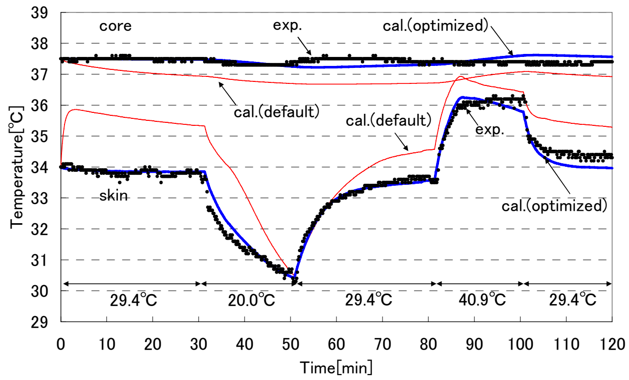


*Figure 7 Calculated and measured results of subject B (Core and skin temperatures)*

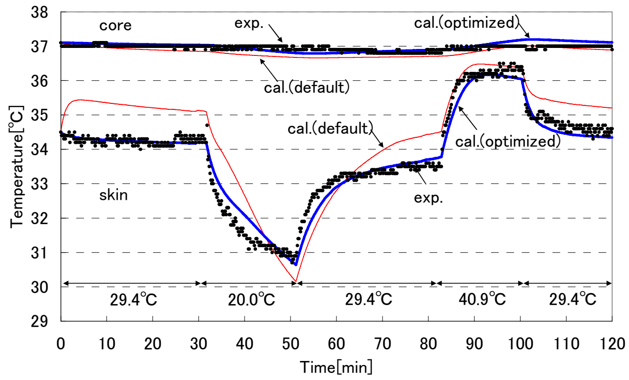


*Figure 8 Calculated and measured results of subject C (Core and skin temperatures)*

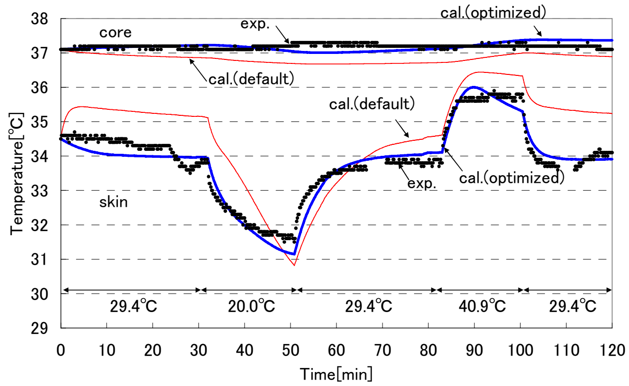


*Figure 9 Calculated and measured results of subject D (Core and skin temperatures)*

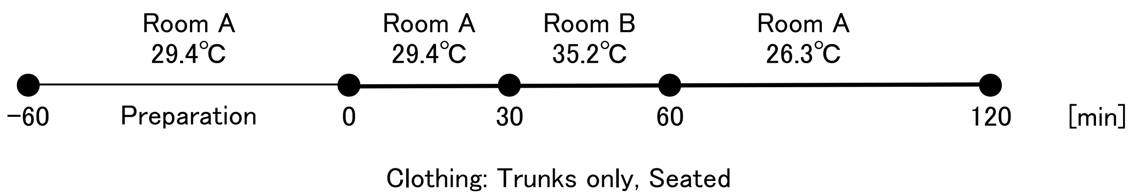


*Figure 10 Schedule of experiment for verification*

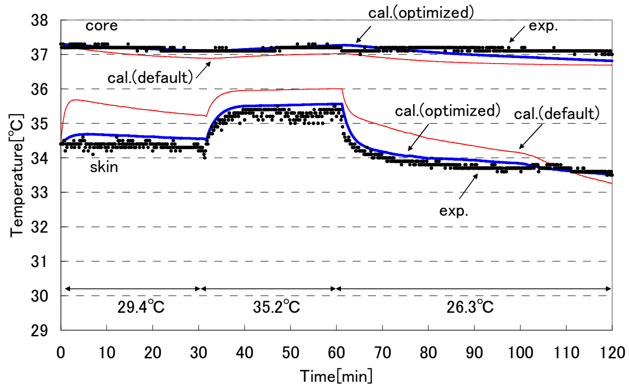


*Figure 11 Calculated and measured results of subject A (Core and skin temperatures)*

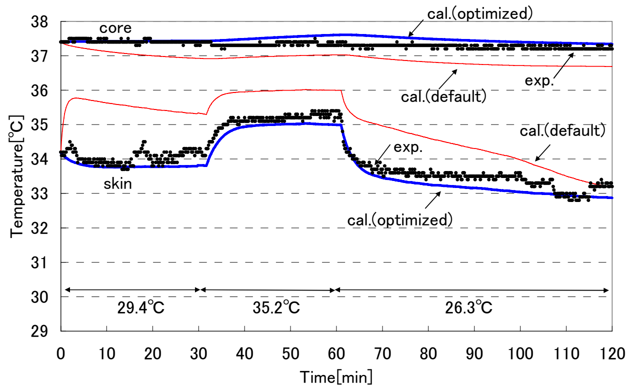


*Figure 12 Calculated and measured results of subject B (Core and skin temperatures)*

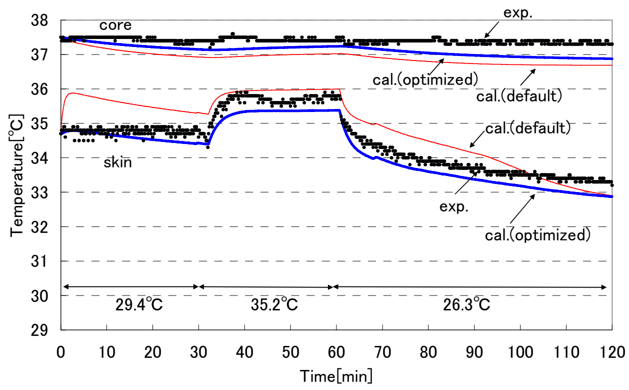


*Figure 13 Calculated and measured results of subject C (Core and skin temperatures)*

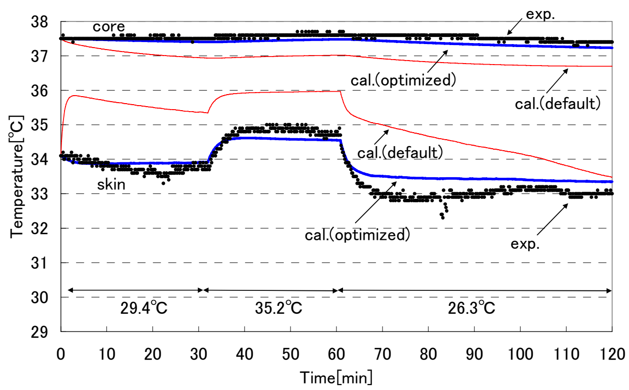


*Figure 14 Calculated and measured results of subject D (Core and skin temperatures)*

*Table 1 Information on subjects*

| | AGE | HT | WT | SEX | BSA | FITNESS |
|---|---|---|---|---|---|---|
| | [year] | [cm] | [kg] | [–] | [$m^2$] | [–] |
| A | 25 | 169 | 55.6 | Male | 1.64 | Healthy |
| B | 24 | 167 | 66.0 | Male | 1.73 | Healthy |
| C | 24 | 163 | 54.8 | Male | 1.59 | Healthy |
| D | 24 | 174 | 76.8 | Male | 1.89 | Healthy |

HT: Height, WT: Weight, BSA: Body surface area calculated from height and weight [10]

*Table 2 Measured items and methods*

| ITEM | METHOD (INSTRUMENT) |
|---|---|
| Core temperature (tympanic, rectal) | Thermocouple (T type, 0.2 mm in diameter) |
| Skin temperature (head, forearm, back of hand, instep, calf, thigh, abdomen) | Thermocouple (T type, 0.2 mm in diameter) |
| Heart rate | Photoelectric pulse wave method (Cat Eye) |
| Body weight | Electric balance (Mettler Toledo KCC 150) |
| Air and globe temperatures | Thermocouple (T type, 0.2mm in diameter) |
| Relative humidity | Electric resistance method (T and D, TR-72S) |
| Wind velocity | Hot wire method (Kanomax, 6543) |

*Table 3 Weight loss (difference between weight before and after experiment)*

| | WEIGHT LOSS | |
|---|---|---|
| | [g/h] | [g/(h·$m^2$)] (per body surface area) |
| A | 61.4 | 37.0 |
| B | 89.9 | 52.9 |
| C | 53.8 | 33.6 |
| D | 94.5 | 52.0 |

*Table 4 Environmental conditions (measured values averaged for time)*

| Time[min] | 0 to 31 | 31 to 51 | 51 to 81 | 81 to 101 | 101 to 120 |
|---|---|---|---|---|---|
| | Room A | Room B | Room A | Room B | Room A |
| Air temperature[℃] | 29.4 | 20.0 | 29.4 | 40.9 | 29.4 |
| Relative humidity[%] | 47.5 | 55.6 | 47.6 | 53.5 | 47.8 |
| Globe temperature[℃] | 29.6 | 20.2 | 29.5 | 40.2 | 29.6 |
| Wind velocity[m/s] | 0.10 | 0.24 | 0.10 | 0.12 | 0.12 |

*Table 5 Candidate parameters for potimized two-node model in optimization (calculations performed for all combinations of these six parameters)*

| pr1 | pr2 | pr3 | pr4 | pr5 | pr6 |
|---|---|---|---|---|---|
| 37.7 | 34.7 | 100 | 12.6 | 150 | 1 |
| 37.5 | 34.5 | 80 | 10.08 | 120 | 0.8 |
| 37.3 | 34.3 | 60 | 7.56 | 90 | 0.6 |
| 37.1 | 34.1 | 40 | 5.04 | 60 | 0.4 |
| 36.9 | 33.9 | 20 | 2.52 | 30 | 0.2 |
| 36.7 | 33.7 | 10 | 1.26 | 15 | 0.1 |
| 36.5 | 33.5 | 5 | 0.63 | 7.5 | 0.05 |
| 36.3 | 33.3 | | 0.315 | 3.75 | 0.025 |
| 36.1 | 33.1 | | 0.1575 | | 0.0125 |
| 35.9 | 32.9 | | 0.07875 | | 0.00625 |
| 35.7 | 32.7 | | | | |
| 35.5 | 32.5 | | | | |
| 35.3 | 32.3 | | | | |
| 35.1 | 32.1 | | | | |
| 34.9 | 31.9 | | | | |

*Table 6 Calculation conditions*

| | |
|---|---|
| Air temperature | Measured data |
| Air humidity | Measured data |
| MRT | Equal to air temperature |
| Convective heat transfer coefficient | 3.1[W/(m$^2$・K)] |
| Radiative heat transfer coefficient | 4.65[W/(m$^2$・K)] |
| Clothing | 0.1[clo] |
| Metabolic rate | 58.2[W/m$^2$] |
| External mechanical efficiency | 0 |
| Thermal conductance between core and skin | 5.28[W/(m$^2$・K)] |

*Table 7 Combination of parameters that minimizes difference between experimental and calculated skin and core temperatures in two-node model for each subject, and value of objective function (J)*

| Subject | Parameter | | | | | | J |
|---|---|---|---|---|---|---|---|
| | Pr1 | Pr2 | Pr3 | Pr4 | Pr5 | Pr6 | |
| | $T_{cr,set}$ [℃] | $T_{sk,set}$ [℃] | Perspiration [g/(m$^2$・h・K$^2$)] | Basal blood flow rate [kg/(m$^2$・h)] | Vaso dilation [kg/(m$^2$・h・K)] | Vaso constriction [1/K] | |
| A | 36.1 | 32.7 | 10 | 1.26 | 15 | 0.00625 | 51.1 |
| B | 36.9 | 32.3 | 20 | 0.07875 | 15 | 0.00625 | 54.9 |
| C | 36.7 | 32.1 | 20 | 2.52 | 30 | 0.00625 | 61.3 |
| D | 37.1 | 33.1 | 100 | 7.56 | 7.5 | 0.00625 | 71.1 |
| default | 36.6 | 34.1 | 100 | 6.3 | 75 | 0.5 | |

*Table 8 Environmental conditions (measured values averaged for time)*

| Time[min] | 0 to 32 | 32 to 61 | 61 to 120 |
|---|---|---|---|
| | Room A | Room B | Room A |
| Air temperature[℃] | 29.4 | 35.2 | 26.3 |
| Relative humidity[%] | 47.1 | 47.3 | 46.0 |
| Globe temperature[℃] | 29.6 | 35.0 | 27.0 |
| Wind velocity[m/s] | 0.10 | 0.11 | 0.12 |