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Evaluation of calculation methods of mean skin temperature for use in thermal comfort study

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A method was established to evaluate calculation methods of mean skin temperature, in order to find appropriate ones for use in human thermal comfort study. In this method three indexes, including reliability, sensitivity and number of measurement sites, were proposed. Under air temperatures of 21 °C, 24 °C, 26 °C, and 29 °C, 22 subjects' local skin temperatures (21 sites) and electrocardiograms were measured, and their thermal sensation and thermal comfort were inquired. Human heart rate variability indicated the physiological relation between mean skin temperature and ambient temperature for the sensitivity evaluation. Adopting the evaluation method, 26 types of mean skin temperature calculation methods were evaluated based on the experimental data. The results indicate that a calculation method of mean skin temperature with 10 sites is the most appropriate one, due to its high reliability, excellent sensitivity and fewer measuring sites. When it was applied to reflect thermal comfort, the performance was good.

1. Introduction

Mean skin temperature (MST) is an important physiological parameter reflecting human response to cold or thermal stimulus and states of heat exchange between human body and a thermal environment. Human thermal comfort is defined as being "that condition of mind in which satisfaction is expressed with the thermal environment" [1]. As indicated in both of its thermophysiological definition [2] and energetic definition [3], MST plays a dominating role [4]. Therefore MST is often measured as an essential physiological parameter relating with thermal comfort (e.g. [5–8]).

Values for MST are obtained by summing the products of a finite number of local skin temperatures and the corresponding weighting factors. Up to now, many MST calculation methods have been established from the field of physiology, distinguished by the number of skin temperature sites and weighting factors. In the studies on thermal comfort, subjects' MST was measured with one of these MST calculation methods. For example, Bulcao used a 10-site weighed MST calculation method [5], Gagge adopted an average of 10 sites as mean skin temperature [6], and Hasebe and Huizenga chose a 7-site method [7,8]. The MST calculation methods themselves cause differences in the MST values. That is to say if different one was used, the results might be distinct. However, in these studies no reason was given to explain why the MST calculation method was chose. Considering the importance of an appropriate MST calculation method in obtaining a reasonable result, it is necessary to compare various MST calculation methods and find out which are suitable for use in thermal comfort study.

In the present work, a method was established to evaluate different MST calculation methods considering the effect of ambient temperature on skin temperature, which is the most important environmental factor affecting human thermal comfort. And also, the most appropriate one for future use in study on thermal comfort was discussed.

2. Methods

2.1. Subjects

12 male and 10 female college students (mean ± SEM of age: 23.9 ± 0.4 years, height: 170.6 ± 1.1 cm, weight: 61.2 ± 1.6 kg) were recruited for the experiment. All subjects were healthy non-smokers who were not taking prescription medication and had no history of cardiovascular disease. All protocols were approved by the university's ethics committee and conformed to the guidelines

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contained within the Declaration of Helsinki. Verbal and written informed consent was obtained from each subject prior to the participation in the protocol. Subjects were asked to avoid caffeine, alcohol, and intense physical activity at least 12 h prior to each experimental session.

2.2. Instrumentation

Subjects' local skin temperatures were measured with copper-constantan thermocouples attached to the skin measuring sites, as shown in Fig. 1. During the measurement, the thermocouples were linked to a multi-channel data collector with internal reference junction (KEITHLEY 2700, Keithley Instruments, USA), and skin temperatures were automatically recorded to a computer via the data collector, at 5 s interval. Before the measurement, all the thermocouples were calibrated against a standard mercury thermometer with precision of 0.1 °C. Error of the thermocouples was 0.2 °C.

Subjects' electrocardiogram (ECG) was recorded by a Powerlab 8/30 system (AD Instruments, Australia). For ECG measurement, the standard bipolar limb leads (ML-1340, AD Instruments, Australia) and the adhesive ECG pads (MLA-1010, AD Instruments, Australia) were linked to the data acquisition system (Powerlab 8/30, AD Instruments, Australia) through a bioamplifier (ML-132, AD Instruments, Australia). The Powerlab 8/30 system was calibrated before the experiment. The frequency of sampling for ECG was set at 400 times per s.

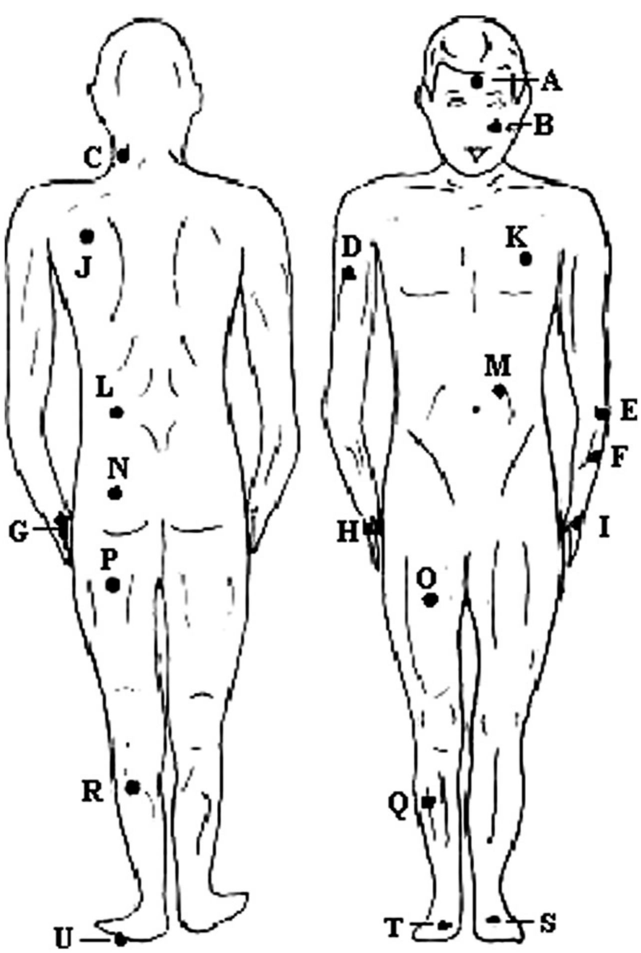

Fig. 1. Measuring sites of skin temperature. A forehead, B left check, C left neck, D right upper arm, E left elbow, F left forearm, G left palm, H right hand, I left hand, J left back, K left chest, L left lumbar, M left abdomen, N left buttocks, O anterior thigh, P posterior thigh, Q anterior calf, R posterior calf, S left foot, T right foot, U left sole.

The ambient temperature was measured with a standard mercury thermometer (Shanghai Huo er Co, China). Indoor air velocity was tested using an anemoscope (TSI Compuflow 8585, E&E Process Instrumentation, Canada). And the relative humidity of indoor air was measured with a dry–wet bulb thermometer (Shanghai Huachen Medical Instruments Co, China). The mean radiant temperature was obtained according to Eq. (1), where the black-bulb temperature was measured by a standard thermometer (D 150 mm, Shanghai Huo er Co, China).

$$T_r = \left[(t_g + 273)^4 + 0.4 \times 10^8 (t_g - t_a)^{5/4}\right]^{1/4} - 273 \quad (1)$$

where T_r is mean radiant temperature, t_g black-bulb temperature and t_a is air temperature. The indoor environmental parameter measurement site was located in the center of the plane at 0.6 m height (near the subject).

2.3. Experimental protocol

In order to consider the effect of the order of air temperature change on MST, the subjects were divided into two groups and in each group a different combination of ambient temperatures was designed. Group 1 (6 men and 5 women, G1) was exposed to an indoor environment with the temperature order of 21 °C, 24 °C, 26 °C and 29 °C, for group 2 (6 men and 5 women, G2) the order was 29 °C, 26 °C, 24 °C and 21 °C. The experiment (all the four indoor temperatures) was done for only one subject on a single day. During the experiment the subject was blind to the exposure temperature.

The summer clothing (vest and shorts) with a total clo of about 0.3 [1] was compulsory for every subject. Under each ambient temperature, a subject's local skin temperatures at 21 measurement sites and ECG were recorded for 5 min. After the measurement, he or she was asked to complete a questionnaire about thermal sensation and comfort. During the exposure and measurement the subjects were asked to lie quietly in a bed but keep awake.

After the measurement at one exposure temperature was finished, the exposure temperature was set to the next value. The experimental temperature reached the new value in 20 min. After the regulation of the environmental temperature began, the subject accommodated to the new exposure temperature. The experimental data in earlier studies indicated that mean skin temperature and thermal sensation became stable within 40 min under a new thermal environment (the change of environmental temperature was less than 10 °C) [8–10]. In this study, the measurements were made after the subject had stayed at a steady ambient temperature for at least 40 min.

The experiment was performed in a climate chamber (see Fig. 2) during May. All measurements were carried out between 13:00 (1 h after lunch) and 17:30. As shown in Fig. 2, there was only a window in the climate chamber and no direct solar radiation entered. The air temperature was controlled using a wall-mounted air conditioner. The indoor air velocity near the subjects was kept under 0.05 m/s, and the relative humidity of air was not dependently controlled.

2.4. Thermal sensation and thermal comfort

At different air temperatures, an occupant may have distinct thermal sensation. Here, the ASHARE 7-point scale was used to assess the subjects' thermal sensation (Fig. 3). The ASHARE scale is