Individual Difference in Transient Thermophysiological Responses to Stepwise Change in Air Temperature: A Study Based on Experiments for Sedentary Young Male Subjects

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Abstract

In order to quantitatively assess the individual differences in the thermophysiological responses, human subjects were exposed to a series of stepwise air temperature changes, and the rectal and skin temperatures and weight change were measured. The differences between subject responses were evaluated not only for steady state but also for a transient state. Ten young males were used as subjects and were monitored in a sedentary state. From the results of the transient exposure to cold and hot environments for 150 min. (29 °C, 30 min. – 20 °C, 20 min. – 29 °C, 60 min. – 38 °C, 20 min. – 29 °C, 20 min.), it was shown that the individual differences in rectal temperatures amounted to a standard deviation of 0.3 K, and that for mean skin temperature the standard deviation was 0.5 K for both steady and transient states. Local skin temperatures, measured at seven points to represent each body segment, showed larger individual differences than those for mean skin temperature, which suggests the existence of individual differences in skin temperature distributions. In addition, the skin temperature time derivative at the beginning of a step change in air temperature and body weight change were studied from the viewpoint of the individual difference. It was shown that the individual differences in rectal temperature, skin temperature distribution, and sweat rate were significant, and that the difference between individuals for skin temperature change during the transient state was almost the same as that for the thermally neutral and steady state. Furthermore, correlations between the responses and basic body parameters (the body weight, body surface area, and body fat percentage of the subjects) were studied using correlation analysis. As the results indicated, body fat percentage had greater influence on thermophysiological responses than height, body weight and surface area, and the correlation coefficients were fairly high for each of the thermophysiological responses measured in this study. For the thermally neutral and steady state data, rectal temperature showed a positive correlation with body fat percentage, while mean skin temperature showed a negative correlation with body fat percentage. These findings suggest that body fat percentage might be a promising parameter for explaining individual differences in thermophysiological responses.

Keywords: individual difference, skin temperature, core temperature, thermal transient, subject experiment

Introduction

Human thermal comfort forms the basis for design and control of indoor environments. When conducting studies on human thermal comfort, it is essential to carry out experiments involving human subjects and to obtain thermophysiological variables such as body temperature distribution including skin and core temperatures, sweating rate, and blood flow rate. It is widely known that the physiological data obtained from different subjects show individual differences even if the subjects are exposed to the same thermal environmental conditions. However, the quantity of the data to assess these individual differences is not sufficient, especially for transient states. Furthermore, specific trends in these differences have not been sufficiently characterized for practical application of the obtained results and findings. It is important for applications related to thermal comfort, e.g., as air conditioning, to identify distinctive parameters that yield the observed individual difference.
Cannon et al. (1960) compared fat and thin men on the basis of shivering and heat loss during steady state cold exposure through subject experiments. They showed that the metabolic rate was less for fat men than for thin men. Fanger et al. (1975) studied gender differences in preferred ambient air temperature. They did not find a significant difference in preferred temperature between males and females, or in mean skin and rectal temperatures under the same thermal environmental and clothing conditions. Wagner et al. (1985) investigated the influence of age and gender on thermophysiological responses during cold exposures by carrying out experiments involving both male and female subjects belonging to two age groups (young and old). The responses were characterized by changes in rectal and mean skin temperatures. Havenith et al. (1990) studied the influence of individual characteristics of young male and female subjects on their thermophysiological responses under hot or warm exposure accompanied by exercise through regression analysis of their experimental data. Natsume et al. (1992) compared old and young subjects on the basis of preferred ambient temperature. They studied the influence of initial ambient temperature and season to identify differences between the two subject groups. Nishimura et al. (1993) investigated the influence of body fat percentage on skin temperature and showed that skin temperatures at extremities were higher and that skin temperatures at the trunk were lower for the group with higher body fat percentage. Schellen et al. (2012) investigated gender differences in thermal comfort in non-uniform thermal environments. In their subject experiments, it was shown that the mean skin temperatures of the females were lower than those of the males, and that the core temperature of the females were higher, under a 0.6 clo condition. Thus, the individual differences in body temperature regulation have been studied from various viewpoints. However, a holistic characterization of individual differences has not been fully elucidated, and existing quantitative information on individual differences is insufficient for indoor thermal environment design oriented towards individual thermal comfort, especially for a transient state.

To address this lack in individualized thermal comfort data, this study explored transient thermophysiological responses of ten subjects with exposure to the stepwise changes in air temperature, including both hot and cold exposures. Specifically, this study targeted young male subjects in a sedentary state. First, the individual differences in the rectal and skin temperatures are shown quantitatively for both steady and non-steady states. Secondly, in order to elucidate individual differences in thermophysiological responses based on fundamental physical characteristics, correlations have been identified between the thermophysiological responses, i.e., the core and skin temperatures, and the subjects’ body weight, height and body fat percentage, which were used as the basic parameters for characterizing the individual’s body composition.

**Methods**

The selected subjects were ten healthy male students, 24 years old with a standard deviation (S.D.) of 2 years, 170 cm in height (S.D. 5 cm), 68.0 kg in weight (S.D. 10.7 kg), and with body fat percentage 17.6% (S.D. 5.5%), as shown in Table 1. The schedule of the experiments is shown in Figure 1. In the experiments, the subjects were exposed to a thermal transient condition beginning with nearly thermally neutral condition, followed by a reduced air temperature, a second neutral condition, an increased air temperature, and finally, a third neutral condition. This schedule is selected to cover a wide range of transient state experienced in common daily life. The experiments were conducted in two climatic chambers (control precisions of temperature and relative humidity (rh) were ±0.5 °C and ±3%, respectively) to simulate a thermally homogeneous environment. Before the start of each experiment, the subject remained sedentary under the initial environmental condition (29.4°C, 47%rh) for 1 hour. The subjects wore only trunks (undershorts, 0.03 clo). During the experiments, the core and skin temperatures of the subjects and the environmental conditions (air temperature, relative humidity, globe temperature, and wind velocity) were measured continually at intervals of 10 s. For the temperature measurement, thermocouples (T-type, 0.2 mm in diameter) were used. The data were recorded at 10-second intervals using a data logger (CADAC 21, Eto Denki Co., with a minimum scale value of 0.1 °C and with a precision of ±0.2 °C for the temperature measurement by the T-type thermocouple). The seven-point method proposed by Hardy and DuBois (Mitchell et al. 1969) was employed to measure the skin temperature. For the core temperature, the rectal temperature was measured with the sensor inserted to the depth of at least 10 cm from the anus.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Height [cm]</th>
<th>Weight [kg]</th>
<th>Body surface area[m²]</th>
<th>Body fat percentage [%]</th>
<th>Age [year]</th>
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<tr>
<td>A</td>
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<td>C</td>
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<td>Average</td>
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<td>10.7</td>
<td>0.13</td>
<td>5.5</td>
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</table>
The body surface area of the subjects was calculated on the basis of their height and weight (Kurazumi et al. 1994). Their body fat percentage was measured by using the bioelectrical impedance method (OMRON HBF-362).

Written informed consent for participation was obtained from all the subjects after the explanation of the experimental procedures.

Results

Body Temperature at the Steady and Thermally Neutral State

The skin and rectal temperatures in the steady and thermally neutral state (reported as the average of the data from 0 min to 30 min in Figure 1) for all ten subjects are shown in Figure 2, along with their standard deviations and maximum/minimum values.

As shown in Figure 2, the differences in rectal temperatures between subjects had a standard deviation of 0.3 K, which is significantly large, relative to nearly constant rectal temperatures, even during large stepwise changes in air temperature, as shown in Figure 3.

As shown in Figure 2, the standard deviation of the mean skin temperatures, based on the Hardy and DuBois’s 7-point method, is 0.5 K for steady and thermally neutral state (reported as the average of the thermally neutral state (n=10)).

The correlations between these physiological parameters and individual physical characteristics of the subjects, such as height, weight, surface area, and fat percentage, are studied (Table 2). Comparatively strong negative correlations are found between the mean skin temperature and the body fat percentage, while a positive correlation is found between the rectal temperature and the body fat percentage. For the skin temperatures at the abdomen and the thigh, a similar tendency with the mean skin temperature is indicated but not for the other locations. The mean skin temperature is based on the Hardy and DuBois’s 7-point method, where the weights of the local skin temperatures at abdomen and thigh are large. The method accounts for the strong negative correlation between the average skin temperature and the body fat percentage. Thus, it might be deduced that the body fat percentage, as a whole, is a better parameter for explaining the individual differences in the skin temperatures than body height, weight, and surface area and that the body fat percentage might be a good candidate parameter for describing individual features in body temperatures.

NOTES (Mean skin temperature based on the Hardy and DuBois’s 7-point method)

$$T_{sk} = 0.07*T_{sk,head} + 0.14*T_{sk,forearm} + 0.05*T_{sk,hand} + 0.35*T_{sk,abdomen} + 0.19*T_{sk,thigh} + 0.13*T_{sk,leg} + 0.07*T_{sk,foot}$$

Body Temperature during a Transient State

The rectal and mean skin temperatures of the subjects for the transient state are shown in Figure 3. The
differences between subjects were approximately constant during the entire transient process for both rectal and mean skin temperatures as indicated by “S.D.” and “Max. - Min.” within Figure 3. The standard deviation for all the data for 150 minutes is 0.3 K for the rectal temperature and 0.5 K for the mean skin temperature. These values are nearly the same as those for the steady and thermally neutral state.

The local skin temperatures, measured at seven points on the body surface, show larger variations at certain durations of the transient process. For example, as shown in Figure 4, after exposure to the low-temperature conditions, i.e. the recovery process from the cold exposure, the difference in the skin temperature of the hands and feet increases, while those of other body parts closer to the center of the body are approximately constant. However, as a whole, the difference is approximately constant through a series of the transient process for each of the body locations as shown in Figure 4, and the magnitudes of the individual differences for each segment of the body are similar to that for steady state, e.g., the foot shows larger difference than the other segments in both steady and transient states.

Table 3 shows the time derivatives of the mean skin temperature (dTs/dt) when the subjects move from Room A to Room B (occurring at the 30th min and 110th min. in Figure 1) from the thermally neutral state to either the low or high air temperature condition. In Table 3, the value for each subject is shown. For a subject whose absolute value of dTs/dt at a decrease in air temperature is larger than the average, the value at the increase tends to be smaller than the average. This trend corresponds with the finding that the absolute value of the time derivative of the mean skin temperature at the stepwise decrease in air temperature shows a negative correlation with the body fat percentage of the subjects, while at an increase in air temperature there is a positive correlation, as shown in Table 4.

**Body Weight Loss**

Body weight loss for a subject during the experiment should be closely related to the sweating rate. As shown in Table 5, the difference between subjects is significant and the value of the loss ranges from 40 to 104 [g/hour], and 21.8 to 54.8 [g/hour/m²] (per body surface area). As shown in Table 6, weight loss shows a stronger positive correlation with body fat percentage than with the height, weight or body surface area of the subject.

**Discussion**

**Magnitude of Individual Difference**

The experimental data indicated that rectal temperature varied significantly between subjects (0.3 K standard deviation) during the sedentary condition,
Figure 4 Local skin temperatures (n=10): head, forearm, hand, abdomen, thigh, calf, and foot. The SDs and the difference between the maximum and the minimum of the subjects are also shown.
Despite observing very little fluctuation in each subject’s rectal temperature for a 9 K of step change in air temperature. The skin temperatures were measured at 7 points on the body surface, and the average skin temperature, determined using the Hardy and DuBois’s method (Mitchell et al. 1969), had a standard deviation of no more than 0.5 K throughout the transient process. There are some instances where the measured difference between subjects became larger than 0.5 K for a part of the experiment. However, by averaging the local skin temperature data, it was shown that the difference between subjects converged to a smaller level. These tendencies are true for both the transient and steady state data. These results suggest the existence of individual differences in skin temperature distributions.

For the average skin temperature, the time derivative at the moment of change in air temperature was determined. The absolute value of time derivative can be interpreted as the ‘ease of skin temperature change’ with respect to a change in ambient air temperature. For a subject with a large absolute time derivative value for an air temperature decrease, the derivative value for a temperature increase tended to be small. This finding might be related to individual characteristics such as the thermal capacitance of the body surface region, sweating rate, and skin blood flow regulation.

The body weight change data includes the change due to respiration. However, considering an extreme high air temperature process is included in the exposure in this study, a large portion of the weight change would be due to evaporation of sweating. The body weight change data shows that the individual differences in sweat rate varied by as much as 2.5 times. This is a significant individual difference in sweat rate.

Several studies have focused on differences in thermophysiological responses due to gender (for example, Fanger et al. 1975), and age (for example, Natsume et al. 1992). In this study, the subjects were limited to healthy young male student subjects, and significant individual differences in the thermophysiological responses were still observed between subjects. These differences might be largely explained by body composition.

**Influences of Body Composition Parameters on Individual Differences**

In this study, correlations between thermophysiological responses and physical characteristics such as height, body weight, body surface area, and body fat percentage of the subjects were studied. The rectal and the mean skin temperatures of the subjects during the steady and thermally neutral state showed a strong
positive correlation and a negative correlation with their body fat percentage, respectively; however, such strong correlations were not found with the height, body weight and the body surface area of the subjects. The other physiological characteristics investigated in this paper, such as the absolute value of the time derivative of the mean skin temperature for a stepwise change (decrease and increase) in air temperature and weight loss during the experiment, also showed much higher correlation with body fat percentage than with the other body parameters. The result of the correlation analysis suggests that the body fat percentage is a promising parameter for characterizing individual differences in thermophysiological responses.

For body fat percentage, Nishimura et al. (1993) found from their subject experiments that trunk skin temperature was lower for the group with high body fat percentage. This finding is in agreement with our results, i.e., that the trunk (abdomen) skin temperature has a negative correlation with body fat percentage as shown in Table 2.

**Application to Human Thermal Model**

One of the most promising methods to evaluate thermal comfort in the design of a thermal environment is to use a human thermal model (a model describing temperature regulation of human body). It is a model to predict the thermophysiological response of a human body by numerical calculations based on heat balance equations for each discretized part of the human body (for example, Stolwijk 1971, Gagge et al. 1971). In these models, thermophysiological responses including regulation of blood flow, regulatory sweating, shivering were modelled using a simple empirical function, and at the same time, set point temperatures of each body part were given in order to express the on/off switching of the thermoregulatory responses. In other words, a specific set of coefficients were given as a means to calculate and express the thermophysiological responses. Consequently for a particular set of thermal environmental conditions, these models provide a unique solution for body temperature distribution; however, such models are inherently incapable of characterizing individual differences without determining the appropriate coefficients for each individual. Therefore, if a method to determine the individual characteristics in body temperature regulatory system were developed, then the numerical model would become a much more powerful tool for the design of thermal environments. In this sense, quantitatively clarifying the individual differences in thermoregulatory responses is an important issue. Several attempts have been made (Zhang et al. 2001, Havenith 2001, Marken Lichtenbelt et al. 2004, Takada et al. 2009). Unfortunately, the information provided by these studies is insufficient for prediction of individual thermophysiological responses. The data obtained in this study will serve as a basis for such purposes.

**Conclusions**

In order to clarify the basic characteristics of individual differences in thermophysiological responses for both transient and steady states, experiments were conducted involving ten young male subjects in a sedentary position with exposure to stepwise changes in ambient temperature, and the obtained data were analyzed on the basis of identifying differences between the individual thermophysiological responses. It was shown that the individual differences in rectal temperature, skin temperature distribution, and sweat rate were significant, not only at steady state but also during the transient state. In addition, the data indicated that the differences between individual skin temperatures during the transient state were nearly the same as those for the thermally neutral and steady state. Moreover, the correlation analysis suggests that body fat percentage might be a more promising parameter for explaining individual differences in thermophysiological responses than the height, weight and body surface area of a subject.

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