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Abdul, Munir

Takada, Satoru

Matsushita, Takayuki

Kubo, Hiroko

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PREDICTION OF HUMAN THERMOPHYSIOLOGICAL RESPONSES DURING SHOWER BATHING

Abdul Munir

Department of Architecture, Faculty of Engineering, Syiah Kuala University, Darussalam, Banda Aceh 23111, Indonesia

Satoru Takada

Department of Architecture, Graduate School of Engineering, Kobe University, Rokko, Nada, Kobe 657-8501, Japan

Phone: +81 78 803 6038

Fax: +81 78 803 6038

Email: satoruta@kobe-u.ac.jp

Takayuki Matsushita

Department of Architecture, Graduate School of Engineering, Kobe University, Rokko, Nada, Kobe 657-8501, Japan

Hiroko Kubo

Department of Environmental Health, Faculty of Human Life and Environment, Nara Women's University, Kitauoya-nishimachi, Nara 630-8506, Japan

ABSTRACT

This study develops a model to predict the thermophysiological response of the human body during shower bathing. Despite the needs for the quantitative evaluation of human body response during bathing for thermal comfort and safety, the complicated mechanisms of heat transfer at the skin surface, especially during shower bathing, have disturbed the development of adequate models. In this study, an initial modeling approach is proposed by developing a simple heat transfer model at the skin surface during shower bathing, applied to Stolwijk's human thermal model. The main feature of the model is the division of the skin surface into three parts: a dry part, a wet part without water flow and a wet part with water flow. The area ratio of each part is decided by a simple formula developed from a geometrical approach based on the shape of the Stolwijk's human thermal model. At the same time, the convective heat transfer coefficient between the skin and the flowing water is determined experimentally. The proposed model is validated by a comparison with the results of human subject experiments under controlled and free shower conditions. The model predicts the mean skin temperature during shower fairly well both for controlled and free shower bathing styles.

Keywords: Human thermal model, Thermophysiological response, Shower bathing, Convective heat transfer coefficient, Subject experiment, Modeling

INTRODUCTION

Bathing is a common daily human activity in which change in the body temperature is sharper than that in other activities performed while the body is exposed to air. Such a sharp temperature change is explained by the fact that the clothing is removed during bathing and the heat transfer coefficient between the skin and water is higher than that between the skin and air. Even though the water temperature varies, depending on the culture or habit of the person, it can be said that bathing is one of the most extreme activities from the viewpoint of the heat transfer of the human body. Therefore, it is important to quantitatively evaluate the responses of the human body not only from the viewpoint of thermal comfort, but also the safety factors during the bathing activity.

To study the effect of extreme thermal environmental conditions on the human body or to evaluate thermal comfort in a bathroom and dressing room, the prediction of thermophysiological response of the human body by a numerical simulation will be a powerful tool. However, thus far the number of studies that have examined the thermophysiological response of the human body during bathing is limited, and most studies have used experimental approaches. Hashiguchi et al. (2002), Tochihara (1999), and Ohnaka et al. (1995) evaluated the effect of room temperature during and after bathing and the method of bathing (including immersion and shower bathing) on the thermophysiological response. Chiba et al. (2005) clarified the cause of death and the risk factors that are related to sudden death in the Japanese senior population while bathing in a Japanese style “hot bath.”

As examples of studies that are based on an analytical approach, a thermal model of the human body has been used to simulate the immersion bathing process to analyze the thermophysiological response (Yokoyama et al. 2005). Based upon the Stolwijk multi-node model of temperature regulation (Stolwijk 1971), some researchers have focused on developing the thermal model of the human body for immersion in cold water (Montgomery 1974, Tikuisis 1988). However, no model has been proposed for simulating the thermophysiological response during shower bathing.

For the modeling approach, the difference between immersion and shower bathing is in the heat exchange mechanism on the skin surface. The heat transfer mechanism during shower bathing is more complicated in comparison to that of immersion bathing. During immersion bathing, it is easier to distinguish the body part in the water from that out of the water and to describe the heat exchange at the skin surface. For the body part in the water, the convective heat transfer between the skin and the water should be considered, while for the body part out of the water, the normal condition of air exposure should be applied. On the other hand, during shower bathing, the body part receiving shower water would be constantly changing, and even the part that is not receiving shower water at that time would be wet if the part has received the shower water at another time. In addition, the convective heat transfer coefficient between the skin and the shower water could be different from that between the skin and the still water in the bath tub; the specific value of the coefficient for the shower does not exist in the literature.

In this paper, an initial modeling approach to predict the thermophysiological response of the human body during shower bathing is proposed. A heat transfer model at the skin surface during showering is applied to Stolwijk's human thermal model (Stolwijk 1971) to describe the heat exchange mechanisms that occur during shower bathing. The skin surface is divided into three parts; a dry part, a wet part with water flow and a wet part without water flow. The area ratio of each skin part is estimated by a geometrical approach that is based on the segmented body shape of Stolwijk's human thermal model. The heat transfer coefficient between the skin and the flowing water is determined experimentally. The proposed shower model is validated with the results of human subject experiments during shower bathing

HUMAN THERMAL MODEL DURING SHOWER BATHING

Model of heat transfer on the skin during shower bathing

Heat transfer on the skin surface during shower bathing will vary depending on how the shower water is sprayed onto a bathing person, particularly on the distribution of the sprayed water. In this study, a simple model for describing heat transfer on the skin surface during shower bathing is proposed by differentiating the skin surface into three parts, as shown in Fig. 1; a dry part, a wet part that is not covered by flowing water and a wet part that is covered by flowing water. The dry part represents the body segments that are not sprayed by shower water. The segments that are sprayed by shower water are considered to be wet and are divided into the parts that are uncovered and covered by flowing water. The uncovered part is the surface area that is not continuously sprayed by water but that is wet with an existing thin water layer. The covered part of the skin is the area where the flowing water exists on the skin surface. These divisions are applied to each body segment of Stolwijk's human thermal model. The following assumptions are made in the model:

a) The dry skin surface is never exposed to the shower (unwashed) and treated as the air exposure condition, which exchanges heat with the ambient by convection, radiation, and evaporation of regulatory sweating and skin diffusion.

b) For the wet part that is not covered with flowing water, a thin water film is formed. The temperature of this film is equal to the skin temperature while the surface is regarded as being wet under exposure to the air, which exchanges heat with the ambient by convection, radiation, and evaporation from the water film.

c) On the wet part that is covered with flowing water, the shower water flows fast enough and is sprayed randomly enough to classify the temperature of the water on the skin as uniform over the entire body. The heat is exchanged between the skin and the flowing water by convection.

The heat and moisture transfer coefficients of the skin that is exposed to the air are determined in the same way as in the Stolwijk model (Stolwijk 1971). There are two parameters that should be provided, particularly in this shower model: one is the ratio of the skin surface area that is covered by the flowing shower water and the other is the heat transfer coefficient between the skin and the flowing shower water. The former is determined by a simple formula that uses a geometrical approach while the latter is determined from a measurement that is performed using a "replicated skin model." The processes of determining these parameters are described in the following sections.

Analyzing the thermophysiological response during shower bathing

The heat transfer model for the skin surface during shower bathing is combined with the human thermal model to simulate the thermoregulatory response during shower bathing. The Stolwijk model is adopted as the human thermal model in this study. Except for the boundary condition at the skin surface, the Stolwijk model is basically used in its original form in this paper.

The Stolwijk model consists of six segments (head, trunk, arms, hand, legs, and feet), and each of the segments is divided into four layers (core, muscle, fat, and skin). In addition, the model has a central blood compartment that is thermally connected to all of the other nodes. The heat balance equations of a segment "*i*" for each node (1: core, 2: muscle, 3: fat, and 4: skin) are as follows.

$$C(i,1)\frac{dT(i,1)}{dt} = Q(i,1) - BC(i,1) - TD(i,1) - E(i,1) \quad (1)$$

$$C(i,2)\frac{dT(i,2)}{dt} = Q(i,2) - BC(i,2) + TD(i,1) - TD(i,2) \quad (2)$$

$$C(i,3)\frac{dT(i,3)}{dt} = Q(i,3) - BC(i,3) + TD(i,2) - TD(i,3) \quad (3)$$

$$C(i,4)\frac{dT(i,4)}{dt} = Q(i,4) - BC(i,4) + TD(i,3) - E(i,4) - Q_t(i,4) \quad (4)$$

The heat balance equation for the central blood compartment is

$$C_{CB}\frac{dT_{CB}}{dt} = \sum_{i=1}^{6}\sum_{j=1}^{4} BC(i,j)\,. \quad (5)$$

For the dry segment, heat exchange occurs by convection and radiation with the ambient while evaporative heat loss occurs due to sweating and skin diffusion.

$$Q_t(i,4) = Q_a(i) \quad (6)$$

$$Q_a(i) = \left(\alpha_c(i)\cdot(T(i,4) - T_a(i)) + \alpha_r(i)\cdot(T(i,4) - T_r(i))\right)\cdot S(i) \quad (7)$$

$$E(i,4) = E_{sw}(i) + E_{diff}(i)\,. \quad (8)$$

The sensible heat from the skin surface to the ambient is accomplished by radiation and convection (Eq. 7). Heat radiation transfer is described by the temperature difference between the skin surface temperature and the mean radiant temperature.

The heat loss by sweating $E_{sw}(i)$ varies due to the temperatures of the skin nodes and the head core node, which describes the sweat secretion due to themoregulatory control. The value of the evaporative heat loss $E_{diff}(i)$ through skin diffusion is considered to be a constant that is proportionally distributed for each skin compartment.

For the wet skin segment, $Qt(i,4)$ is written as Eq. 9, which represents both the uncovered and covered area of the skin surface. Heat is exchanged between the flowing water and the covered skin by convection, while it is exchanged between the ambient and the uncovered skin by both convection and radiation. The ratio of the coverage area in Eq. 9 is represented by $\beta(i)$ while that of the uncovered part is $(1-\beta(i))$. Since the water layer exists on the surface of the uncovered skin, the latent heat loss is given as the maximum evaporation due to the vapor pressure on the skin at the saturation level (Eq. 11). On the other hand, there is no latent heat loss on the covered skin ($E(4,i) = 0$) because the shower water covers the skin surface.

$$Q_t(i,4) = \beta(i) \cdot Q_w(i) + (1-\beta(i)) \cdot Q_a(i) \tag{9}$$

$$Q_w(i) = \alpha_{cw}(i) \cdot (T(i,4) - T_w(i)) \cdot S(i) \tag{10}$$

$$E(i,4) = E_{\max}(1-\beta(i)) \,. \tag{11}$$

$$E_{\max}(i) = LR \cdot \alpha_c(i)(P_{sk,sat}(i) - P_a(i))S(i) \tag{12}$$

Measurement of the heat transfer coefficient between the skin and the shower water

Method

For showering, the convective heat transfer coefficient (α_{cw}) between the skin surface and the flowing water is determined by experiment because the convective heat transfer coefficient (α_{cw}) that is suitable for the showering case is not available. Although the value for the case of water spray on a solid surface at high surface temperature and high velocity has been shown, for example in the field of steel manufacture (Stewart et al. 1995), it would not be directly applicable for the showering case.

In this study, the heat transfer coefficient between the skin surface and the flowing water is determined by exposing a "replicated skin model" to the shower by measuring the temperature difference between the skin surface and the flowing water and by measuring the heat flux at the skin surface, (Eq. 13). The "replicated skin model" is made from a Styrofoam board (900 mm × 300 mm × 30 mm) and a thin aluminum sheet (120 mm × 120 mm × 0.3 mm), as illustrated in Fig. 2. An aluminum sheet is pasted to a hole in the Styrofoam board such that the surfaces of the sheet are exposed to the shower on one side (front surface) and to ambient on the other side (rear surface). The shower water is sprayed onto the top side of the sheet so that the front surface of the aluminum sheet is directly exposed to the flowing water. The temperature of the water is measured in the shower head. By considering that the distance between the shower head and the plate is relatively close (20 cm), the heat loss from the water between the showerhead and the plate could be neglected.

The heat flux at the front surface of the plate could be regarded as equal to that of the rear surface because the aluminum sheet is thermally thin (Eqs. 14 and 15). The heat flux at the rear surface is determined by the temperature difference between the rear surface and the ambient, and the heat transfer coefficient between the rear surface and the ambient provided in the preparatory test shown in Figure 3 (Eq.16). Thus, the heat transfer coefficient between the skin and the shower water is determined.

$$q_{front} = \alpha_{cw}(T_w - T_{s,front}) \tag{13}$$

$$q_{rear} = q_{sheet} = q_{front} \, . \tag{14}$$

$$q_{sheet} = -\lambda \frac{\partial T}{\partial x} \tag{15}$$

$$q_{rear} = \alpha(T_{s,rear} - T_a) \tag{16}$$

The temperature of the water is controlled with a gas water heater that was installed to provide hot water for showering. Water at various temperatures (25°C, 30°C, 37°C, 40°C, and 45°C) is sprayed onto the front surface of the board at a flow rate of 11 liters/min, which is a common flow rate for showering (Ohnaka et al.1994 Herrmann et al. 1994, Ohnaka et al.1995). Details of the measurement items and instruments are summarized in Table 1.

Result

On the basis of the regression result that is shown in Fig. 4, Eq.17 shows the relation between the heat flux and the temperature difference between the water and the front surface of the sheet.

$$q_{front} = 104(T_w - T_{s,front}) \; . \tag{17}$$

From this equation, the heat transfer coefficient (α_{cw}) for showering between the skin surface and the flowing water can be determined to be 104 W/m^{2}K.

Estimation of the ratio of skin area covered by flowing water

The ratio of the skin area that is covered by flowing water during a shower (hereafter referred to as "coverage area ratio") is estimated by a geometrical approach for each body segment. The coverage area ratios are defined for each body segment for the Stolwijk model. It is assumed that the head segment is not sprayed by the shower water; rather, it is considered to be the dry part. Therefore, the coverage area ratio is defined for the trunk, arms, hands, legs, and feet segments.

The coverage area ratio is dependent on the method of shower bathing. In this study, the coverage area ratio is estimated for two cases: the controlled shower case and the free shower bathing case. For the controlled shower case, the showerhead and the subject standpoint are fixed while the shower water is sprayed onto the chest or back of the subject from a fixed showerhead; this case was used by Ohnaka (Ohnaka et al. 1995) and is hereafter referred to as the “fixed shower case”. For the case of the free shower, the water shower is assumed to be sprayed uniformly; this assumption would be valid as a first approximation since we will tend to spray uniformly if no restriction obstructs the way of showering (hereafter referred to as the “uniform shower case”).

In the estimation of the coverage area ratio by a geometrical approach, the following assumptions are made:

a) The geometrical form of the body segments is obtained by expanding the cylinder form of the Stolwijk model to the flat form, as shown in Fig. 5(a).

b) The water is sprayed on the upper part of the trunk segment and flows down to the legs and feet (Fig. 5(a)).

c) The width of the water flow (*d*) onto the skin surface of all of the segments is constant.

d) The general form of the coverage area ratio is the width of the water flow (*d*) to the total width of the segment (circumference: *c*), which can be written as:

$$\beta(i) = \frac{d}{c(i)} . \tag{18}$$

e) The shower water is continuously sprayed onto the front and back sides for the fixed shower while it is alternatively sprayed onto the front, right, back, or left sides for the uniform shower (Fig. 5(b)).

f) An equal amount of water flows onto the legs and feet segments for any direction of the showerhead (Fig. 5(c)). The coverage area of the feet segment is equal to the leg segment.

g) The legs and feet are assumed to be the same width.

Based on the above assumptions, the coverage area ratio is modeled (as shown in Tables 3 and 4) for the fixed and uniform shower cases, respectively. Following Tables 3 and 4, the coverage area during the shower bathing cases is estimated (as shown in Tables 5 and 6) by considering the dimensional characteristics of the subjects that are involved in the experiments (Table 2), i.e., the radius and circumference of each body segment. The coverage area ratio varied depending on the differences in the subjects' body sizes, as described in the methods above. As shown in Table 5, the coverage area ratio of subject A is larger than that of subject B because of the difference in the surface areas of their bodies. Because the shower water is sprayed onto the chest or back in the fixed shower case, the coverage area ratio of the arm and hand segments is zero. However, in the uniform shower case, the arm and hand segments receive water. On average, the coverage area ratios of the arm and hand segments become smaller than those of the trunk, leg, and feet segments, even in the uniform shower case.

VALIDATION OF THE SHOWER MODEL DURING CONTROLLED SHOWER BATHING

Method of validation

The proposed shower model is validated by comparing the calculated and experimental results of the mean skin temperature during controlled shower bathing experiments. The case of controlled shower bathing is tested to validate the model under the condition of least uncertainty with respect to the preferences or personal habits of the subjects. A series of shower experiments were conducted under different water temperatures, which ranged from 23°C to 39°C. Calculations were performed using the heat transfer coefficient between the skin and the shower water, and the coverage area ratio. The environmental variables that were measured during the human subject experiments were considered as boundary conditions.

Experimental method

Two healthy male subjects, whose anthropometric data are shown in Table 2, were exposed to both a hot water shower (heated water, 38 – 39°C) and a cold water shower (unheated water, 23 – 28°C). Each of the subjects participated in four experiments – two hot water and two cold water shower experiments. Before taking a shower, the subjects were sedentary and rested in a dressing room for at least 1 h while dressed in only shorts. The subjects then moved to the bathroom and took a 10-min controlled shower in a standing position. The angle of the shower head is fixed on the wall at a height of 160 cm and was at the same position for both subjects. The subjects themselves adjusted their body position so that the sprayed water fell on their chests. The distance of the shower nozzle and the chest of both subjects were insignificantly different. The shower water was alternatively sprayed on the chest and back for a minute by changing the body position. The physiological response and the environmental conditions were measured during the experiments, as previously reported (Munir 2008).

The physiological response of the skin temperature at 10 sites (forehead, chest, abdomen, upper back, lower back, arm, hand, thigh, leg, and foot) and the environmental conditions (air temperature, humidity, and globe temperature) were measured at intervals of 10 s. The measured variables and the instruments that were used are detailed in Table 7. The mean skin temperature is approximated by a modified-seven-point Hardy/DuBois weighting average. In this approximation, the abdominal skin temperature in the 7-point Hardy/DuBois weighting average is replaced by the average temperature of the trunk segment (chest, abdomen, upper back, and lower back) as the weighted temperature of the covered and uncovered parts of the trunk skin segment. All of the experiments were performed in a non-air-conditioned bathroom; therefore, the ambient conditions were not strictly constant, i.e., the air temperature ranged from 25 – 28°C, as shown in Table 8. The experimental data for the environmental conditions and the physiological response for shower bathing have already been reported (Munir 2008).

Calculation methods

Calculations were performed on the basis of the measured environmental conditions (Table 8) (Munir 2008). The heat transfer coefficients for each skin segment, both under exposure to air and during shower bathing, are shown in Table 9. The coverage area ratio of each skin segment was estimated by the method that is outlined in the previous section for a fixed shower case, which is based on the weight and height of each subject. The geometrical characteristics of the subjects that were used in the model and the estimated coverage area ratios for the fixed shower are shown in Table 5. The coverage area of the head segment during the shower is set to zero, which represents the subjects taking a shower without washing their hair. The metabolic rate during the sedentary position in the dressing room is set as 60 W/m^2; it was 70 W/m^2 during the standing shower (ASHRAE 2005).

Validation results

A comparison between the experimental and calculated results is shown in Figs. 6–8. The calculated results are in good agreement with the experimental results; both subjects showed a fairly small temperature deviation during the shower, i.e., less than 1°C (root mean square deviation; *RMSD*) under all of the experimental conditions. These results suggest that the model effectively predicts the heat transfer on the skin surface during shower bathing. The errors in the calculated results originate not only from the shower model but also from the human thermal model (Stolwijk model). Most of the discrepancies in subject A appear even before the subject takes a shower (Fig. 6). The experimental results during air exposure, prior to the shower, were initially different between the subjects. For subject B, the discrepancy before the shower is less than that for subject A (Fig. 7). Between the calculated and experimental data, the mean skin temperature difference during the 10-min shower is less than 1ºC, as shown in Fig.8. There are no significant differences between subjects A and B in the predicted result. On the whole, the model predicts the temperature response during the fixed shower bathing case with reasonable accuracy.

VALIDATION OF THE SHOWER MODEL DURING FREE SHOWER BATHING

Method of validation

The validity of the shower model is also evaluated using alternative experimental data of shower bathing, during which subjects showered freely in sitting position without washing their hair (uniform shower case) (Ishiguro et al. 2004). During uniform shower bathing case, the flow rate of the shower and the conditions of head washing (no washing) were controlled; however, the subjects freely sprayed the water over all the body segments. The behavior of the subjects during showering was not recorded in detail. However, it could be hypothesized that, during showering, people try to ensure that the water covers their body as uniformly as possible. Data from 10 subjects are available, and this number is sufficiently large to consider the abovementioned behavior as common to all subjects; even though each subject has different showering habits. Therefore, for this case, the coverage area ratio is estimated by considering the uniform shower case handled by the geometric approach. Similar to the fixed shower case discussed in the previous section, in the uniform shower bathing case, the Stolwijk model is used as the thermal model of the human body.

Experimental method

Healthy subjects (10 females) (Table 2) took showers for 5 min each in the sitting position, with the water temperature set to 42°C, after resting in the dressing room for 20 min while dressed in bathrobes. During the shower, the subjects sat on a bathroom chair had no back (with a seat of 30 cm×20 cm, and a height of 30 cm, commonly used in Japan). After showering, drying, and dressing, the subjects moved to the dressing room again and rested. The metabolic rate during the sedentary position in the dressing room and during the sitting shower is set as 60 W/m^2 (ASHRAE 2005). Skin temperatures, core temperatures, and environmental conditions of the bathroom and dressing room were measured at intervals of 30 s.

Methods of calculation

Calculations were performed based upon the measured environmental conditions (Table 10) and the heat transfer coefficients provided in Table 9. The coverage area ratio of each skin segment was estimated by considering the uniform shower case, and based on the average body characteristics of the 10 subjects

(Table 2). The geometrical characteristics of the subjects and the estimated coverage area ratios are shown in Table 6.

The surface area of the skin in contact with the floor during the standing shower, and on contact with the chair during the sitting shower, is not considered in the calculation. This is because the contact area is comparatively small, i.e., about 1 – 2% of the total surface area in the sitting posture and less than 1% in the standing posture (Kurazumi et al. 2004). Additionally, the thermal conductivity of the chair (made from plastic) is sufficiently small to ignore.

Validation results

The calculated and experimental results of the average mean skin temperature are shown in Fig. 9. We can observe that the calculated results of the mean skin temperature are in good agreement with the experimental results. A free shower bathing includes many subjective variables; the experimental results show that there is a wide range of deviation in mean skin temperature, approximately 2°C during the shower. From this viewpoint, the calculated skin temperatures during and after showering are in reasonably good agreement with the experimental data.

DISCUSSION

Applicability of the shower model

It has been demonstrated that the physiological responses of the human body during controlled shower bathing can be simulated by the proposed shower model with reasonable accuracy, for the eight cases as shown in Figs. 6–8. This shows that using the geometrical approach for determining the ratio of the skin area covered by flowing water in a fixed shower case is fairly accurate.

In addition, the validity of the proposed shower model has also been verified for uniform shower bathing, which is significantly similar to ordinary showering. In modeling the area on the skin surface covered by flowing water, it is assumed that people tend to spray shower water in order that the water covers their body as uniformly as possible. Although the exact way in which showering occurs will differ between individuals, as it did even among the ten subjects who were involved in the experiments, the results of the free showering validation experiments support the validity of the uniform shower case model for comprehending the general tendencies of heat flux at the skin surface quantitatively.

The purpose of the model proposed in this paper is not to pursue the detailed characteristics for each shower case, but to quantitatively represent general characteristics of the thermal responses of the human body. This model can be regarded as a basis for the numerical evaluation of human thermophysiological response in bathing environments, from the viewpoint of thermal comfort and safety factors during a shower. Using this model, the body's comfort state could be evaluated using mean skin temperature as a thermal comfort criterion. Furthermore, physiological response characteristics could be used as a basic tool in evaluating the thermally extreme conditions of bathing in relation to accidental death reported during bathing.

The simulation results of the uniform shower bathing case support the possibility of the application of this model to a common style of daily shower bathing. In this study, other showering styles, such as showering using a water scoop, are not considered. For considering these cases, further studies are necessary.

The convective heat transfer coefficient between skin and the flowing shower water

Since the heat transfer coefficient between the skin and the water (α_{cw}) is many times greater than that between the skin and the ambient air (α_c), the heat transfer that is caused by flowing water plays a significant role in the proposed shower model. Figure 9 shows that the value of α_{cw} sensitively influences the thermal response of the human body during a shower. From our experiments, the value of α_{cw} is proposed to be 104 W/m^{2}K, with a standard deviation of ca. 28 W/m^{2}K.

For comparison purposes, Table 11 shows the values of the heat transfer coefficient between the skin and the water under the condition that the body is immersed in water (not showering), which was obtained in previous studies. The measured results are wide ranging and reflect the difficulty of determining the value of α_{cw}. The value of α_{cw} for the showering conditions that were considered in this study is close to that for the immersion condition for water velocities of 0.1 m/s and 0.25 m/s (Boutelier et al. 1977). By considering the important role of α_{cw} in the shower model, it would be beneficial to determine α_{cw} with higher precision (for example, by using real human skin).

The Stolwijk thermoregulatory model

The original Stolwijk model is combined with the proposed shower model to evaluate the thermal response of the human body during shower bathing. Since our main concern is the mechanism of heat transfer on the skin surface as a boundary condition in the Stolwijk model, the individual characteristics of the subjects with respect to anthropometrics, body fat, and metabolic rate have not been considered in this calculation. The original constants for the human body's regulatory control from Stolwijk's model are adopted to this shower model.

Although the local skin temperature is an important variable in studying human thermal comfort, it is a future work to be studied. In this paper, the average response of the skin temperature has been evaluated. There are two reasons for this. One reason is that this is an initial model of shower bathing; thus, for simplicity, an average response is targeted. The other reason is in the human thermal model of Stolwijk. It has been evaluated that Stolwijk's model predicts the mean skin temperature well (Munir et al. 2009) but it shows some discrepancies in predicting the local skin temperature.

When subjects A and B are compared for the fixed shower case, the agreement between the experimental and calculated skin temperatures is different; the agreement is better for subject B, especially for the air exposure period that occurs before the shower. Nonetheless, during shower bathing, heat exchanges mostly occur by the contact of water with the skin surface; for both subjects A and B, the experimental and calculated skin temperatures show reasonable agreement for both the tendency and the absolute value.

Application of the shower model to another human thermal model

The shower model was developed as a boundary condition for the heat transfer on the skin surface during shower bathing. To apply it to other human thermal models, in which the division of the body segments is different from that in the Stolwijk model, it is necessary to translate or recalculate the coverage area ratio. However, it can be said that the methodology that is proposed in this study would be applicable to all other human thermal models.

CONCLUSION

This study has proposed an initial modeling approach for predicting the thermophysiological response during shower bathing by developing a simple heat transfer model at the skin surface during shower bathing that is applied to the Stolwijk's human thermal model. The heat exchange mechanisms that occur on the skin surface during shower bathing are modeled by discriminating the skin surface into a dry part, a wet part covered by the water flow, and a wet part without the water flow. The value of the convective heat transfer coefficient between the skin and the flowing water is determined experimentally, using a "replicated skin model" and the ratio of the covered part to the uncovered part is estimated for each body segment using a geometrical approach. The proposed shower model is combined with the Stolwijk model and validated by the results of the human subject experiments for shower bathing. The results show that the proposed model can predict the thermophysiological response of the mean skin temperature with reasonable accuracy under the conditions of both controlled and free shower bathing. These results suggest that the proposed methodology could be used for various types of shower bathing.

NOMENCLATURE:

$BC(i,j)$ = convective heat transfer from central blood and node (i,j) (W);

$C(i,j)$ = thermal capacitance (Wh/K);

C_{CB} = thermal capacitance of blood (Wh/K);

$E(i,j)$ = evaporative heat loss; Except the skin nodes(j=4) and the trunk core node (i=2, j=1), the values are zero (W);

$E_{max}(i,4)$ = maximum evaporative heat loss from skin surface (W);

$E_{diff}(i)$ = evaporative heat loss through skin diffusion (W);

$E_{sw}(i)$ = evaporative heat loss through sweating (W);

LR = Lewis relation (°C/kPa);

$P_{sk,sat}(i)$ = saturated vapor pressure on the skin surface (kPa);

$P_a(i)$ = ambient vapor pressure (kPa);

$Q(i,j)$ = rate of heat production (W);

$Q_a(i)$ = sensible heat transfer between the skin and ambient (W);

$Q_w(i)$ = sensible heat transfer between the skin and water (W);

$Q_t(i,4)$ = total sensible heat transfer on the skin surface (W);

q_{front} = convective heat flux on the front surface (W/m^2);

q_{rear} = convective heat flux on the rear surface (W/m^2);

q_{sheet} = conductive heat flux in aluminum sheet (W/m^2);

$S(i)$ = segment surface area (m^2).

$T(i,j)$ = node temperature (°C);

$TD(i,j)$ = conductive heat transfer from node (i,j) to node $(i, j+1)$ (W);

T_{CB} = temperature of central blood (°C);

$T_w\ (i)$= water temperature (°C);

$T_a\ (i)$= ambient air temperature (°C);

$T_r\ (i)$= mean radiant temperature (°C);

$T_{s,rear}$ = surface temperature of the rear side (°C);

$T_{s,front}$ = surface temperature of the front side (°C);

t = time (h);

$\alpha\ (i)$= combined heat transfer coefficient between skin and ambient (W/m^{2}K);

$\alpha_c\ (i)$= convective heat transfer coefficient between skin and ambient air (W/m^{2}K);

$\alpha_r\ (i)$= radiation heat transfer coefficient between skin and ambient (W/m^{2}K);

$\alpha_{cw}\ (i)$= convective heat transfer coefficient between skin and water (W/m^{2}K);

$\beta(i)$ = ratio of coverage area (n.d.);

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TABLES

Table 1. Measurement items and instruments.

Item	Instrument
Surface temperature of aluminum sheet (front and rear sides)	Thermocouple (T type, 0.2 mm in diameter)
Air temperature	Thermocouple (T type, 0.2 mm in diameter)
Water temperature [a]	Thermocouple (T type, 0.2 mm in diameter)
Heat Flux [b]	Heat sensor (MF-200, Eko Instrument)

[a] Thermocouple is inserted into showerhead;

[b] Measured only on the rear surface in preparatory experiment, to determine heat transfer coefficient between the rear surface and air;

Table 2. Anthropometric data of subjects.

	Fixed shower bathing		Free shower bathing
Subject	A	B	Average (SD) of 10 Subjects
Age (years)	22	24	21.2 (1.1)
Weight (kg)	48	85	48.1 (3.9)
Height (cm)	164	170	156.2 (4.4)
Body mass index (BMI)[a] (kg/m^2)	17.5	29.2	19.7 (1.2)
Dubois Surface Area (A_{du})[b] (m^2)	1.49	1.96	1.47 (0.07)

[a] Measured by *fat analyzer scale* (OMRON HBF-362);
[b] $A_{du} = 0.202 weight^{0.425} height^{0.725}$ (ASHRAE, 2005);

Table 3. Coverage area ratio in fixed shower case

Segment	Front/back (A)	β(i) (=A)*
Trunk	d/c(i)	d/c(i)
Leg/feet	d/c(i)	d/c(i)
Arm/hand	0	0
Head	0	0

*The shower water is sprayed to the front or back; in the model, the front and back are the same shape, so the coverage area is calculated for the situation shown in Fig. 5(a).

Table 4. Coverage area ratio in uniform shower case

Segment	Front/back (A)	Right/left (B)	β(i) (=(A+B)/2)[a]
Trunk	d/c(i)	d/c(i)	d/c(i)
Leg/feet	d/2c(i)[b]	d/2c(i)[b]	d/2c(i)
Arm/hand	0[c]	1/4[c]	1/8
Head	0[d]	0[d]	0

[a] The coverage area is calculated for the four directions of spraying, as shown in Fig. 5(b), which is a representative of spray from all directions. Then, the coverage area is determined by averaging the four direction cases.

[b] The legs and feet are assumed to be the same width. Although the width of the water exceeds the width of the legs and feet, the rear side can nor be sprayed by the shower. Therefore, only a half of of the legs and feet are covered.

[c] The arms and hands segments receive the water only when the shower head is on the right or left side of the body. When the shower head is on the left or right, a half of the left or right arm/hand is covered (¼ of the total area of arm/hand)

[d] Head segment is not sprayed by shower.

Table 5. Radius and circumference and coverage area of body segments estimated on the basis of weight and height of the subjects participating in the fixed shower bathing experiments.

Segment	Subject A			Subject B		
	Radius (cm)	Circum. (cm)	Coverage Area (β)	Radius (cm)	Circum. (cm)	Coverage Area (β)
	R	*C*	*d/C*	*R*	*C*	*d/C*
Head (sphere)	8.5	-	0.00	10.3	-	0.00
Trunk (cylinder)	11.8	74.4	0.40	15.8	99.0	0.30
Arms (cylinder)	3.6	22.6	0.00	4.8	30.1	0.00
Hands (cylinder)	1.2	7.5	0.00	1.6	10.0	0.00
Legs (cylinder)	5.2	32.4	0.46	6.9	43.1	0.35
Feet (cylinder)	1.3	7.9	0.46	1.7	10.5	0.35

Table 6. Radius and circumference and coverage area of body segments estimated on the basis of weight and height of the subjects participating in uniform shower bathing case experiments.

Segment	Radius (cm)	Circum. (cm)	Coverage Area (β)
	R	*C*	*d/C*
Head	8.5	-	0.00
Trunk	11.8	74.3	0.40
Arms	3.6	22.6	0.12
Hands	1.2	7.5	0.12
Legs	5.1	32.3	0.46[c]
Feet	1.3	7.9	0.46[c]

Table 7. Measured items and methods.

Item	Method (instrument)
Core temperature (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)
Air and globe temperatures	Thermocouple (T type, 0.2mm in diameter)
Relative humidity	Electric resistance method (T and D, RS-12)
Wind velocity	Hot wire method (Kanomax, 6543)

Table 8. Environmental conditions (averaged measured value) in dressing room and bathroom; before, during and after shower bathing.

Subjects [a]	Air Temperature (˚C)	Mean radiant temperature [b] (˚C)	Relative Humidity (%)	Water Temperature (˚C)
A1C	24.6/24.9/25.1	26.5/24.2/23.9	67.6/82.0/83.2	-/22.7/-
A1H	25.0/27.3/26.8	25.5/27.2/26.9	70.3/95.5/94.3	-/38.3/-
A2C	27.6/28.0/28.1	28.3/27.8/27.7	71.4/83.8/83.4	-/28.0/-
A2H	27.9/29.5/29.5	28.4/29.8/29.7	71.9/94.7/93.4	-/38.9/-
B1C	25.6/25.2/25.6	26.9/24.5/24.4	70.7/81.1/80.6	-/22.7/-
B2H	26.1/28.0/27.7	26.5/27.9/27.9	71.5/95.5/93.4	-/38.3/-
B2C	27.8/27.8/27.9	28.5/27.6/27.5	58.0/77.3/76.8	-/27.6/-
B2H	28.0/29.8/29.8	28.6/30.0/29.8	58.9/89.3/87.0	-/39.0/-

[a] A: Subject A; B: Subject B; 1: Experiment-1; 2: Experiment-2; C: Cold water shower; H: Hot water shower

[b] The mean radiant temperature was determined in two ways: For the dressing room, it was determined by the measured values of the globe temperature, the air temperature and the air velocity, and for the bathroom, the measured values of the wall surface temperatures were inserted to the formula for standing person (ASHRAE 2005).

Table 9. Heat transfer coefficients for air exposure and showering

	Air exposure [a]		Showering [b]
Segment	α_r (W/m^2.K)	α_c (W/m^2.K)	α_{cw} (W/m^2.K)
Head	6.4	3.2	-
Trunk	5.2	2.5	104.0
Arms	5.0	3.5	104.0
Hands	3.5	3.9	104.0
Legs	4.7	3.2	104.0
Feet	4.7	3.5	104.0

[a] Stolwijk (1971)
[b] Experimental result in this paper

Table 10. Calculation Conditions for free shower bathing case.

Variables	Dressing room	Bathroom
Air Temperature (°C)	24.1	26.1
Mean Radiant Temperature (°C) [a]	24.1	26.1
Relative Humidity (%)	60.1	92.2
Water Temperature (°C)	-	41.9

[a] MRT is regarded to same as the air temperature.

Table 11. Heat transfer coefficient between skin and water for the human body in water.

Author	Heat transfer coefficient, α_{cw} (W/m^{2}K)	Conditions
Boutelier et al. (1977)	43	Human Subject, rest in still water, thermal neutrality
	63	in flowing water, v =0.05 m/s
	81	in flowing water, v =0.1 m/s
	147	in flowing water , v = 0.25 m/s
Nadel et al (1974)	230	Human subject, rest in still water
	460	Rest in flowing water
	580	Swimming

FIGURES

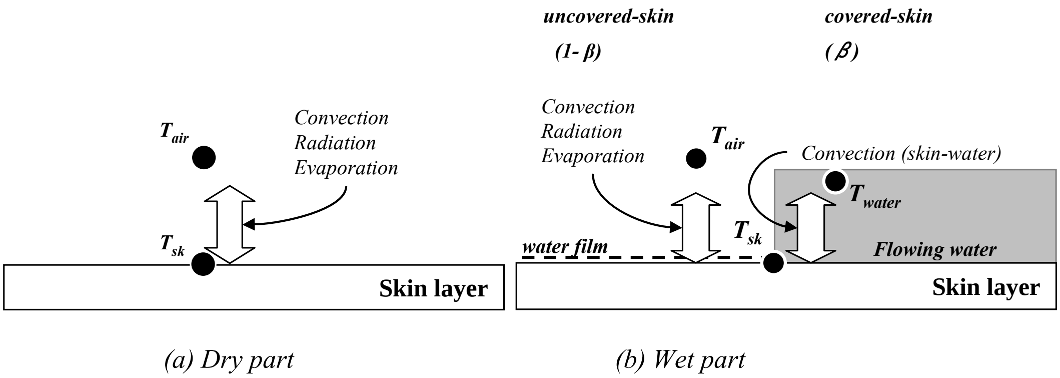

Fig. 1. Heat transfer model for the skin surface during shower bathing.

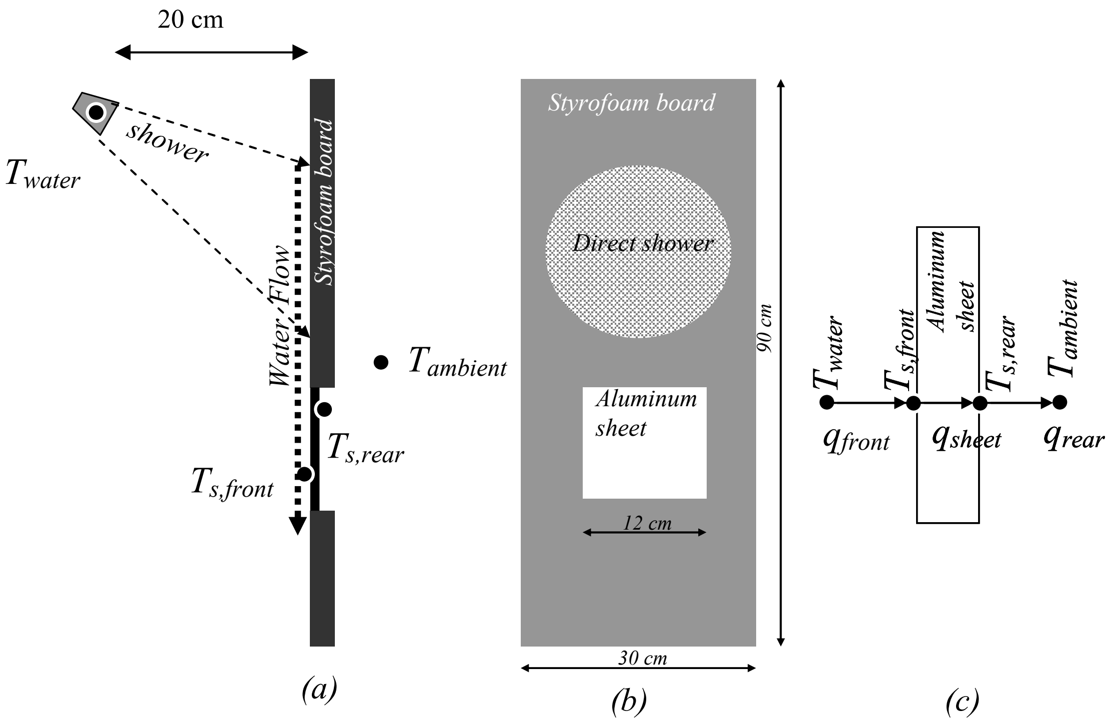

Fig. 2. Schematics of experiments using the "replicated skin model" to determine convective heat transfer coefficients between the skin and the shower water, (a) vertical cross section, (b) front view of the model, and (c) illustration of heat flux around measured point.

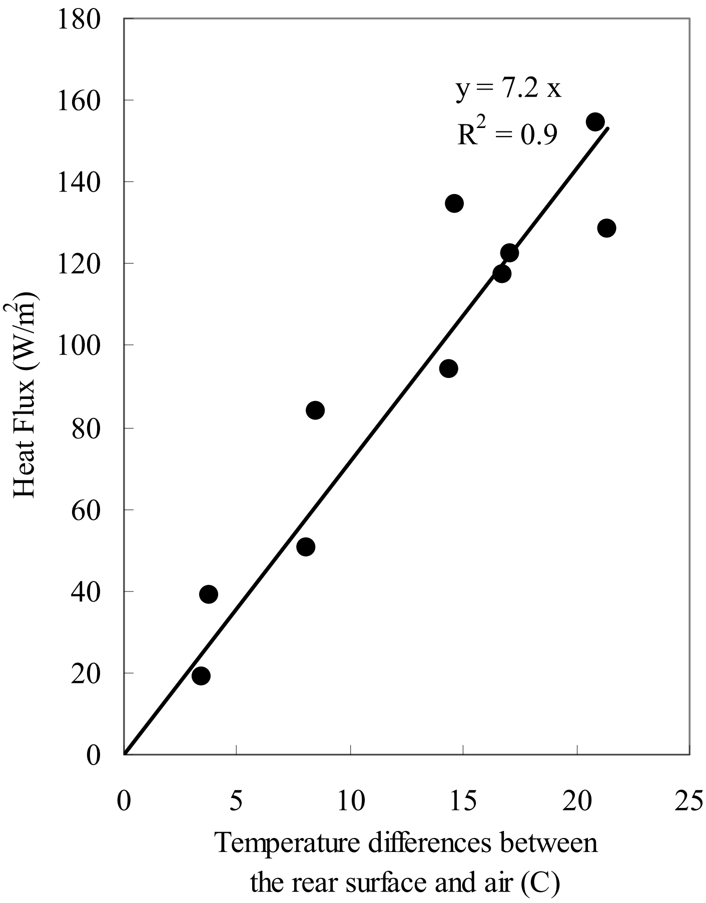

Fig. 3. The experimental results for the convective heat transfer coefficient at the rear surface that is in contact with air. The heat flux is measured on the rear surface of the plate with a heat flux sensor. In this preparatory experiment, the aluminum sheet is replaced with a thin plastic plate to obtain stable heat flux data. The other setup is the same as shown in Fig. 2. The value of the combined heat transfer coefficient (α) between the rear surface and the ambient is determined to be 7.2 W/m^2K.

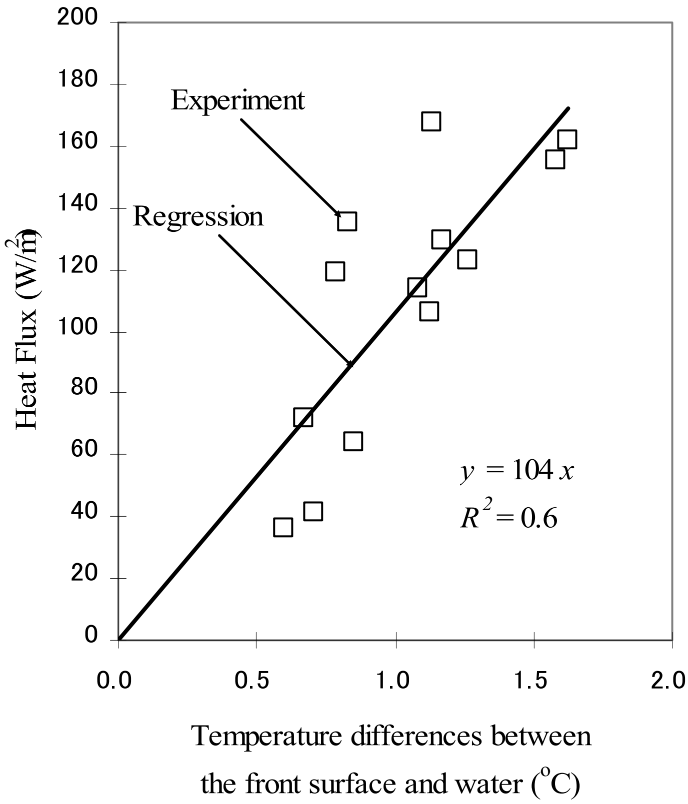

Fig. 4. The overall results for the convective heat transfer coefficient between the surface and the flowing water during showering. The heat flux is determined from the temperature difference between the rear surface and the ambient, and the heat transfer coefficient at the rear surface is obtained from Figure 3.

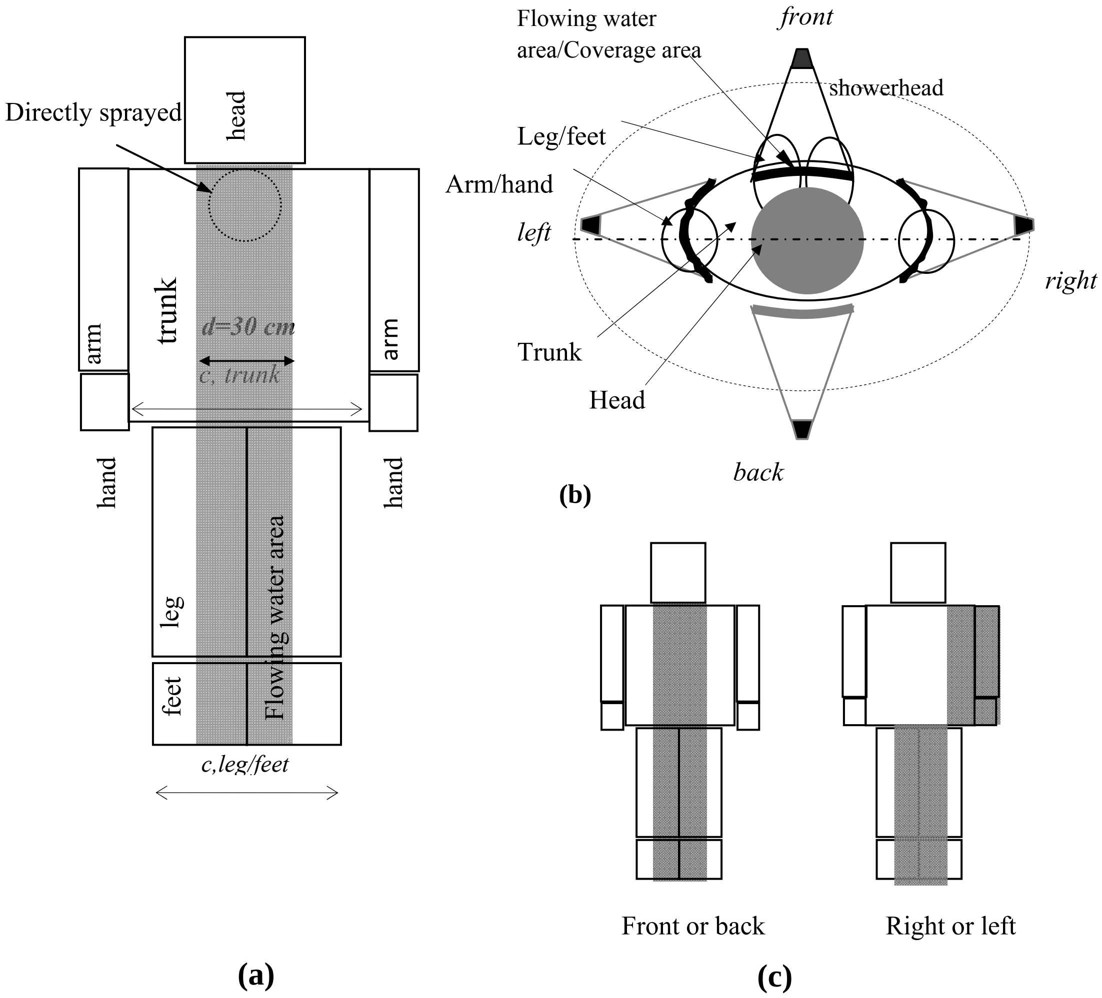

Fig. 5. Geometrical approaches for estimating the coverage area ratio, (a) body segments are expanded as flat surfaces; the circle on the trunk encloses the area in which the shower water is sprayed directly and "*d*" is the width of the flowing water (30 cm), determined experimentally by showering on a flat surface; (b) top view of the human body under the uniform shower, where water is sprayed from any direction for one cycle; The showerhead position is simplified to be only four possible directions: from the front, left, back, and right sides of the body; (c) coverage area ratio of the segments when the showerhead is positioned at the front or back and at the left or right side; The arm and hand receive water only when the showerhead is facing the side, and the legs and feet receive water irrespective of the direction of the showerhead.

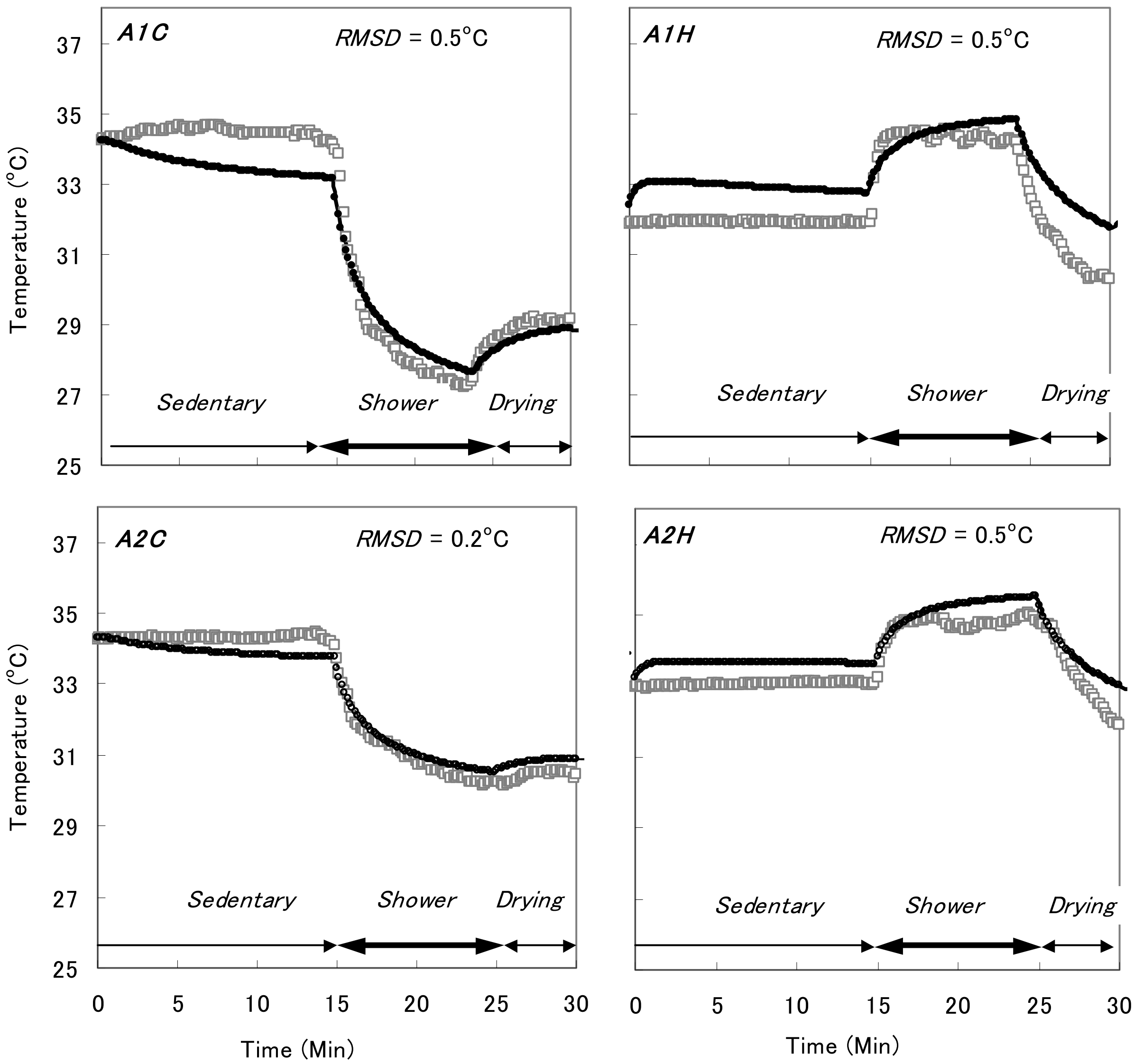

Fig. 6. The calculated mean skin temperature in comparison to the experimental results for subject A; (A1: experiment 1, A2: experiment 2, C: cold water shower, H: hot water shower, RMSD: root mean square deviation in temperature during shower from 15th min to 25th min)

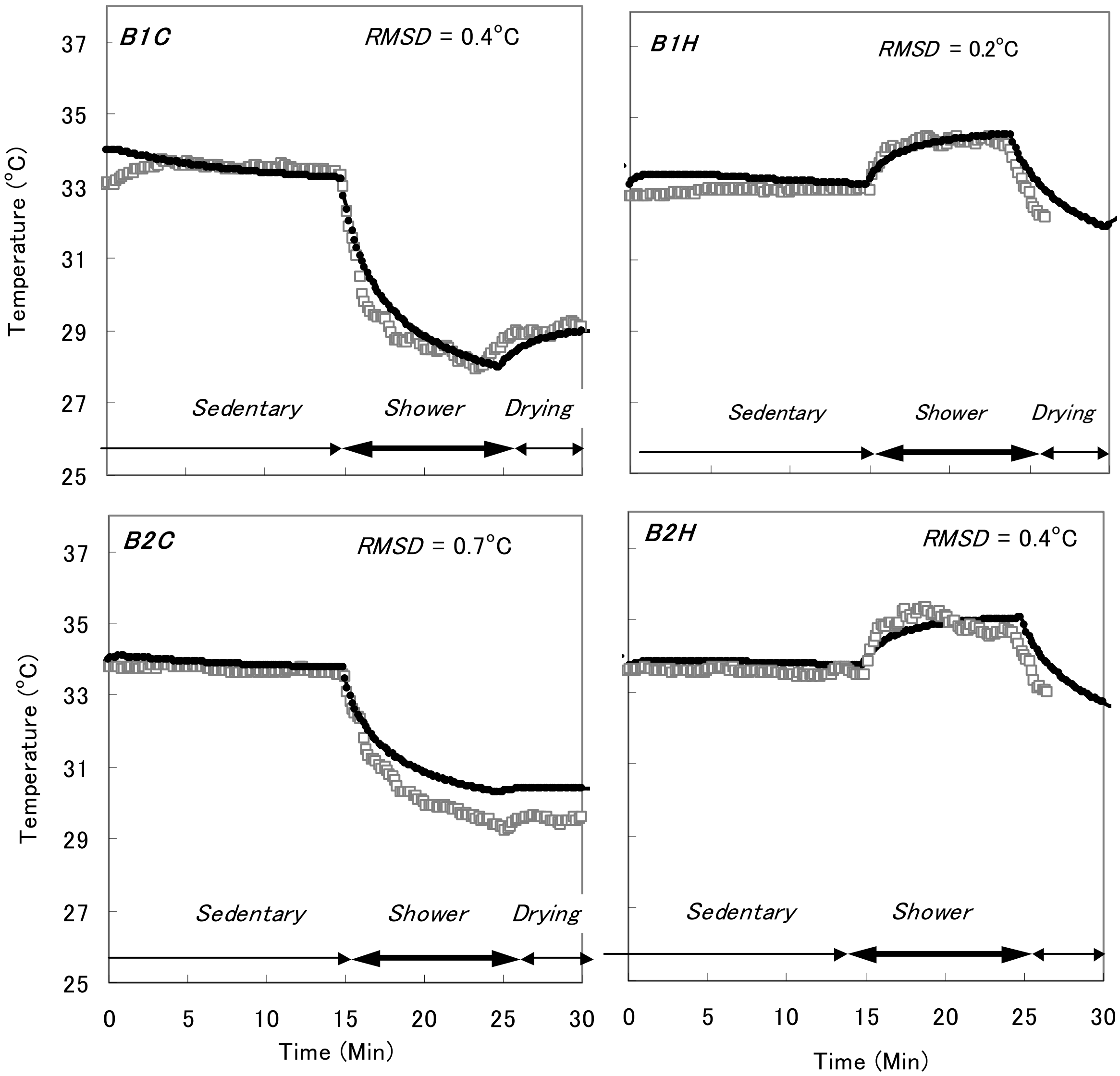

Fig. 7. Calculated mean skin temperature compared to experimental results for subject B; (B1: experiment 1, B2: experiment 2, C: cold water shower, H: hot water shower, RMSD: root mean square deviation in temperature during shower from 15th min to 25th min)

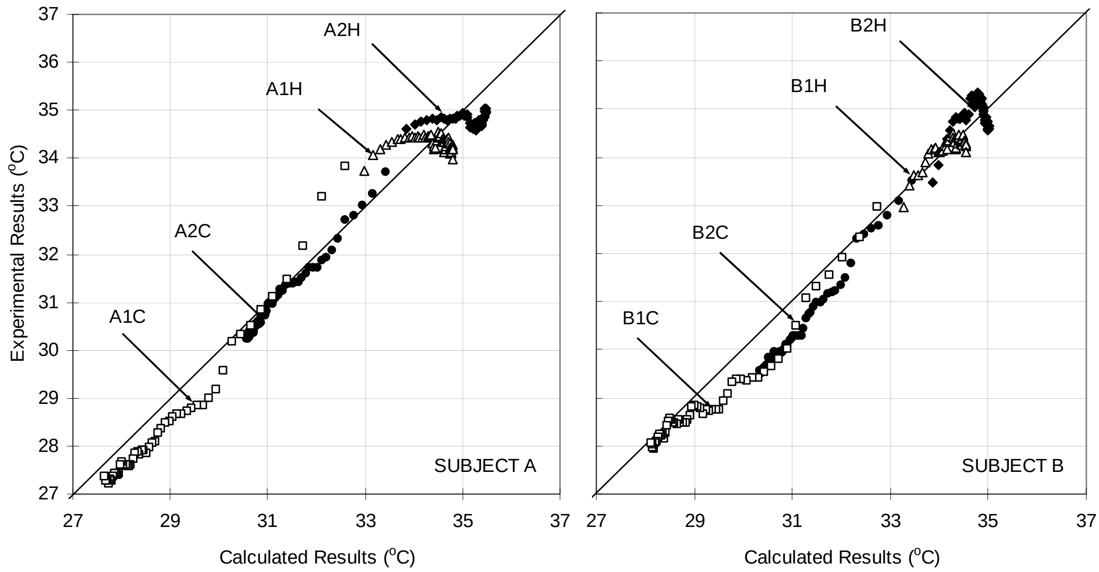

Fig. 8. Calculated mean skin temperature compared to experimental results during a ten-minute shower, for all experiments (the labels are explained as follows: A: subject A; B: subject B; C: cold water shower; H: hot water shower; 1: experiment 1; 2: experiment 2)

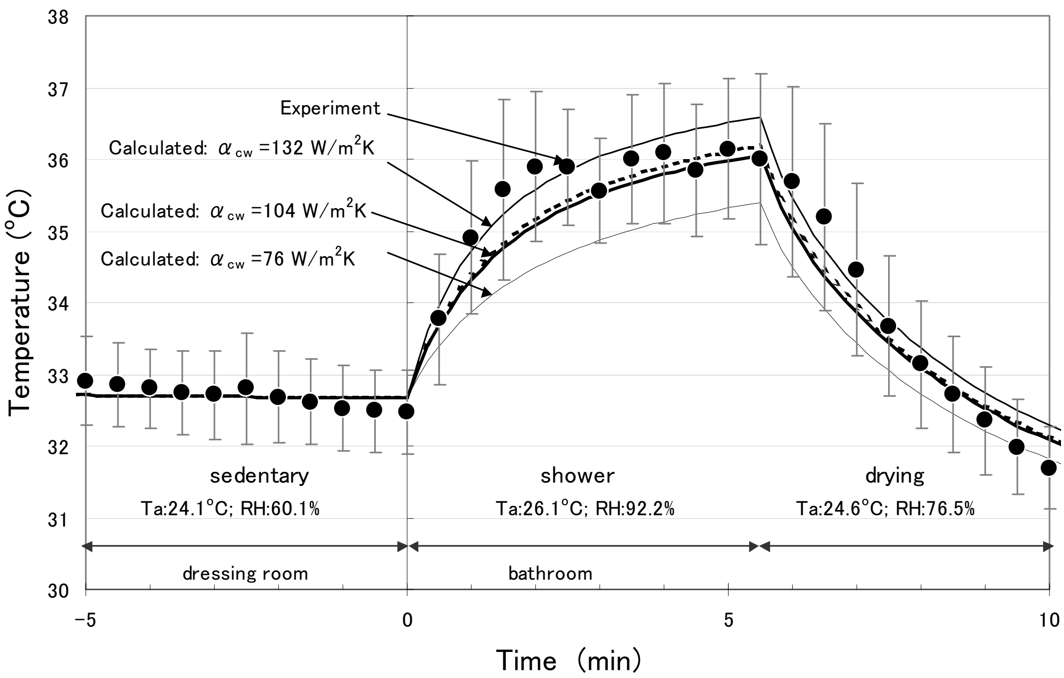

Fig. 9. Calculated mean skin temperature compared to experimental results, for free shower bathing (Ishiguro et al. 2004); with the calculated values for upper and lower ranges of heat transfer coefficient between the skin and the water during the shower; (dashed line: the result considering the vinyl coverage on the left arm/hand in the experiment, refer to the note in Table 4 for the coverage area of the arms and hands segments in the free shower bathing).