*J. Kor. Soc. Cloth. Ind.*
*Vol. 2, No. 5, pp.398-404(2000)*
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# Effects of Individual Sweating Response on Changes in Skin Blood Flow and Temperature Induced by Heat of Sorption Wearing Cotton Ensemble

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**Abstract:** We examined the effect of individual sweating responses on thermoregulatory responses induced by heat of sorption, immediately after the onset of sweating. The present study consists of two experiments. In experiment 1, made of 100% cotton (C) and 100% polyester (P) clothing were exposed in the chamber at ambient temperature (Ta) of 27.2°C and relative humidity (rh) raised from 50% to 95% at five different increase rates of environmental vapor pressure (VP). The increase rate of clothing surface temperature (Tcs), peak Tcs and peak time showed significant correlation with the increase rate of environmental VP in C-clothing ($p<0.05$). In experiment 2, seven female subjects were studied during leg water immersion (35-41°C) for 70min in Ta of 27.2°C and 50%rh. There were significant positive correlations in the increase rate of clothing microclimate VP vs. changes in Tcs, skin blood flow, mean skin temperature and mean body temperature ($p<0.05$). The present results showed that individual clothing microclimate VP had significant effects on thermoregulatory responses induced by heat of sorption wearing C ensembles.

**Key words:** heat of sorption, skin blood flow, sweating, individual variation, clothing microclimate vapor pressure

## INTRODUCTION

It has established that with further increase in hygroscopicity of the fibres, the amount of heat of sorption is evolved (Morton and Hearle, 1975). We have reported that when the subjects were wearing clothing ensembles made from hygroscopic fabrics, their thermoregulatory responses were significantly greater than when wearing poor-hygroscopic clothing ensembles, accompanying evolution of heat of sorption *perse* induced by sweating during heat load (Tanaka *et al.*, 2001).

We have shown the qualitative mechanism as follows: In cotton (C) clothed subjects, secreted sweat from the human body was transferred from skin to clothing as evaporative heat loss. The water vapor evaporated from the skin was absorbed partially into the clothing and then produced heat of sorption and increased clothing surface temperature (Tcs), that is, the way of heat loss was changed in quality from the evaporative heat loss into the non-evaporative heat loss on clothing. Increased Tcs caused promotion of non-evaporative heat loss from the clothing surface to the environment. On the other hand, non-evaporative heat loss from the skin to the clothing surface was limited, because the gradient between Tcs and skin temperature was reduced. Consequently, the heat stored in the skin induced a rising skin temperature, and then it would have induced a rising skin blood flow (SBF) through vasodilatation in the skin. We have observed that the rising SBF enhanced increase in skin temperature more and more until the end of experiment.

The above-stated mechanism occurs after the onset of sweating. It is well known that there are intrinsic individual differences in sweating response. Various factors to influence individual sweating responses have been found; for instance, age (Inoue et al., 1998; Wagner *et al.*, 1972), menstrual cycle (Wells and Horvath, 1972), hydration state (Nadel *et al.*, 1980), physical training (Araki *et al.*, 1981; Roberts *et al.*, 1977), body composition (Bar-or *et al.*, 1969), heat acclimation (Inoue *et al.*, 1995; Nadel *et al.*, 1974) and circadian rhythm (Aoki *et al.*, 1995; Stephenson *et al.*, 1984). Therefore, individual sweating responses, if subjective sweating res-ponses are altered with the above-mentioned factors will influence the mechanism that heat of sorption in hygroscopic clothing enhances thermoregulatory responses. How-ever, the effect of individual variations in sweating on thermoregulatory responses relating to heat of sorption has been little examined.

The aim of this study is to investigate how individual differences in sweating contribute to the above-mentioned mechanism by focusing on individual sweating rates (increase rate of sweating).

The present investigation consists of 1) observing the effects of two different clothing materials on thermo-

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graphic measurements of Tcs while raising the environmental humidity in a chamber without any subjects (Experiment 1) and 2) thermophysiological observation during heat load induced with lower-legs water immersion (Experiment 2).

This study follows our previous research (Tanaka *et al.*, 2001).

## METHODS

Two different clothing were selected for the present study (Experiment 1 and 2), one made of 100% cotton (C) and the other 100% polyester (P). Each clothing ensemble consisted of a short-sleeved blouse, knee breeches and underwear. The blouses and breeches were made of C or P based on same paper pattern in our laboratory. Both fabrics have similar heat conduction and heat transfer properties, and their physical properties are presented in detail in Table 1.

### Experiment 1 (environmental VP transition)

C and P blouses were fixed on the wire frames in the shape of clothing in a controlled climatic chamber (TBL-15W4YPX Tabai Espec Co. Ltd., Japan) at an ambient temperature (Ta) of 27.2± 0.5°C, and a relative humidity (rh) of 50± 3%. The rh of the air was changed from 50% (1.8 kPa) to 95%rh (3.4 kPa) at five different rising rates of environmental VP (0.3, 0.6, 1.1, 2.4 and 3.4 kPa·10 min$^{-1}$) and then was kept at a constant for at least 30 min after reaching 95% rh. The Ta was maintained at a constant throughout each measurement. The surface temperatures of both pieces of clothing were measured via a thermo-camera (thermovision870 Agema, Sweden) and recorded each minute by the thermography system. Then the clothing surface temperatures (Tcs) were calculated as an average for each blouse surface area of approximately 2290 cm$^2$. Details are explained in our previous report (Tanaka *et al.*, 2001).

**Table 1.** Physical properties of the fabrics

| Variables | | Cotton | Polyester |
|---|---|---|---|
| Density Wale | (no. · inch$^{-1}$) | 64 | 78 |
| Course | (no. · inch$^{-1}$) | 58 | 62 |
| Thickness | (mm) | 0.33 | 0.22 |
| Weight | (g · m$^{-2}$) | 139 | 104 |
| Porosity percentage | | 0.73 | 0.66 |
| Heatconduction | (kcal · m$^{-1}$ · h$^{-1}$ · $^{-1}$) | 0.052 | 0.052 |
| Heattransfer | (kcal· m$^{-1}$· h$^{-1}$· $^{-1}$) | 13.1 | 13.1 |
| Permeability constant | (10$^{E-11}$m$^2$) | 3.0 | 6.6 |
| Water vapor transmission resistance | (cm) | 2.156 | 2.141 |

### Experiment 2 (human sweating)

**Subjects**: Seven female subjects volunteered for the experiment. The physical characteristics [mean (range)] of the subjects were as follows: age 21.9 (21-24) years, height 160.6 (152-166) cm, body mass 55.4 (52-64) kg, body surface area 1.52 (1.38-1.66) m$^2$ according to Fujimoto and Watanabe (1965), and percentage of body fat 23.5 (20.1-29.3)%. They participated in the experiment at the same time of the day in the luteal phase of their menstrual cycle from November to December. The subjects were requested to ingest a fixed light meal and 200 ml of water 3h prior to the measurement, and after that to refrain from taking any food or water until the end of each heat load. Each subject was informed of the purpose and procedure of the study in detail, and their consent was obtained prior to the experiment.

**Measurements**: Skin temperatures on chest, upper-arm, thigh and calf were measured with attached thermistors and Mean skin temperature ($\overline{\text{Tsk}}$) was calculated according to the equation of Ramanathan (1964). Rectal temperature (Tre) was obtained by inserting a precision thermistor probe into the rectum 10cm beyond anal sphincter. Mean body temperature ($\overline{\text{Tb}}$) was then calculated as: $\overline{\text{Tb}} = 0.2 \cdot \overline{\text{Tsk}} + 0.8 \cdot \text{Tre}$.

Cumulative evaporation rate (CER) from the subjects and their clothing was measured every 30 sec by a continuous weighing technique using precision scales (KCC 150S Mettler, Germany). CER was compensated by evaporation rate from the water bath. The amount of sweat absorbed in the clothing was determined by the difference in clothing weight before and after the heat load. All temperature and CER data were recorded every 30 sec using a personal computer.

SBF at forearm was measured by a laser-Doppler flowmeter (ALF-21 Advance, Japan) and their outputs were sampled every second by a personal computer through the data logger, then calculating the average for 1 min. Heart rate (HR) was measured every minute with a pulse watch.

Clothing microclimate temperature and humidity, Tcs were measured at the chest, upper-arm and thigh every minute by using calibrated temperature-humidity sensors (HMM 36UST Vaisala, Finland) and recorded with data collectors. These sensors were fixed on the skin and on the clothing surface with adhesive tape. To keep the distance of the gap between the skin and the clothing constant, frame-spacers were inserted at the above three sites.

For thermal sensation and soaking sensation, the category scale was evaluated in 9 and 7 scales, respectively. Also, comfort sensation was assessed by using a 7-point scale, according to Miura *et al.* (1960). All voting was recorded every 5 min.

**Procedures**: Experiments were conducted twice in each subject, once with C-clothing and once with P-clothing. Four out of seven subjects wore C-clothing prior to P-clothing and the others wore P-clothing prior to C-clothing. The subjects dressed in either the C- or P-clothing and entered into a climatic chamber (Ta of 27.2± 0.5°C, 50± 3%rh and an air velocity of 0.2 m·s$^{-1}$). They sat quietly on the chair, and were fitted with measuring sensors. First they immersed their legs to the knee into a water bath at a water temperature (Tw) of 35°C for 10 min then the Tw was raised from 35°C to 41°C over 15 min, after which the Tw was maintained at a constant of 41°C for 45 min. The methods of the study are described in more detail in our previous paper (Tanaka *et al.*, 2001).

**Data analysis :** Fig. 1 shows a typical sample of the time courses of vapor pressure in clothing microclimate (VP) during heat load in the experiment. The onset of sweating was determined by the point at which clothing microclimate VP increased at greater rate than the rate of 0.16kPa·min$^{-1}$ after natural fluctuation without sweating. Also, the rate of changes in clothing microclimate VP was calculated as the slope of the regression line of clothing microclimate VP for 10 min after the onset of sweating. The changes in skin blood flow (ΔSBF), mean skin temperature (Δ$\bar{T}$sk) and clothing surface temperature (ΔTcs) were calculated by the differences between the value at sweating onset and the peak value for 10 min after the onset of sweating. We employed ΔTcs as an index of heat of sorption in this study.

The results were analyzed by standard linear regression analysis. Significance level of $p<0.05$ was accepted.

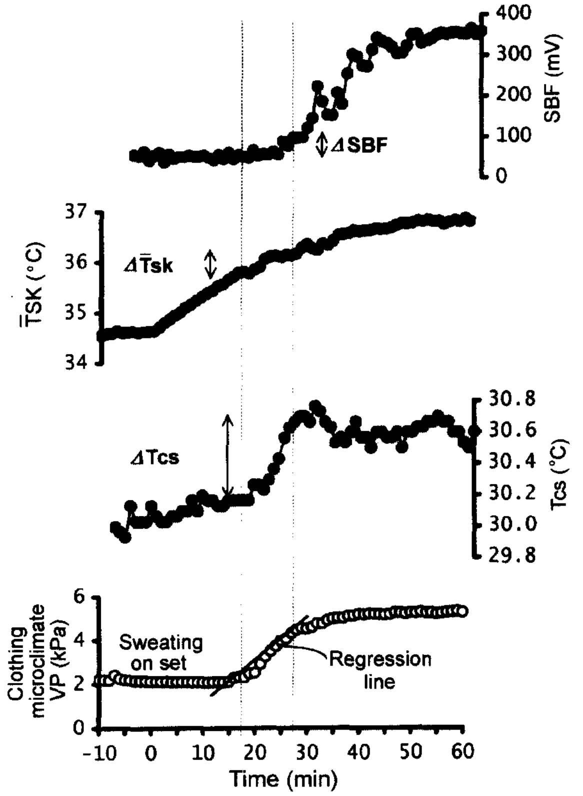

**Fig. 1.** Typical sample of the time courses of skin blood flow (SBF), mean skin temperature ($\bar{T}$sk), clothing surface temperature (Tcs) and clothing microclimate vapor pressure (VP), for cotton clothed subject during heat load in Experiment 2. Regression line shows the relationship between clothing microclimate VP and time in min after the onset of sweating. Arrows indicate the changes in SBF (ΔSBF), $\bar{T}$sk (Δ$\bar{T}$sk) and Tcs (ΔTcs) for 10 min after the onset of sweating. The left dotted line shows sweating onset time at 15min and the right dotted line shows 10 min after the onset of sweating at 25min during heat load.

## RESULTS

The Tcs rose during humidity transition with the

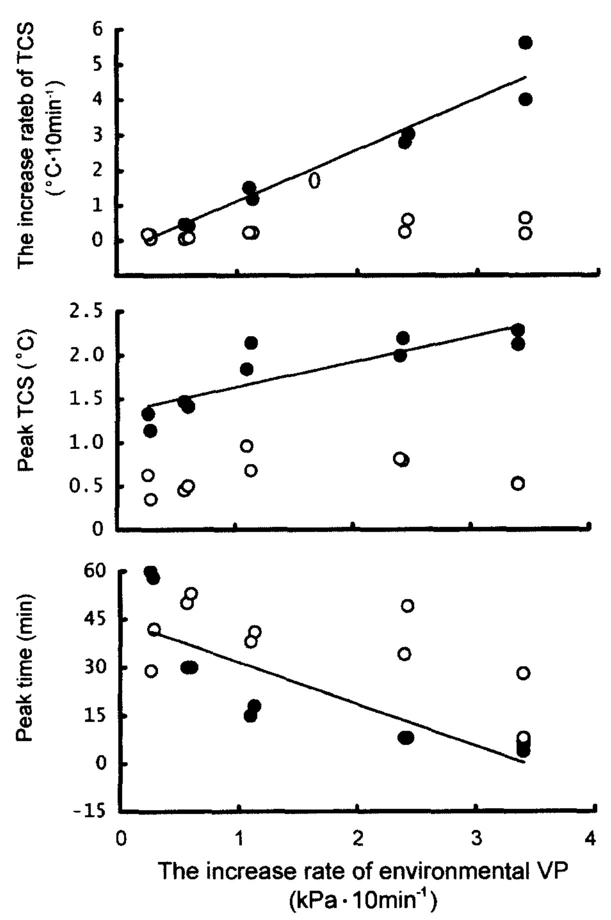

**Fig. 2.** Comparison of the increase rate of clothing surface temperature (Tcs) and time in min until it shows peak value (top), peak Tcs (middle) and peak time (bottom) in cotton (●) and polyester (○) blouses at five different increase rates of environmental VP in Experiment 1.

increase of environmental humidity at five different increasing rate of environmental VP with the C-blouse. Then peak value of Tcs showed when environmental VP reached to 3.4 kPa (95%rh).

Fig. 2 shows the relationship between the slope of the regression line for Tcs and time in min until Tcs shows peak value, peak Tcs and peak time, and the increasing rate of environmental VP during the environmental VP transition at five different rates in Experiment 1. The relationships between the slope of the regression line for Tcs and time in min, and the rate of change in environmental VP showed a significantly positive correlation with both blouses (C: $y = 1.46x - 0.34$, $r = 0.97$, $p<0.05$; P: $y = 0.12\ x + 0.07$, $r = 0.70$, $p<0.05$), however, the slope with the P-blouse was very shallow. The higher increase rate of environmental VP showed the larger peak Tcs during environmental VP transition in spite of constant Ta. There was a significantly positive correlation between the peak Tcs and the increasing rate of environmental VP in the C-blouse ($y = 0.29x + 1.35$, $r = 0.85$, $p<0.05$). The highest peak Tcs reached 2.28°C at the change in environmental VP transition of 3.4 kPa·10 $\text{min}^{-1}$ and the lowest change in Tcs showed 0.33°C at 0.3 kPa·10 $\text{min}^{-1}$. On the other hand, there was no significant correlation in the P-blouse. The relationship between the peak time and the rate of changes in environmental VP showed a significantly negative correlation in C-blouse ($y = -13.01x + 44.63$, $r = -0.83$, $p<0.05$), however, it was not significant in P-blouse.

Fig. 3 indicates the relationship between ΔTcs and the rate

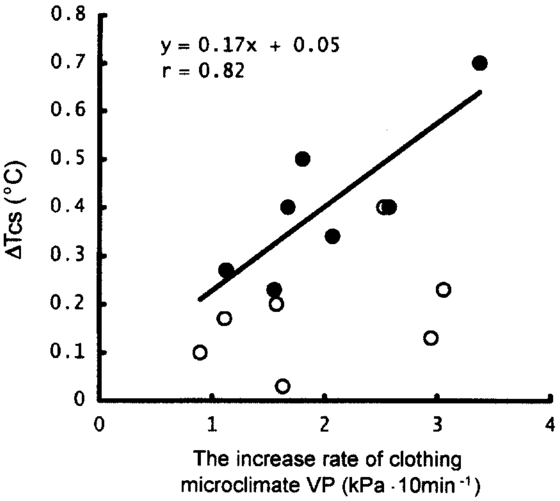

**Fig. 3.** Relationship between changes in clothing surface temperature (ΔTcs) and the increase rate of clothing microclimate VP for 10 min after the onset of sweating, for cotton (●) and polyester (○) clothing in Experiment 2.

**Table 2.** Regression analyses showing the relationships between the increase rate of clothing microclimate vapor pressure (VP) (kPa·10 $\text{min}^{-1}$) vs ΔSBF, ΔTsk, ΔTre ΔTb, ΔHR, ΔThermal, ΔSoaking and ΔComfort for 10 min after the onset of sweating, respectively

| | | Clothing | Regression line | | |
|---|---|---|---|---|---|
| | | | a | b | r |
| The increase rate of clothing microclimate VP vs. | ΔSBF (mV) | C | 58.27 | -74.54 | 0.81* |
| | | P | 20.10 | -4.69 | 0.64 |
| | ΔTsk (°C) | C | 0.17 | -0.05 | 0.81* |
| | | P | -0.03 | 0.29 | -0.13 |
| | ΔTre (°C) | C | 0.06 | -0.06 | 0.76 |
| | | P | 0.06 | -0.02 | 0.72 |
| | ΔTb (°C) | C | 0.10 | -0.08 | 0.93* |
| | | P | 0.02 | 0.07 | 0.29 |
| | ΔHR (bpm) | C | -3.74 | 19.42 | -0.68 |
| | | P | -3.89 | 19.49 | -0.65 |
| | ΔThermal | C | -0.13 | -1.70 | -0.39 |
| | | P | 0.39 | -1.33 | 0.44 |
| | ΔSoaking | C | 0.58 | -2.56 | 0.36 |
| | | P | -0.32 | -0.53 | -0.45 |
| | ΔComfort | C | 1.24 | -3.78 | 0.64 |
| | | P | 0.93 | -2.76 | v0.52 |

Regression line: y=ax+b, r: correlation coefficient, ΔSBF: Change in skin blood flow, ΔTsk: Change in mean skin temperature, ΔTre: Change in rectal temperature, ΔTb: Change in mean body temperature, ΔHR: Change in heart rate, ΔThermal: Change in thermal sensation, ΔSoaking: Change in soaking sensation, ΔComfort: Change in comfort sensation, C: cotton, P: polyester. *Significant correlation coefficient of the regression line showing the relationship between the variables.

of changes in clothing microclimate VP during heat load in human subjects of Experiment 2. The relationship in C-clothing showed a significantly positive correlation, with a regression line of $y = 0.17x + 0.05$ ($r = 0.82$, $p < 0.05$). In contrast, no significant correlation was observed in P-clothing.

The results from the regression analysis for the relationships between the increasing rate of clothing microclimate VP and, $\Delta$SBF, $\Delta\overline{T}$sk, $\Delta$Tre, $\Delta\overline{T}$b, $\Delta$HR, $\Delta$Thermal, $\Delta$Soaking and $\Delta$Comfort are listed in Table 2, respectively. In C-clothing, there were significant correlations ($p < 0.05$) in the increase rate of clothing microclimate VP vs. $\Delta$SBF, $\Delta\overline{T}$sk and $\Delta\overline{T}$b, however, correlations in $\Delta$Tre, $\Delta$HR, $\Delta$Thermal, $\Delta$Soaking and $\Delta$Comfort were not significant. No significant correlations in the increase rate of clothing microclimate VP vs. all thermophysiological variables were observed in P-clothing. The slopes of the regression lines were steeper for C-clothing and shallower for P-clothing in most variables except $\Delta$Tre and $\Delta$Thermal.

## DISCUSSION

Cutaneous blood vessels respond to reflexes arising from central (core temperature) or peripheral (skin temperature: Tsk) thermal stimuli (Rowell, 1986). It was suggested that reflex effects of raising Tsk on cutaneous vasodilatation are mediated through the sympathetic nervous system (Pergola *et al.*, 1994).

The reflex control of SBF over most of the body surface is determined by a balance between a noradrenergic vasoconstrictor system and an active vasodilator system (Kenney, 1997). Active vasodilatation has been linked mechanistically to eccrine sweat gland function. The link between vasodilatation and sweating remains somewhat elusive and no primary neurotransmitter has been defined.

Recently several studies have shown that both control of the cutaneous vasculature can be distinguished by plotting SBF against local sweating rate (Hirata and Kondo, 1994; Inoue *et al.*, 1998)

In this study, Tcs in the subjects wearing hygroscopic C-clothing ensembles was markedly raised because of heat of sorption, following a transferred water vapour from the skin through sweating secretion has been absorbed into the clothing. As a result the temperature gradient between skin and clothing was reduced and skin temperature was raised, for dry heat loss from the skin was held down. This increase in skin temperature would trigger enhancing further thermoregulatory responses involving increased SBF (Tanaka *et al.*, 2001).

### Individual variation in the increasing rate of clothing microclimate VP and heat of sorption

We examined the relationship between clothing microclimate VP and local sweating rate to confirm whether the increase in clothing microclimate VP expresses the increase in sweating rate (unpublished data). The subjects wore long-sleeved C-clothing ensembles of the same material as our experimental subjects who immersed their legs in a water bath at Tw of 28-41°C for 70min, while Ta of climatic chamber maintained at 25°C. Clothing microclimate VP using by temperature-humidity thermistor and local sweating rate ($\dot{M}$sw) measured by a ventilated capsule on the forearm was measured throughout the water immersion. Correlation of clothing microclimate VP with $\dot{M}$sw is shown in Fig. 4. With the start of heat load, there were proportional increases in clothing microclimate VP and $\dot{M}$sw. The correlation coefficient between the two measurements was very high ($r = 0.99$). Therefore, the changes in clothing microclimate VP indicate sweating rates.

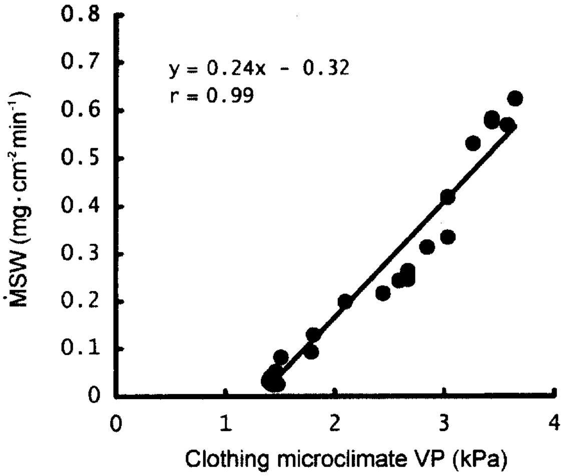

**Fig. 4.** Relationship between clothing microclimate VP and local sweating rate ($\dot{M}$sw) during heat load with lower-legs water immersion.

In this study, we have examined the effects of individual sweating rate on the above proposed mechanism. Individual sweating rate was significantly correlated to $\Delta$Tcs; i.e., the amount of heat of sorption in C-clothing, and there is no correlation in P-clothing by contrast (Fig. 3). There were similar results in physical tests (Expl) where the relationships between the increase rate of environmental VP and the amount of heat of sorption showed a significant correlation in C-clothing but not in P-clothing (Fig. 2). The results of both experiments showed that the more rapid sweating occurred, the greater and more rapid heat of sorption was produced in C-clothing.

### Individual variation in the increasing rate of clothing microclimate VP and thermoregulatory responses

With increase in sweating rate, change in SBF, $\overline{T}$sk and

$\overline{T}$b were enhanced further in C-clothed subjects, however, these changes were not obtained in P-clothing which has little property to evolve the heat of sorption (Table 1). It suggests that the foregoing mechanism was modified in proportion to individual sweating rate as a whole, which is again supported by present findings.

Individual values in the increasing rate of clothing microclimate VP extended from 1.1 kPa·10 min$^{-1}$ to 3.4 kPa·10 min$^{-1}$ for C-clothed subjects (Fig. 3). When minimum (1.1 kPa·10 min$^{-1}$) and maximum (3.4 kPa·10 min$^{-1}$) values for the increasing rate of clothing microclimate VP in C were put in regression line at Fig. 3, $\Delta$Tcs showed 0.24°C and 0.63°C, respectively. The difference between them was 0.39°C. In the same way, the difference in $\Delta$SBF was 134 mV, in $\Delta\overline{T}$sk was 0.39°C, and in $\Delta\overline{T}$b was 0.26°C (Fig. 3 and Table 1). For P-clothing, when the minimum and the maximum values were employed for same calculations, $\Delta$Tcs showed 0.14°C and 0.27°C, respectively. The difference between them was 0.13°C. Similarly, the difference in $\Delta$SBF was 46mV, in $\Delta\overline{T}$sk was 0.07°C, and in $\Delta\overline{T}$b was 0.05°C. Unlike C-clothing, there was little difference on thermoregulatory responses in P-clothing. If the increase rate of sweating is slow, the difference in thermoregulatory responses on account of clothing material was also small; on the other hand, as the increase rate of sweating is rapid, the difference in clothing material on thermoregulatory responses induced by heat of sorption become greater.

Many researchers have reported varied factors to affect sweating responses. In this study, experiments were carried out for similar age women in the same point of them and menstrual cycle; furthermore, they were neither hypohydrated nor hyperhydrated because their hydration state before the test was similar. Therefore the effects related to age (Inoue *et al.*, 1998; Wagner *et al.*, 1972), menstrual cycle (Wells and Horvath, 1974) and hydration state (Nadel *et al.*, 1980) could be ignored.

On the other hand, it is well known that sweating rate fluctuates with physical training, body composition, seasonal adaptation and circadian rhythm at least. It is suggested that a long-distance runner be included among the participants and accordingly her sweating response might be promoted when compared to the other subjects (Araki *et al.*, 1981; Roberts *et al.*, 1977). Actually this physical trained subject showed the maximum increase rate of clothing micro-climate VP in seven subjects, and her $\Delta$SBF, $\Delta\overline{T}$sk and $\Delta\overline{T}$b were very high in C-clothing, but not in P-clothing. It is suggested that a small difference in body composition might affect sweating responses, however, because percentage body fat in our subjects extended slightly from 20.1% to 29.3%, the difference might be extremely small, in agreement with Havenith *et al.* (1990; 1994). In addition, the effect associated with seasonal adaptation must not be ignored.

This study was performed from early November to late December, while the outdoor air temperature was gradually lowering. Mean ambient temperatures in Kobe city (Japan) measured 17.1°C at the beginning of November and 7.7°C toward the end of December (Kobe national weather station), and a decline by 9.4°C was observed during the test period. It is impossible to deny the findings that heat acclimation have improved sweating responses (Inoue *et al.*, 1995; Nadel *et al.*, 1974) applied to our observation. As regards circadian rhythm, Stephenson *et al.* (1984) have reported that the slope of the local sweating rate to esophageal temperature relation was constant over the day.

Our subjects participated in the examination at the same time of day on two separate days, beginning at 10:00 for two subjects, and at 14:00 for five subjects. However, the diurnal variation might not affect individual sweating rates at present, as shown by Stephenson *et al.* (1984). If some above-mentioned factors were made quite even, individual variability in the change in clothing microclimate VP implying sweating rate might exist.

In summary, the amount of heat of sorption was in direct proportion to individual sweating response; thus, thermoregulatory responses, i.e. SBF, $\overline{T}$sk and $\overline{T}$b were enhanced more greatly in C-clothed subjects. In contrast, we obtained no effect of sweating response in P-clothing at all. The present study shows that individual variation in sweating responses has significant effects on thermoregulatory responses, when subjects wear clothing ensembles made from hygroscopic fabrics.

## ACKNOWLEDGMENTS

The authors are grateful thanks to Prof. Y. Kamata, Jissen Women's University for advising clothing material, Dr. K. Mabuchi, University of Tokyo for advising of thermographic measurement and Prof. A. Cary, Kobe Womenís University, for critical reading of this manuscript. We finally thank to our subjects for their participation and cooperation. This work was supported by a Grant-in-Aid for Scientific Research from the Ministry of Education, Science and Culture of Japan (Grant No. 07308001 and 10897003).

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(Received December 12, 2000)