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VALIDITY OF THE TWO-NODE MODEL FOR PREDICTING STEADY-STATE SKIN TEMPERATURE

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ABSTRACT

The validity of the two-node model for predicting the skin temperature in the thermal steady state is studied by comparing the calculated and experimental results for various thermal conditions. For the experimental results of steady-state skin temperature, in addition to the authors' original experimental data, literature data for mean skin temperature are collected, incorporating 56 conditions and 233 subjects in total. The results show that the two-node model (the 1986 edition) that is widely used for calculating SET* predicts effectively the steady-state skin temperature in the low-activity conditions. Additionally, the changes that were made to the two-node model by Gagge et al. and ASHRAE are summarized. It is shown theoretically and by experimental validations that, of these changes, the addition of the shivering model represents the most significant improvement in terms of predicting the skin temperature in the steady state.

KEYWORDS

Thermal model of human body; Two-node model; Steady state; Skin temperature; Subject experiment; Shivering

1. INTRODUCTION

Many thermal models of the human body have recently been proposed, and several of these models treat the thermal system of the human body as a set of many nodes [1-4]. These models are expected to be utilized for a wide variety of purposes. In order to apply these models to designing or controlling the architectural environment, it is important to clarify their reproducibility [5], which has not been done sufficiently. Validation of a model requires a comparison of its results with experimental data. In reality, however, it is not easy to obtain an experimental data set large enough for the model validation, because the data sets need to cover a wide range of thermal conditions and human subject characteristics. Therefore, there are only a limited number of the thorough validations of a thermal models of the human body [2,5,6-10].

Individual differences in the characteristics of the thermophysiological responses of the human body are also an important issue in this field [11-13]. These differences make it difficult to validate the thermal models of the human body. Thus, one of the approaches is to determine the average behavior of the human thermal system for a large number of subjects.

From these perspectives, this paper evaluates the validity of the two-node model, which is one of the simplest human thermal models, by focusing on the steady state. The two-node model (TNM) was proposed by Gagge et al. [14]. It is famous not only as a necessary scheme for calculating SET* but also as a foundation for developing a new human thermal model. The steady-state solutions of the TNM for skin temperature, skin heat flux, and skin wettedness are used to calculate SET*, and the steady-state solution is a basis for studying non-steady-state solutions. This paper combines the authors' original data with literature skin temperature data from several sources that cover a wide range of environmental conditions from low temperatures to high temperatures. The data are compared with the results calculated by the TNM. The selected experimental data were collected and describe a sedentary steady state. The validity of the calculated steady-state skin temperatures are compared against two versions of the TNM: the 1971 (original) edition [15] and the 1986 edition, which is the latest edition by Gagge et al. that is typically recognized as the TNM [16].

2. METHODOLOGY

2.1 Experimental data

Theoretically, the thermophysiological state in steady state is decided when the six elements of the thermal environment (air temperature, air humidity, wind velocity, thermal radiation, clothing, and metabolic rate) are given, unless the condition is too hot or too cold to be well regulated. In order to obtain the experimental data on the thermophysiological state in steady state, the subjects were put into an artificial climate chamber, and the six elements of the thermal environment were fixed until the steady state was achieved. The experiment continued until thermophysiological parameters, such as skin and core temperatures and sweating rate, became constant.

This paper utilizes data from several subject experiments in which multiple subjects were exposed to the same environmental conditions. In addition to the authors' original experimental data, literature data for mean skin temperature are collected, most of which are based on Hardy and DuBois' seven-point method. The collected data set incorporates 56 conditions and 233 subjects in total, and exposure conditions range from 16 to 40 ºC for air temperature, from 40% to 72% for relative humidity, and from 0.06 to 0.6 for the clo value. The resultant skin temperatures range from 29.4 to 36.1 ºC. Studied conditions and the resultant skin temperatures are detailed in Table 1; the metabolic rate does not contain the contribution from shivering. If the original literature presented skin temperature in the transient state, the terminal constant value was used. In order to understand the average behavior of the majority, data for all the subjects in a single set of experimental data were averaged. Several sources lacked detailed descriptions of wind velocity or the thermal radiation; in these cases, the wind is assumed to be calm and the mean radiant temperature is assumed to equal the air temperature because all of the selected experiments were conducted indoors.

2.2 Basic equations of TNM

The basic equations of TNM are as follows.

The heat balance equation of the core node:

$$cm_{cr}\frac{dT_{cr}}{dt} = A\left(-q_{cr:sk} - q_{cr:am} + M - W\right) \tag{1}$$

The heat balance equation of the skin node:

$$cm_{sk}\frac{dT_{sk}}{dt} = A\left(q_{cr:sk} - q_{sk:am}\right) \tag{2}$$

The heat flow from core to skin by blood flow and heat conductance, from core to ambient by respiration, and from skin to ambient by convection and radiation are as follows.

$$q_{cr:sk} = \left(c_{bl}\rho_{bl}\dot{V}_{bl}\cdot\frac{1}{3600}\cdot\frac{1}{1000} + K_{min}\right)\left(T_{cr} - T_{sk}\right) \tag{3}$$

$$q_{cr:am} = 1.4\cdot 10^{-3}\cdot M\left(34 - T_{am}\right) + 0.0023\cdot M\left(44 - P_{am}\right) \tag{4}$$

$$q_{sk:am} = \left\{\alpha_c\left(T_{sk} - T_{am}\right) + \alpha_r\left(T_{sk} - T_{mrt}\right)\right\}F_{cl}$$

$$+ 0.06\cdot r\cdot\alpha'\cdot F_{pcl}\cdot\left(P_{sk,sat} - P_{am}\right) + 0.94\cdot r\cdot\dot{m}_{rsw}\cdot\frac{1}{3600}\cdot\frac{1}{1000} \tag{5}$$

The mass of each node is expressed as the mass ratio of skin to total body:

$$m_{cr} = m_{bm}\left(1 - \alpha\right) \tag{6}$$

$$m_{sk} = m_{bm}\alpha \tag{7}$$

$$\alpha = C_{\alpha 1} + \frac{C_{\alpha 2}}{\dot{V}_{bl} + C_{\alpha 3}} \tag{8}$$

where the mass ratio of skin to total body is a function of the skin blood flow rate (this ratio is a constant in the 1971 edition).

The signals for body temperature regulation are defined as follows:

$$wsig_{cr} = \begin{cases} T_{cr} - T_{cr,set} & \left(T_{cr} > T_{cr,set}\right) \\ 0 & \left(T_{cr} \le T_{cr,set}\right) \end{cases} \tag{9}$$

$$wsig_{sk} = \begin{cases} T_{sk} - T_{sk,set} & \left(T_{sk} > T_{sk,set}\right) \\ 0 & \left(T_{sk} \le T_{sk,set}\right) \end{cases} \tag{10}$$

$$wsig_{bm} = \begin{cases} T_{bm} - T_{bm,set} & \left(T_{bm} > T_{bm,set}\right) \\ 0 & \left(T_{bm} \le T_{bm,set}\right) \end{cases} \tag{11}$$

$$csig_{cr} = \begin{cases} 0 & \left(T_{cr} \ge T_{cr,set}\right) \\ T_{cr,set} - T_{cr} & \left(T_{cr} < T_{cr,set}\right) \end{cases} \tag{12}$$

$$csig_{sk} = \begin{cases} 0 & \left(T_{sk} \ge T_{sk,set}\right) \\ T_{sk,set} - T_{sk} & \left(T_{sk} < T_{sk,set}\right) \end{cases} \tag{13}$$

where

$$T_{bm} = \alpha \cdot T_{sk} + \left(1 - \alpha\right) \cdot T_{cr} \tag{14}$$

The skin blood flow rate is expressed as a function of the warm signal from the core and the cold signal from the skin:

$$\dot{V}_{bl} = \frac{\dot{V}_{bl,basal} + C_{bl,dil} \cdot wsig_{cr}}{1 + C_{bl,str} \cdot csig_{sk}} \tag{15}$$

The sweating rate is expressed as a function of the warm signals both from the whole body and from the skin in the 1986 edition:

$$\dot{m}_{rsw} = C_{rsw,M2} \cdot wsig_{bm} \cdot exp\left(\frac{wsig_{sk}}{C_{rsw,P2}}\right) \tag{16}$$

In the 1971 edition, the sweating rate is expressed in terms of warm signals from both the core and the skin.

$$\dot{m}_{rsw} = \left(C_{rsw,M1} \cdot wsig_{cr} \cdot wsig_{sk} + C_{rsw,Mex1} \cdot wsig_{cr}\right) \cdot 2^{\left(T_{sk} - T_{sk,set}\right)/C_{rsw,P1}}$$

$$= \left(C_{rsw,M1} \cdot wsig_{cr} \cdot wsig_{sk} + C_{rsw,Mex1} \cdot wsig_{cr}\right) \cdot exp\left(\frac{wsig_{sk} - csig_{sk}}{C_{rsw,P1} \cdot ln\, 2}\right) \tag{17}$$

The increase in the metabolic rate due to shivering is expressed as a function of the cold signals from both the core and the skin.

$$M_{shiv} = C_{shiv} \cdot csig_{cr} \cdot csig_{sk} \quad (18)$$

All of the coefficients included in the temperature regulation equations are summarized in Table 2.

2.3 Calculation conditions

The steady-state solution is obtained by executing the non-steady calculation for ten hours, beginning from the initial skin and core temperatures at the set point values. The other conditions used in the calculations are summarized in Table 3.

3. COMPARISON BETWEEN EXPERIMENTAL AND CALCULATED RESULTS

Calculated, steady-state skin temperatures for the experimental data are shown in Figure 1, where they are compared to measured skin temperatures (Table 1). Based on the 1986 edition of the TNM, the calculated and experimental values agree for conditions ranging from low to high temperatures. On the other hand, based on the 1971 edition, the calculated skin temperatures show good agreement with experimental results for high-temperature conditions but not the low-temperature conditions, where the skin temperature is less than 33 ºC. This difference is due to the fact that shivering is incorporated into the 1986 edition but not the 1971 edition of the model.

Calculated core temperature, skin blood flow rate, sweating rate, shivering rate, and mass ratio of skin to whole body are shown in Figures 2 through 6. These values are compared to measured skin temperatures for a more-detailed description of the calculated results, not for the validation of the model. Core temperatures (Figure 2) calculated from the 1971 edition are low for low air temperature conditions due to the absence of the shivering model. The skin blood flow rate (Figure 3) calculated from the 1986 edition is higher under low air temperature conditions and lower under high air temperature conditions due to differences in the coefficients of vasoconstriction and vasodilation, which are shown in Table 2. The sweating rates in both editions (Figure 4) are similar despite differences in the form of the equation and the coefficients. Shivering and variable mass ratios of the skin to whole body are included in only the 1986 edition of the model (Figures 5 and 6).

The differences between calculated and experimental skin temperatures are 0.56 K for the 1986 edition and 1.6K for the 1971 edition, on average, the RMS difference. The 1986 edition of TNM can predict the skin temperature with satisfactory precision for a wide range of environmental conditions from low to high air temperature.

4. DISCUSSION

4.1 Causes of the differences in reproducibility between different editions of the TNM

Calculated results from the 1986 edition nearly match experimental results for all range of the temperature environment. On the other hand, the steady-state calculated skin temperatures calculated from the 1971 edition are lower than the measured skin temperatures in a low-temperature environment; this is because of the absence of the shivering model in the 1971 edition, not because of the difference in the sweating and skin blood flow model between the two editions, as explained below. For a high-temperature environment, calculated results from both editions agree with the experimental results; thus, the discussion below focuses on the low-temperature cases.

In the steady state, the heat balance equations of the core and skin nodes (Equations 1 and 2) are as follows.

$$0 = -q_{cr:sk} - q_{cr:am} + M - W \tag{19}$$

$$0 = q_{cr:sk} - q_{sk:am} \tag{20}$$

From these equations, the following equation is derived:

$$0 = -q_{sk:am} - q_{cr:am} + M - W \tag{21}$$

Because sweating does not occur in the low-temperature environment, the difference in the sweating model does not influence the skin temperature and

$$\dot{m}_{rsw} = 0 \tag{22}$$

Therefore, equation (21) becomes:

$$0 = -\{\alpha_c(T_{sk} - T_{am}) + \alpha_r(T_{sk} - T_{mrt})\}F_{cl} - 0.06 \cdot r \cdot \alpha' \cdot F_{pcl} \cdot (P_{sk,sat} - P_{am})$$

$$-1.4 \cdot 10^{-3} \cdot M(34 - T_{am}) - 0.0023 \cdot M(44 - P_{am}) + M - W \tag{23}$$

From equation (23), skin temperature is obtained as follows:

$$T_{sk} = f(T_{am}, T_{mrt}, P_{am,} \alpha_c, \alpha_r, \alpha', F_{cl}, F_{pcl,} M, W) \tag{24}$$

Therefore, steady state skin temperature is controlled by given conditions of the environment, clothing, and activity (including shivering) without any relationship to the sweating and skin blood flow rate models. The shivering model is the essential difference between the 1971 and 1986 editions from the viewpoint of steady-state skin temperature. In the 1986 edition, the decrease in skin temperature in a low-temperature environment is suppressed by shivering.

Although skin ratio and its variation due to the skin blood flow rate are larger in the 1986 edition, they are related to the capacitance of the core and skin nodes and are unrelated to the steady-state characteristics.

4.2 Evolution of the TNM

As shown in Table 4, several versions of the TNM were developed between the 1971 and 1986 editions and after the 1986 edition. The model framework remains basically constant in all of the editions, but the values of the coefficients in the regulatory responses change. In the 1972 version [26], the shivering model and the skin ratio change model are introduced and the form of the sweating regulation equation is changed. The authors (Gagge et al.) might have attempted to modify the model to agree with experimental results. As discussed in section 4.1, the results of the steady-state skin temperature calculated by the TNM agree well with experimental results after the introduction of the shivering model. Therefore, the authors were likely studying experimental data other than skin temperature (core temperature, sweating rate, skin blood flow rate, etc.) or data for a non-steady state.

Although data for core temperature, sweating rate, and skin blood flow rate are more difficult to obtain than data for skin temperature, it is necessary to check the agreement between the experimental and calculated results for these parameters [7].

According to the recent ASHRAE Handbook of Fundamentals, “the TNM can be used to predict physiological responses or responses to transient situations, at least for low and moderate activity levels in cool to very hot environments” [29] . The evidence of this description, however, is not explicitly shown by the comparison between measured and calculated results. It is necessary to study the validity of the TNM in transient situations.

4.3 Subject experiment

This paper utilizes data measured by various researchers; thus, experimental skin temperature values are associated with heterogeneous conditions (e.g., the number of the subjects averaged, the method (the precision) of the measurement, the exposure time to a constant thermal condition, and the gender of the subjects). The authors tried to select only the data that was suitable for the analysis of steady-state skin temperature for which a detailed explanation of the experimental conditions was available.

Although each experimental data set includes some error due to the variety in the conditions, the number of the data sets in this paper is large enough to evaluate the averaged behavior of a large population.

4.4 Difficulty in obtaining thermophysiological data in the steady state

It is not difficult to obtain a steady-state solution using a human thermal model that simulates the exposure to a constant thermal condition. The steady-state solution is derived by putting zero in the terms that represent the rate of body temperature (the left side of equations (1) and (2)). In this paper, the steady-state solution is obtained by the non-steady state calculation for a sufficiently long time (this is described in 2.3). Under a constant thermal condition, the influence of the initial condition to the non-steady solution becomes smaller as the calculation progresses until the influence is eliminated when it reaches the steady-state.

In a subject experiment, however, it is more difficult to obtain strictly steady-state data. The longer the exposure time, the more the data would approach steady state, but the harder the subject experiment becomes. Thus, data sets involving long exposure times are limited and precious. In this paper, the authors tried to select the data that had the longest possible exposure times to constant thermal conditions. Most of the exposure times ranged from 60 to 90 minutes.

4.5 Previous attempts for validation of thermal models of the human body

In this paper, the validation is focused on the steady-state solution of the TNM. For the TNM of the 1986 edition, Doherty et al. [7] conducted an extensive validation for a wide range of conditions, including high and low activities, and they found that the experimental and the calculated results agreed better for resting conditions than they did for high-activity conditions. Their analysis included a lot of experimental data for a short time of exposure (e.g., less than 30 minutes), and it was not entirely clear that the validation was for the steady state. In the present paper, the data were from longer exposures to clarify the precision of the steady-state solution of the TNM, even though the activity level was limited to resting conditions.

Berglund [32] studied the precision in predicting thermal comfort for a wide range of temperature conditions, and the TNM was included in the prediction model. The results, however, were outputted as thermal comfort. Therefore the validity of the TNM could not be assessed. Minami et al. [19] also studied the validity of the TNM for high-temperature environments and proposed an improved equation of the regulatory sweating control. When a new human thermal model is proposed, the proposer usually shows the validity of the model by comparing the calculated results from the new model with experimental results [2,8-10,33]. However, the validation of a widely used model, such as the TNM, leaves rooms for future studies.

In this paper, the authors focused on the steady-state skin temperature solution of the TNM, which provides an important basis for developing new human thermal models or evaluating thermal comfort (and is necessary for calculating SET*), by comparing the experimental data collected from the literatures.

5. CONCLUSION

Based on the experimental results for a large number of subjects under various thermal environmental conditions, the validity of the two-node model for predicting steady-state skin temperature was evaluated. The prevailing edition of the two-node model (the 1986 edition) can predict steady-state skin temperature with satisfactory precision for an average person. In addition, the evolution of the two-node model since 1971 was summarized. The introduction of the shivering model improved the prediction of steady-state skin temperature. The other changes in the model were likely intended to improve the other capabilities of the model for predicting in non-steady state or thermophysiological variables other than skin temperature.

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NOMENCLATURE

c: Specific heat [J/(kg·K)]

$csig$: Cold signal [K]

m: Mass [kg]

$\dot{m}_{rsw}$: Regulatory sweating rate [g/(m^2·h)]

q: Heat flux [W/m^2]

r: Evaporative heat of water [J/kg]

t: Time [s]

$wsig$: Warm signal [K]

A: Body surface area [m^2]

$C_{bl,basal}$: Skin blood flow rate under thermally neutral conditions [liter/(m^2·h)]

$C_{bl,str}$: Coefficients of vasoconstriction [1/K].

$C_{bl,dil}$: Coefficients of vasodilation [liter/(m^2·h·K)]

$C_{rsw,M1}$: Coefficient in sweating rate model [g/(m^2·h·K^2)]

$C_{rsw,Mex1}$: Coefficient in sweating rate model [g/(m^2·h·K)]

$C_{rsw,M2}$: Coefficient in sweating rate model [g/(m^2·h·K)]

$C_{rsw,P1}$: Coefficient in sweating rate model [K]

$C_{rsw,P2}$: Coefficient in sweating rate model [K]

C_{shiv}: Coefficient of shivering model [W/(m^2·K^2)]

$C_{\alpha 1}$: Coefficients in skin mass ratio model [n.d.]

$C_{\alpha 2}$: Coefficient in skin mass ratio model [liter/(m^2·h)]

$C_{\alpha 3}$: Coefficient in skin mass ratio model [liter/(m^2·h)]

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]

M_{shiv}: Increase in metabolic rate due to shivering [W/m^2]

P: Vapor pressure [mmHg]

T: Temperature [°C]

$\dot{V}_{bl}$: Skin blood flow rate [liter/(m^2·h)]

W: External work [W/m^2]

α: Skin mass ratio [n.d.]

α_c: Convective heat transfer coefficient [W/(m^2·K)]

α_r: Radiative heat transfer coefficient [W/(m^2·K)]

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

ρ : Density [kg/m^3]

SUFFIX

am: ambient

bl: blood

bm: whole body (average of core and skin)

cr: core

dl: vasodilation

mrt: mean radiant temperature

rsw: regulatory sweating

sat: saturated

set: set point

sk: skin

str: vasoconstriction

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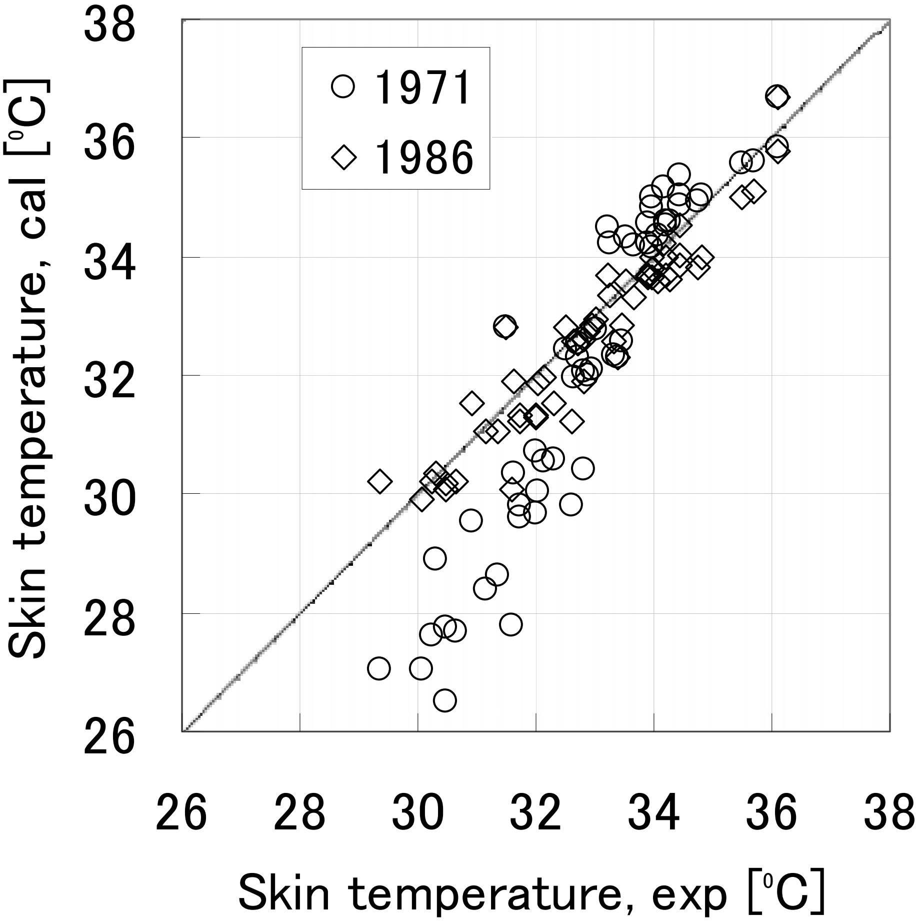

Figure 1 Comparison of calculated steady-state skin temperature and measured skin temperature

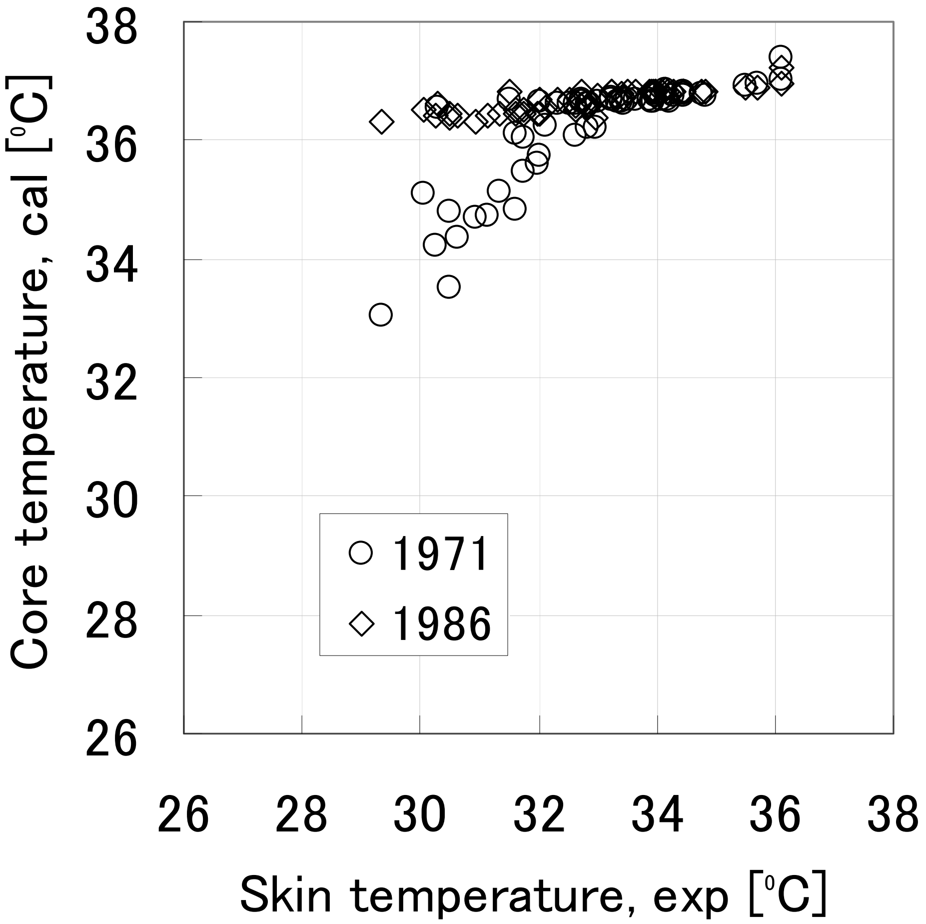

Figure 2 Comparison of calculated steady-state core temperature and measured skin temperature

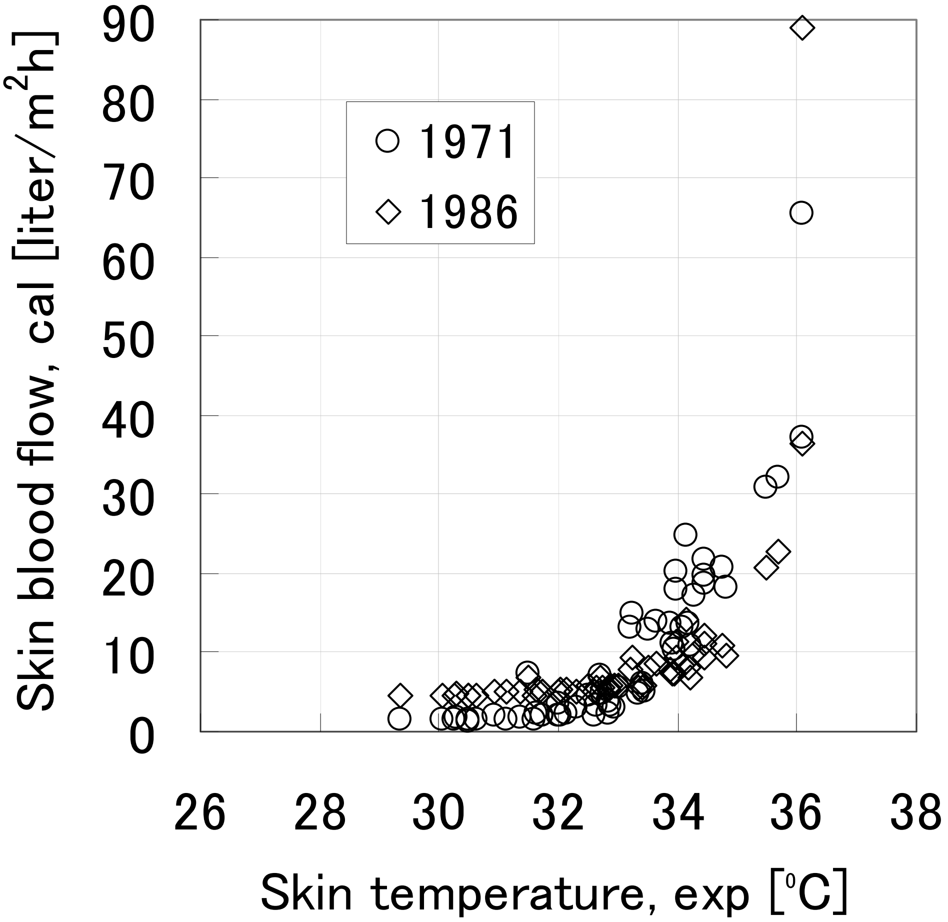

Figure 3 Comparison of calculated skin blood flow rate in the steady state and measured skin temperature

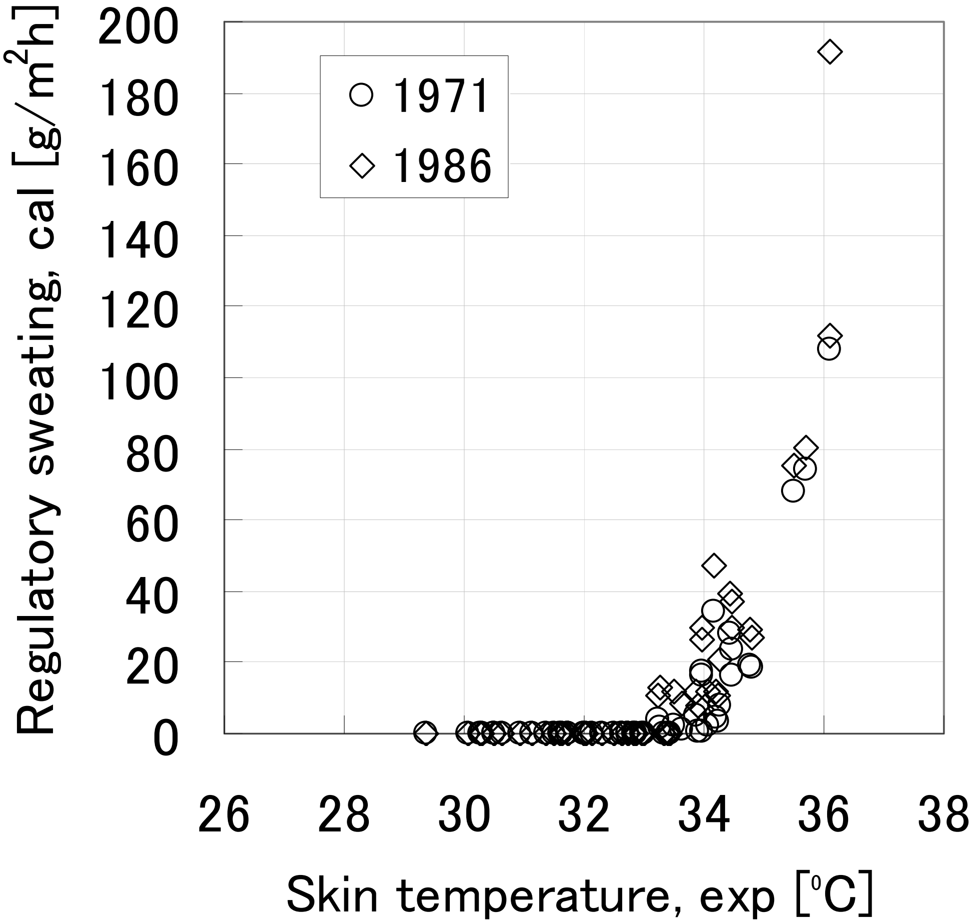

Figure 4 Comparison of calculated sweating rate in the steady state and measured skin temperature

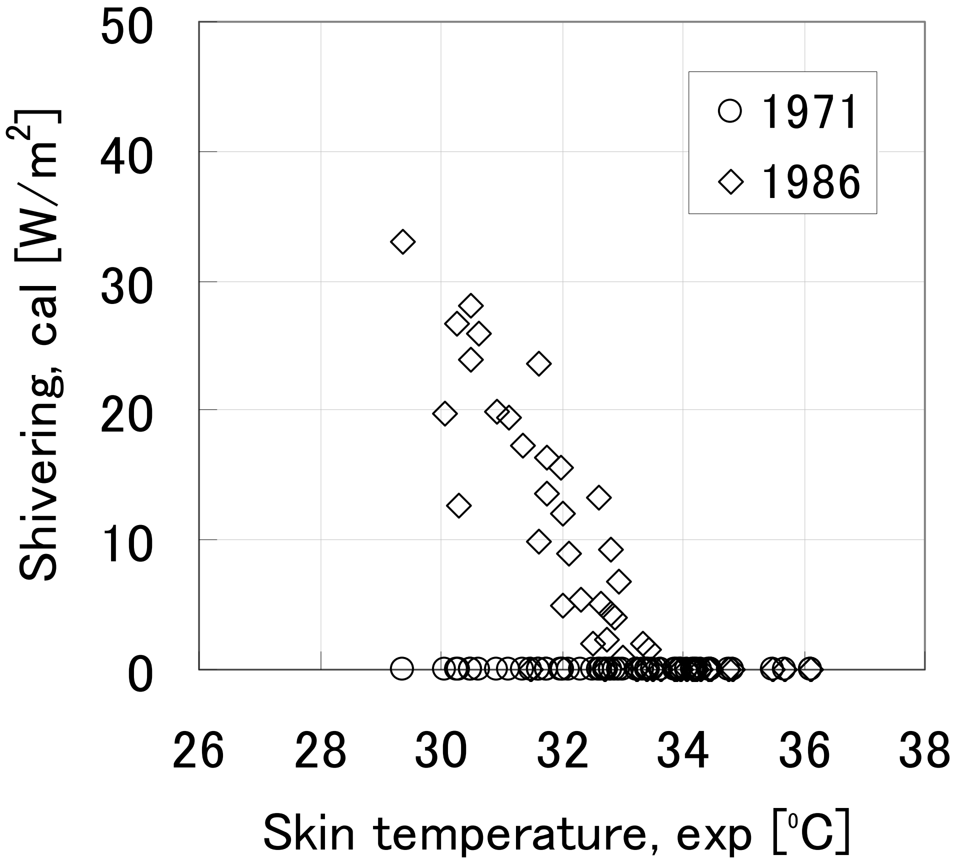

Figure 5 Comparison of calculated shivering in the steady state and measured skin temperature

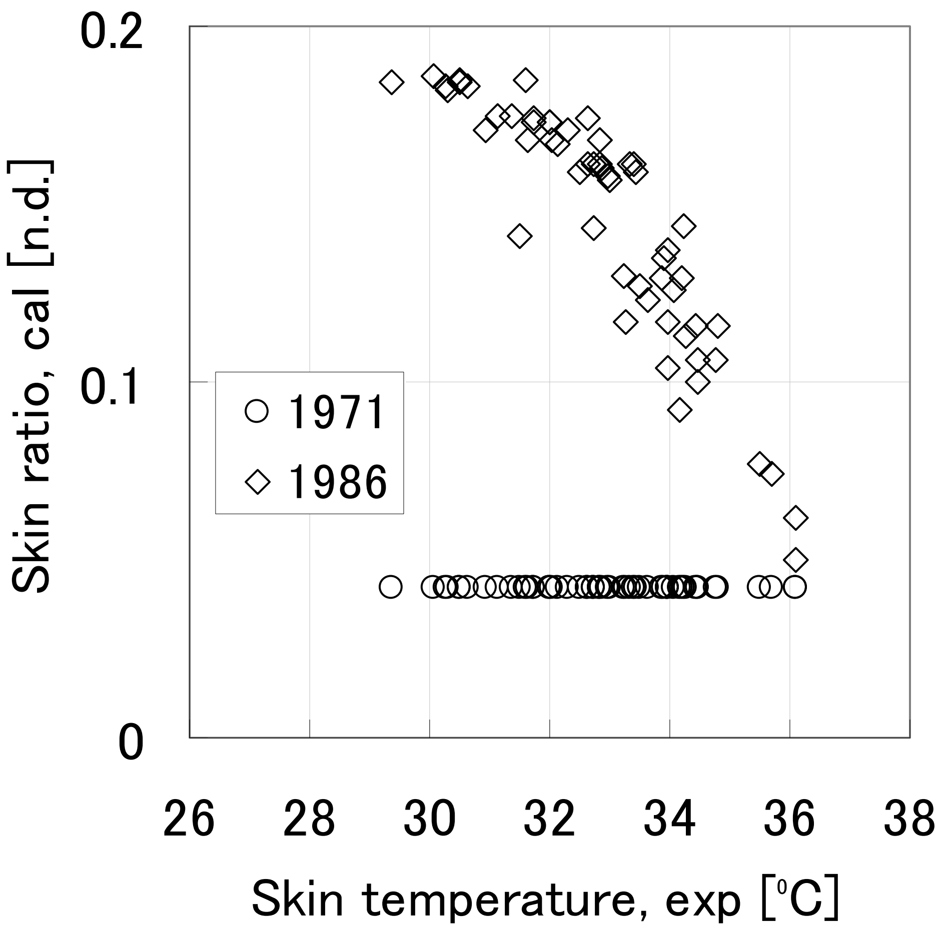

Figure 6 Comparison of calculated skin mass to whole body ratio in the steady state and measured skin temperature

Table 1 Details of the experiments used to validate TNM for the steady state, including calculated results associated with each experimental data set [11-19]

Reference		Thermal Environmental Conditions				Experimental Conditions			Subjects				Mean Skin Temperature in Steady State		
		Air Tempera-ture [℃]	Relative Humidity [%]	Clothing [clo]	Metaboric Rate [Met]	Exposure Time [min]	Method of Selecting Steady-State Data**	Method of Measuring Skin Temperature	Average Height [cm]	Average Weight [kg]	Total Number of Subjects		Experimental Mean Skin Temperature [℃]	*Calculated Mean Skin Temperature[℃]*	
											Male	Female		*1971 Edition*	*1986 Edition*
	Authors	29.4 26.3 38.8	47.0 46.1 68.1	0.06	1.0*	90 60 40	A	Thermocouple	169.5 167.8 170.7	65.1 62.5 64.7	28 4 7	0 0 0	34.3 33.4 36.1	*34.6* *32.7* *36.7*	*33.6* *32.7* *36.7*
[17]	Mori et al. (2003)	26.8 31.1 30.4	47.0 49.6 43.6	0.06	1.0*	60	A	Thermocouple	172.5 178.0 174.5	59.0 69.5 74.0	2 4 2	0 0 0	31.5 34.5 34.5	*32.7* *35.0* *34.8*	*32.6* *34.0* *33.8*
[18]	Tamura (1984)	22 25 28 31 34	50	0.1	0.7	120	A	Thermography	154.9	50.1	0	27	29.4 30.9 33.0 34.2 34.4	*27.2* *29.6* *32.1* *34.6* *35.4*	*30.1* *31.4* *32.8* *34.0* *34.5*
[19]	Minami et al. (2008)	35 35 40	50 70 50	0.5	1.0*	60	A	Thermistor			19 12	20 13	35.5 35.7 36.1	*35.6* *35.6* *35.9*	*35.0* *35.1* *35.9*
[20]	Ogawa et al. (1974)	21.8 24.2 26.9 29.2	60	0.06	0.9	90	B20	Thermistor			6	0	31.6 32.6 33.3 34.1	*27.7* *29.7* *32.2* *34.3*	*29.9* *31.1* *32.5* *33.6*
		21.8 24.2 26.9 29.2		0.1	0.8			Thermistor			0	6	30.6 32.0 32.8 33.9	*27.7* *29.6* *32.0* *34.2*	*30.1* *31.2* *32.5* *33.6*
		21.8 24.2 26.9 29.2		0.6	0.8			Thermistor			6	6	32.8 33.4 34.2 34.8	*30.4* *32.6* *34.5* *35.0*	*31.8* *32.8* *33.7* *34.0*
[21]	Ogawa et al. (1975)	21.8 24.2 26.9 29.2	60	0.06	0.9	90	B20	Thermistor			8	0	30.5 31.7 32.7 33.5	*27.7* *29.7* *32.2* *34.3*	*29.9* *31.1* *32.5* *33.6*
		21.8 24.2 26.9 29.2		0.1	0.8			Thermistor			0	8	30.3 31.7 32.6 34.0	*27.6* *29.6* *31.9* *34.1*	*30.1* *31.2* *32.5* *33.6*
		21.8 24.2 26.9 29.2		0.6	0.8			Thermistor			8	8	31.6 32.5 33.2 34.0	*30.4* *32.4* *34.5* *35.0*	*31.8* *32.7* *33.7* *34.0*
[22]	Ogawa et al. (1976)	19.5 22.0 24.5 27.0	60	0.6	0.8	90	B20	Thermistor			8	8	31.4 32.1 33.0 33.9	*28.7* *30.5* *32.8* *34.5*	*31.0* *31.9* *32.9* *33.7*
[23]	Ogawa et al. (1977)	17.1 19.6 21.8 24.2	60	0.6	0.8	90	B10	Thermistor			8	8	30.5 31.1 32.0 32.9	*26.7* *28.5* *30.1* *32.0*	*30.1* *31.0* *31.8* *32.7*
[24]	Arita et al. (1989)	16.1 20.5 24.4 27.7	50	0.6	1.0	90	B10	Thermocouple	167.7	59.6	4	0	30.1 32.3 33.6 34.8	*27.1* *30.6* *34.2* *34.9*	*29.8* *31.4* *33.3* *33.8*
[25]	Yokoyama et al. (2002)	22 24 26 28 30 32	72 64 57 51 45 40	0.06	1.0	60	A	Thermistor	168.3	63.2	3	0	30.3 32.0 32.7 33.3 34.0 34.2	*28.8* *30.0* *31.2* *32.5* *34.0* *34.4*	*30.2* *31.2* *32.3* *33.3* *33.8* *34.2*

* The value of the metabolic rate itself was not measured for this experiment. The value was estimated based on the description of the activity of the subjects.

**The skin temperature data were collected continuously during the exposure in the original literature. In this paper, only the data which were thought to be in the steady state were selected. Basically, the instantaneous data at the end of the exposure time were selected (method A), but in some studies, only the data averaged for some period near the end of the exposure were shown (method B). In method B, the number after ‘B’ shows the time period that was used to average the data. For example, ‘B10’ means the data from 10 minutes prior to the end of the exposure time were averaged.

Table 2 Coefficients included in TNM [14,15]

	$C_{\alpha 1}$ [n.d.]	$C_{\alpha 2}$ [liter/m^{2}h]	$C_{\alpha 3}$ [liter/m^{2}h]	$C_{rsw,M1}$ [g/m^{2}hK^2]	$C_{rsw,P1}$ [K]	$C_{rsw,M2}$ [g/m^{2}hK]	$C_{rsw,P2}$ [K]
1971 edition	0.042	–	–	100	3	–	–
1986 edition	0.042	0.745	0.585	–	–	170	10.7

	$T_{cr,set}$ [°C]	$T_{sk,set}$ [°C]	$V_{bl,basal}$ [liter/m^{2}h]	$C_{bl,dil}$ [liter/m^{2}hK]	$C_{bl,str}$ [1/K]	C_{shiv} [W/m^{2}K^2]	K_{min} [W/m^{2}K]
1971 edition	36.6	34.1	6.3	75	0.5	–	5.28
1986 edition	36.8	33.7	6.3	200	0.1	19.4	5.28

Table 3 Calculation conditions

Air temperature	Experimental values shown in Table 1
Humidity	Experimental values shown in Table 1
Mean radiant temperature	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	Determined based on experiment description as shown in Table 1
Metabolic rate	Determined based on experiment description as shown in Table 1
External work	0 W/m^2
Height	1.77 m
Weight	81.7 kg
Body surface area	1.96 m^2
Time increment	10 s
Time of calculation	10 hours

Table 4 Changes in the TNM [14,15,26-31]

	$T_{cr,set}$	$T_{sk,set}$	$C_{\alpha 1}$	$C_{\alpha 2}$	$C_{\alpha 3}$	$V_{bl,basal}$	$C_{bl,dil}$	$C_{bl,str}$	$C_{rsw,M1}$	$C_{rsw,M2}$	$C_{rsw,P2}$	C_{shiv}
[14] Gagge et al. 1971	36.6	34.1	0.042	−	−	6.3	75	0.5	100	−	−	−
[26] Gagge et al. 1972	37.0	34.0	0.044	0.3509	−0.0014	6.3	150	0.5	−	250	10.7	19.4
[27] Gagge et al. 1976	36.6	34.0	0.004	0.351	−0.0014	6.3	150	0.5	−	200	10.7	19.4
[15] Gagge et al. 1986	36.8	33.7	0.042	0.7452	0.58542	6.3	200	0.1	−	170	10.7	19.4
[28] ASHRAE 1989	36.8	33.7	0.1	1.008	3.96	6.3	200	0.5	−	170	10.7	19.4
[29] ASHRAE 1997	37	34	0.042	0.745	−0.585	6.3	175	0.5	−	170	10.7	19.4
[30] ASHRAE 2001	37	34	0.042	0.745	−0.585	6.3	175	0.5	−	170	10.7	19.4
[31] ASHRAE 2005	37	34	0.042	0.745	−0.585	6.3	50	0.5	−	170	10.7	19.4