PHYSIOLOGICAL AND PSYCHOLOGICAL MODEL OF LOCAL THERMAL SENSATION UNDER LOCAL COOLING

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ABSTRACT

Local thermal sensations of all body parts were studied in neutral-warm room while face, chest and back were each exposed to local cooling air. Dressed in shorts, 30 randomly selected male subjects were exposed to each condition for 30 minutes. During the exposure, local thermal sensation of each body part was reported by subjects on voting scales at regular intervals and their skin temperatures on forehead, cheek, chest and back were recorder continuously. Thermal sensations of the cooling body parts changed with their skin temperature and two kinds of physiological models were obtained for face, chest and back separately. Thermal sensations of the uncooled body parts changed with local cooling while their skin temperature was kept unchanged, and a psychological model were established to describe the effect of local thermal sensations between body parts. Face thermal sensation has bigger impact on thermal sensation of the rest of the body.

KEYWORDS

Local cooling, local thermal sensation, skin temperature, psychological effect

INTRODUCTION

Local cooling is increasingly in focus as an advanced technology to provide an acceptable environment while using less energy. Local thermal sensation, as an important elementary variable, plays a key role in the study on local cooling.

Skin temperature was considered to be the important factor influencing thermal sensation. Gagge et al (1967) found that whole body thermal sensation was roughly a linear function of mean skin temperature between 29 and 34°C. Recently Fiala (2003) developed a physiological model using data from early studies and indicated that the relationship between subjective sensation and skin temperature was linear when the mean skin temperature was between 3°C below and 1°C above its set point, but beyond those points, the relationship approaches the scale limits exponentially.

The effect of local skin temperature on local thermal sensation was studied by Mower (1976). He found that the local thermal sensation of the hand was linear functions of hand skin temperature, regardless of the mean skin temperature for whole body. However, other researchers found that local thermal sensation was a function of both local skin temperature and the overall thermal state of the body (Hildebrandt, Engel et al. 1981, Issing and Hensel, unpublished, from Hensel 1982, Zhang 2003).

The purpose of the present study is to investigate quantitatively the effect of local skin temperature on local thermal sensation and to develop the model of local thermal sensation under local cooling.

EXPERIMENTAL METHODS

Experimental design

The experiment was carried out in the Department of Building Science at Tsinghua University during the period March 2005 to June 2005. A personalized ventilation system was used to supply the local cooling airflow and a set of special clothes was used to fix the cooling body surface area (see Figure 1). Three sensitive body parts: face, chest and back were selected to be cooled locally in the present study. A climate chamber was used to control the ambient room temperature for local cooling. Temperature in the chamber and temperature at the outlet of local airflow was maintained with a precision of ±0.2°C.

Chest cooling Face cooling Back cooling

Figure 1 Devices for local cooling

Three levels of room temperatures, ranging from neutral to warm, and three levels of local cooling target temperatures (target temperature means the air temperature at the center of cooling body part surface), ranging from neutral to slightly cool, were chosen to be studied (see Table 1). The relative humidity was kept constant at 40% and the air speed was less than 0.1m/s in the chamber. The air speed at the outlet of the local cooling airflow was maintained at 1m/s.

Table 1 Experimental conditions

ROOM TEMPERATURE (°C)	TARGET TEMPERATURE (°C)
28，32，35	22，25，28

Measurements

Subjects reported their responses twice before local cooling and 16 times while local cooling, at one-minute intervals for six minutes and then at two-minute intervals for fourteen minutes and then at five-minute intervals. Local thermal sensation for each of the body parts (including face, chest, back and lower body part) were reported on the 7-point ASHRAE scale.

Skin temperatures at face, back and chest were measured by using thermocouples. Considering the temperature difference between forehead and cheek, two measuring positions were chosen for face skin temperature (see Figure 2). The sensors were attached on the surface of the skin closely by using porous adhesive tape, which can keep the skin sweat normally. Temperature in the room and temperature at the outlet of local airflow were measured and recorded every two seconds during each exposure.

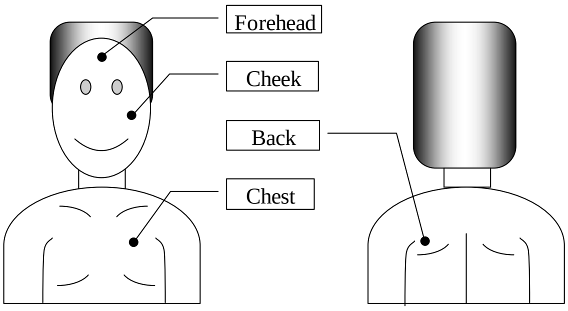

Figure 2 Voting scales

Thirty randomly selected Chinese male students, dressed in short, with a normal range of age, height and weight participated in the experiment. Each test consisted of half an hour pre-conditioning and half an hour exposure. The room temperature was maintained constant for each test and no local airflow existed during pre-conditioning. The total duration of each subject's participation was 27 hours. The sequence of presentation was balanced for each subject using Latin squares. Subjects remained sedentary throughout each exposure. Subjects responding 'very uncomfortable' at any point in time were allowed to terminate the exposure and leave immediately.

RESULTS

Shapiro-Wilk's W test was applied and the results show that human responses obtained in all conditions were normally distributed. They were therefore analysed using repeated measure ANOVA and paired-sample t-tests. It was found that human responses reached steady state within 25 minutes during pre-conditioning ($p>0.05$) and within 20 minutes during local cooling ($p>0.05$) in all conditions. If not mentioned specifically, all responses reported below are steady state responses.

Observations

The change of skin temperature and thermal sensation with time in a face cooling condition was shown in Figure 3. The skin temperature of forehead and cheek decreased gradually while face cooling was supplied (9:14 in the figure) and accordingly face thermal sensation changed with skin temperature. Chest and back thermal sensation changed significantly ($p<0.05$ by using paired-sample t-tests) with face cooling, however, the skin temperature of chest and back kept constant during exposure.

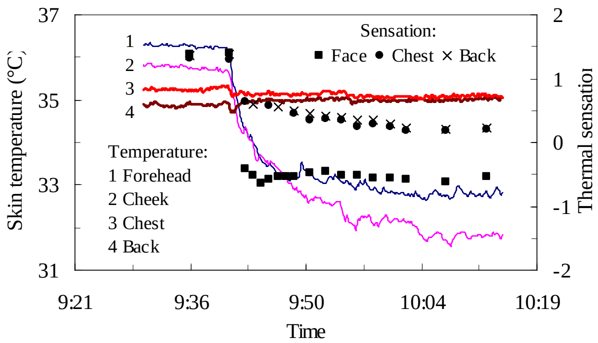

Figure 3 Change of Skin temperature and thermal sensation with time (room temperature 35°C, target temperature 22°C)

The observation in other conditions confirms the above findings. For the cooling body parts, local thermal sensation is affected by local skin temperature. For the uncooled body parts, local thermal sensation is not determined solely by local skin temperature, but influenced psychologically by the change of local thermal sensation of the cooling body parts. Psychological effect of local thermal sensation exists between body parts while local cooling was supplied.

Physiological model of local thermal sensation under local cooling

The relationship between local thermal sensation and local skin temperature was analyzed for face, chest and back cooling separately (see Figure 4~6).

Face thermal sensation (S_{face}) can be represented by a 2-segment linear function of face skin temperature (T_{face}) (see Figure 4):

$$\begin{cases} S_{face} = 0.24T_{face} - 8.24 & (S_{face} \leqslant 0) \quad (1) \\ S_{face} = 1.64T_{face} - 58.34 & (S_{face} > 0) \quad (2) \end{cases}$$

The neutral skin temperature for face is 34.33°C and the slope is much steeper on the warm side than the cold side. The data fits the two lines well (R^2>0.8) and the function is unaffected by the ambient room temperature.

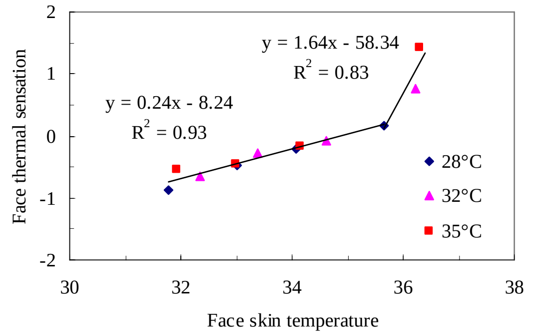

Figure 4 Face thermal sensation as a function of face skin temperature

The relationship between chest thermal sensation (S_{chest}) and chest skin temperature (T_{chest}) was analyzed (see Figure 5) and the similar result was obtained. The neutral skin temperature for chest is 33.45°C and the regression function is:

$$\begin{cases} S_{chest} = 0.31T_{chest} - 10.37 \quad (S_{face} \leqslant 0) & (3) \\ S_{chest} = 0.80T_{chest} - 26.71 \quad (S_{face} > 0) & (4) \end{cases}$$

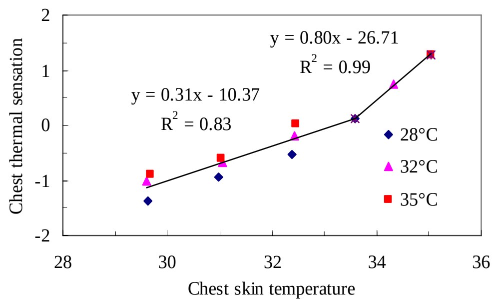

Figure 5 Chest thermal sensation as a function of chest skin temperature

However, the result obtained under back cooling is different from the one under face and chest cooling (see Figure 6). Back thermal sensation (S_{back}) is a set of linear functions of back skin temperature (T_{back}) under different ambient room temperatures (T_{room}):

$$\begin{cases} S_{back} = 0.19T_{back} - 6.45 \ (T_{room} = 28°C) & (5) \\ S_{back} = 0.31T_{back} - 9.79 \ (T_{room} = 32°C) & (6) \\ S_{back} = 0.34T_{back} - 10.46 \ (T_{room} = 35°C) & (7) \end{cases}$$

Subjects felt back with the same skin temperature warmer when the ambient room temperature was higher.

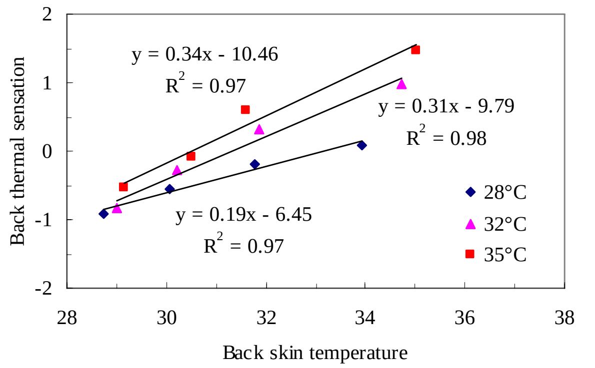

Figure 6 Back thermal sensation as a function of back skin temperature

Psychological model of local thermal sensation under local cooling

The influence of face thermal sensation on chest and back thermal sensation while face cooling was analyzed by using influencing factor method (Zhang et al. 2007), which can be expressed as:

$$\triangle TS_i = f_{ci} \triangle TS_c \qquad (8)$$

where $\triangle TS_i$ is the change of local thermal sensation of the uncooled body part i, $\triangle TS_c$ is the change of local thermal sensation of the cooling body part, and the regression coefficient f_{ci} is the influencing factor of the cooling body part on the uncooled body part i.

Figure 7 shows the effect of face cooling on chest thermal sensation. The change of thermal sensation in the figure means the mean thermal sensation vote during local cooling minus the one during pre-conditioning. A straight line passing origin fits the data well (R^2=0.87) and the slope represents the influencing factor of face on chest. The influencing factor was 0.54 and unaffected by ambient room temperature.

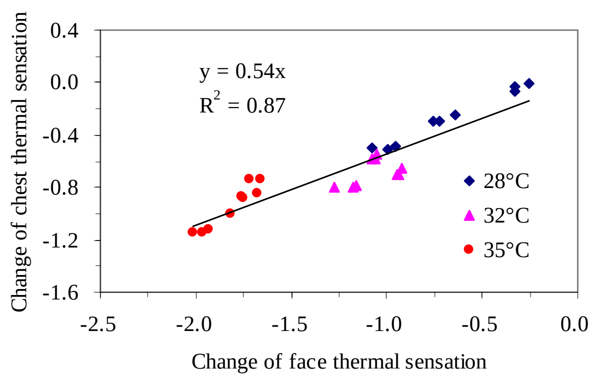

Figure 7 The influencing factor of face on chest

The influencing factor of face on back and lower body part was analyzed in the same way and the results is shown in Figure 8~9. The influencing factor of face on back and lower body part is 0.57 and 0.43 regardless of ambient room temperature.

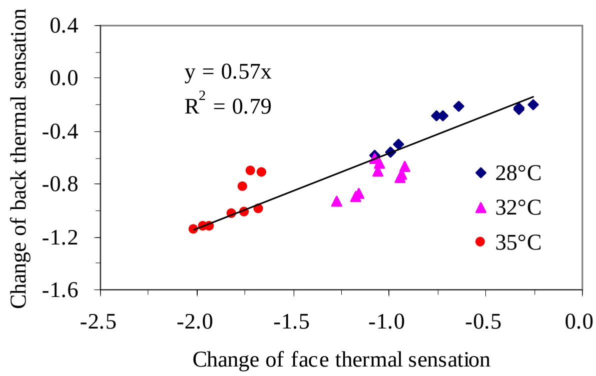

Figure 8 The influencing factor of face on back

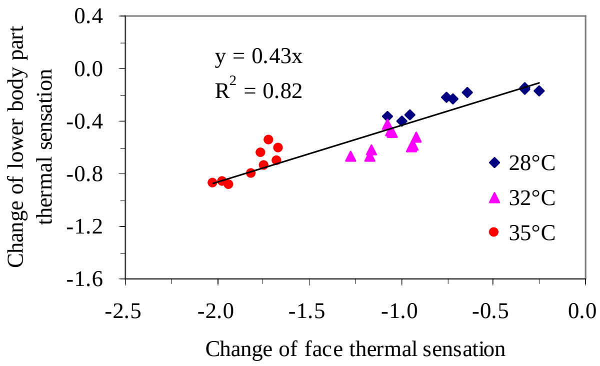

Figure 9 The influencing factor of face on lower body part

The influencing factor of chest and back was analyzed and the results are shown in Table 2.

Table 2 Influencing factors (R^2>0.63)

COOLING BODY PART	FACE	CHEST	BACK	LOWER BODY PART
Face	1	0.54	0.57	0.43
Chest	0.16	1	0.4	0.31
Back	0.18	0.3	1	0.3

Table 2 shows that influencing factor can describe the relationship between local thermal sensation of different body parts well (R^2>0.63) and the equation (8) can be used as the psychological model of local thermal sensation under local cooling. Table 2 also shows that cooling body parts affect siginificantly the rest of the body in the form of local thermal sensation and face has the biggest impact compared with chest and back. The influence of chest on back while chest cooling is close to the one of back on chest while back cooling, however, the influence of face on chest or back is much greater than the one of chest or back on face.

DISCUSSION

The present study shows two kinds of physioligcal model of local thermal sensation. One is 2-segment liner function of local skin temperature for face and chest thermal sensation, and the slope is steeper on the warm side than the cold side, which is similar with the results obtained by Fiala (2003). The other is a function of local skin temperature and ambient room temperatures for back thermal sensation, which is in agreement with Zhang (2003).

Zhang (2003) developed physiological model of local thermal sensation with logistic function based on the observation that the relationship between sensation and skin temperature approaches the scale limits exponentially. The present study was focused on the human responses to moderate stimulus and linear function is appropriate with this range.

CONCLUSIONS

The effect of local skin temperature on local thermal sensation while local cooling was studied in the present experiment and the following conclusions were drawn:

1. For face and chest cooling, local thermal sensation of cooling body part is represented by a 2-segment linear function of local skin temperature and the slope is steeper on the warm side than the cold side.
2. For back cooling, local thermal sensation of cooling body part is represented by a set of linear functions of local skin temperature under different ambient room temperatures.
3. Psychological effect of local thermal sensation exists between body parts while local cooling and the psychological model was developed based on the influencing factor method.
4. Compared with chest and back, face thermal sensation has bigger impact on the thermal sensation of the rest of the body.

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