Physiological thermal response in typical air conditioning Environment

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Abstract. Energy consumption for space cooling is increasing in Chinese residential buildings due to the extensive use of split air conditioners. To build a comfortable indoor environment and reduce energy consumption, comprehensive understanding about human thermal requirements of air conditioning is highly needed. As a reflection of human demand for indoor thermal environment, thermal sensation is usually under the effect of human physiological responses. For these reasons, a series of experiments were conducted in a climate chamber to understand human physiological thermal responses in air conditioning environment. During the experiments, indoor temperature was kept at 29°C in the first 30 minutes and then cooled down to 25°C in the next 30 minutes, after that, indoor temperature was held stable in the final 60 minutes. Twenty subjects were recruited to participate in the experiments. Results reveal that first, the temperature of limbs was lower than trunk due to the blood flood and clothing resistance, second, skin temperature and Thermal Sensation Vote (TSV) may still be in the dynamic change after the ambient temperature reached stable, third, significant linear correlation was found between skin temperature and TSV in the limbs, moreover, individual difference could be found in local skin temperature.

1. Introduction
The energy consumption in Chinese residential buildings is increasing by the urbanization and use of split air conditioners. In an air-conditioned environment, occupants usually turn on or turn off split air conditioner to adjust the ambient temperature after feeling uncomfortable (too cold or too hot). This stimulus-response air conditioning approach will not only cause health problems, but also generate unnecessary energy consumption. Therefore, understanding the appropriate demand is necessary to maintain a comfortable thermal environment [1] and energy saving.

As a reflection of individual demand for thermal environment, thermal sensation is under the effect of human physiological, psychological, and environmental parameters. In the field of building science, many studies have focused their attention on the relationship between thermal sensation and skin temperature. Some studies [2,3] proposed that thermal comfort in humans is determined to a great extent by skin temperature. Zhang Yufeng et al.[4] investigated the thermal sensation of the human body under step change environment in hot and humid area of China and established the relationship between mean skin temperature and thermal sensation. Chen C P. et al. [5] measured the skin temperature after the...
subjects entered from 32°C, 28°C, and 20°C to 24°C and investigated the thermal sensation, it was found that the linear correlation between skin temperature and TSV was significantly when the temperature change was 8°C.

Most of the studies were in two uniform transitional environments [4,5] and gradient change environments [3]. However, in Chinese residential buildings, split air conditioners are often installed, and the air conditioner can be controlled independently for each room. After the air conditioner is turned on, the room temperature gradually decreases until it reaches the set point of room temperature and then remains stable. Due to our investigation, 25°C was selected in this paper as the ambient set temperature, and the purpose of this paper is to making comprehensive understanding on human thermal response under the influence of ambient temperature in Chinese residential buildings.

2. Methods

2.1. Subjects and local skin temperature measurement

A total of 20 healthy subjects (10 males and 10 females) were recruited to participate in this study. All participants were in normal physical condition, emotionally stable, and they were required to avoid doing strenuous exercise before the experiment, and they were asked not to eat food or have tea or energy drinks within one hour before the experiment. The clothing insulation value of subjects was 0.39 clo (thin T-shirt, thin shorts, and slippers).

The skin temperature of ten body parts was measured by using iButton, which included the forehead, chest, belly, back, upper arm, forearm, hand back, thigh, calf, and foot back.

2.2. Environment chamber

A series of experiments for this study were conducted in a climate chamber at Beijing Union University. Mechanical ventilation via vents on the ceiling of the room was used and the indoor environment was moderated by a HVAC system. During the experiment, indoor environment parameters were monitored every minute using a thermal comfort monitoring system (SWEMA 03+) placed at height of 1.2m. The ambient air velocity was controlled at less than 0.05±0.03m/s, and the relative humidity (RH) was also recorded. Detailed information of measurement devices used in the experiment are summarized in Table 1.

2.3. Procedures

During the experiments, the ambient temperature was held at 29°C in the first 30 minutes, during which questionnaires regarding overall thermal sensation were completed according to the 7-point ASHRAE Sensation scale every 10 minutes. Then, indoor temperature was reduced gradually from 29°C to 25°C within the next 30 minutes, in which questionnaires were filled every 10 minutes. Finally, the room temperature was held stable for 60 minutes and questionnaires were filled at intervals of 5 minutes. Subjects were instructed to perform slightly mental and physical work during the entire experiment.

| Parameter          | Accuracy  | Resolution | Instrumental model |
|--------------------|-----------|------------|--------------------|
| Ambient temperature| ±0.3°C    | 0.1°C      | SWA 03             |
| Relative humidity  | ±2%       | 0.1%       | Hygroclip S        |
| WBGT               | ±0.3°C    | 0.1°C      | SWA 52 glob        |
| Air velocity       | ±0.03m/s  | 0.01m/s    | SWA 03             |
| Skin temperature   | ±0.5°C    | 0.065°C    | DS1922L            |

3. Results
3.1. Skin temperature and TSV
Mean skin temperature changes of 10 local body parts are presented in Fig.1. It was found that the temperature of chest and belly was significantly higher than the temperature of forehead and back, and lower temperature were found in the forearm, hand back, upper arm and thigh. Besides, the temperature of calf and foot was the lowest among ten body parts. Comparing the change of skin temperature over time, it can be seen that, in the cooling period, skin temperatures of all ten body parts were decreased as the ambient temperature decreased, and after the ambient temperature became stable, the chest and belly temperature first reached stable at the 60th minute, and the temperature of forearm, hand back, upper arm and thigh finally neatly became stable after the 90th minute. Moreover, downward trends can be found in the lower leg and foot during the whole cooling period.

![Figure 1. Mean local skin temperature for 10 local body parts](image)

Figure 1. Mean local skin temperature for 10 local body parts

Besides, Fig.2 shows the mean TSV change during the experiment. First, with the decrease of the ambient temperature, linear downward trend can be seen in the TSV within the first 50 minutes, and then the decline rate of TSV slowed down, moreover, the TSV nearly became stable after the 85th minute.

![Figure 2. Mean TSV for 10 local body parts](image)

Figure 2. Mean TSV for 10 local body parts
3.2. Relationship between skin temperature and TSV
The linear regression method was used to analyse the relationship between local skin temperature and TSV, and the Spearman ranked correlation was selected to measure the correlation between two variables. The p-values and Spearman’s coefficients of different body parts are listed in Table 2.

| Body Part     | Spearman r | p     |
|--------------|------------|-------|
| Forehead     | 0.061      | 0.822 |
| Chest        | 0.037      | 0.892 |
| Belly        | -0.257     | 0.337 |
| Back         | -0.195     | 0.469 |
| Upper arm    | 0.884      |       |
| Forearm      | 0.876      | 0.000***|
| Hand back    | 0.881      | 0.000***|
| Thigh        | 0.881      | 0.000***|
| Calf         | 0.838      | 0.000***|
| Foot back    | 0.851      |       |

***p<0.01

Results show that, there was a significant correlation between local skin temperature and TSV in the upper arm, forearm, hand back, thigh, calf and foot back, and the Spearman r of these body parts were over 0.8. In contrast, the linear correlation was weak in the forehead, chest, belly and back. Moreover, the Spearman r between skin temperature and TSV of belly and back was under zero, which was -0.257 and -0.195, respectively.

3.3. Individual difference
The skin temperature of the same body parts in different studies varies. By comparing the results of different studies, it was found that the local temperature for the same body part varies greatly though the values of TSV were same. When the TSV=0, the mean temperature of hand back in this study were 32.66°C. However, the temperature of hand was 29.89°C in Choi’s [3] study and 31.69°C in T.Chaudhuri’s [6] study, when the overall TSV is zero. Moreover, for the different subjects in the same study, individual local skin temperature varies [3, 7]. These could be illustrated by the physiological condition of subjects. Gender and BMI difference may explain the discrepancy of skin temperature according to many previous studies [8, 9].

4. Discussion
As shown in the last section, the effect of ambient temperature on skin temperature was significant when the body parts were away from the torsos. This can be illustrated by the adequate blood supply to the vital organs such as brain and heart [10]. Besides, the lowest temperature was found in calf, which was significantly lower than the temperature of foot. This may be due to the thermal resistance difference between the calf and the foot [10]. Clothing plays an important role in maintaining thermal balance of human body [6]. In this study, all subjects were restricted to wear slippers and shorts so as to simulate the clothing condition in Chinese residential building in summer. So their calves were exposed to the environment directly. In comparison, slippers provided a certain clothing thermal resistance for the feet. Moreover, the local skin temperature and mean TSV may change in a period of time after the ambient temperature became stable.

As a reflection for the individual demand for the thermal environment, thermal sensation is under the effect of human physiological and psychological, and environmental parameters. By investigating the thermal sensation and of 18 subjects and indoor temperature, Choi [11] suggested that the overall thermal sensation correlated positively with the indoor temperature. Yu Juan [12] measured the TSV and the physiological parameters of subjects under the 20°C/23°C/26°C/31°C/34°C environment and pointed that the skin temperature, heart rate variability (HRV) and electroencephalogram (EEG) had significant correlation with TSV, respectively. G.wang [13] pointed out that in low pressure...
environment, the average skin temperature could be used as an index to indicate the thermal sensation. As shown in Table.2, significant correlation between skin temperature and thermal sensation can be seen in the limbs, that is, the local skin temperature of limbs can be a reasonable parameter for thermal sensation prediction. However, for better prediction, individual difference should also be taken into consideration.

5. Conclusion and implications
In this study, the physiology and psychological conditions of 20 subjects were analysed to investigate the relationship between local skin temperature and thermal sensation. Results show that, first, the temperature of limbs was lower than that of the trunk due to the blood flood and clothing resistance, second, the skin temperature and TSV might still be in the dynamic change after the ambient temperature reached stable, third, significant linear correlation was found between skin temperature and TSV in the limbs, moreover, individual difference could be found in local skin temperature. This study explains the features of skin temperature change, TSV and their correlation in a typical air conditioning environment, and it provides a certain basis for the construction of thermal environment in Chinese residential building in summer.

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References
[1] Ji W J, Cao B, Geng Y, Zhu Y X and Lin B R 2017 Energy Build. 156 L29
[2] Bulcao C F, Frank S M, Raja S N, Tran K M and Goldstein D S 2000 J. Therm. Biol. 25 L147
[3] Choi J H and Loftness V 2012 Build. Environ. 58 L258
[4] Zhang Y F, Zhang J, Chen H M, Du X H and Meng Q L 2014 Build. Environ. 80 L174
[5] Chen C P, Hwang R L, Chang S Y and Lu Y T 2011 Build. Environ. 46 L2387
[6] Chaudhuri T, Zhai D, Soh Y C, Li H and Xie L 2018 Energy Build. 159 L426
[7] Sharifani P, Talele S, Mun J and Tao Y 2015 1st Int. Symp. on Sustainable Human-building Ecosystems, (Pittsburgh: USA) p 141
[8] Choi J H and Yeom D 2017 Build. Environ. 121 L130
[9] Indraganti M, Ooka R and Rijal H B 2015 Energy Build. 103 L284
[10] Song G S, Lim J H and Ahn T K 2012 Appl Ergon. 43 L211
[11] Choi J H and Yeom D 2017 Energy Build. 149 L201
[12] Yu J 2011 PhD. Thesis. (Donghua University: China)
[13] Wang G, Liu R X, Liu G D, Wang H Y and Zhang B B 2010 HV&AC. 40 L89