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Differential Effects of Cotton and Polyester Ensembles on Changes in Clothing Surface Temperature, Skin Temperature and Skin Blood Flow During Heat Load

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Abstract : The effects of individual sweating rates on thermophysiological responses during the decrease phase of clothing surface temperature (Tcs) with cotton (C) and polyester (P) clothed subjects were examined. Seven women subjects were exposed in a climatic chamber at ambient temperature of 27.2°C, relative humidity of 50%, and their lower-legs were immersed in a water bath at a temperature of 35-41°C for 70 min. During water immersion, Tcs in C-clothed subject rose immediately after the onset of sweating and then Tcs fell gradually. In C-clothed subjects, Tcs decreased directly ($p<0.05$) in proportion to total sweating rate (TSR), however no significant correlation was observed in P-clothed subjects. The relationship be tween TSR and changes in mean skin temperature, and skin blood flow showed negative correlation when wearing C-clothing ($p<0.05$), however, no significant correlation when wearing P-clothing. Individual TSR was correlated with threshold rectal temperature for sweating onset ($p<0.05$) with C- and P-clothed subjects. The results showed that individual TSR had significant effects on not only Tcs but also on thermoregulatory responses during the Tcs decrease phase.

Key words : cotton, polyester, total sweating rate, thermoregulatory responses, threshold rectal temperature

INTRODUCTION

During heat load, clothing surface temperature (Tcs) as an index of heat of sorption for a cotton (C) clothed subject enhanced steeply after the onset of sweating, and then decreased gradually (Tanaka *et al.*, 2001). However change in Tcs for polyester (P) clothing was markedly smaller. The effective difference between clothing materials on Tcs was observed after the onset of sweating. Sweating responses to heat load have been found to be affected by various factors; for example age (Inoue *et al.*, 1998; Wagner *et al.*, 1972), phase in menstrual cycle (Wells and Horvath, 1974), degree of physical training (Araki *et al.*, 1981, Roberts *et al.*, 1977) and seasonal adaptation (Inoue *et al.*, 1995; Stephenson *et al.*, 1984), and so on. Therefore we have examined that the amount of heat of sorption was in direct proportion to individual increase rate of clothing microclimate vapor pressure (VP), and thermoregulatory responses were enhanced further in C-clothed subjects immediately after the onset of sweating (= during Tcs increase phase) more recently (Tanaka and Hirata, in press). However there are no reported findings of individual sweating rates on thermoregulatory responses during the gradual decrease phase in Tcs. In this phase, the effect of heat of sorption could be attenuated, since clothing microclimate VP has been kept at a high value and sweating continued. It has also been reported that clothing microclimate temperature has remarkably decreased after walking in C (Ha *et al.*, 1996).

The purpose of the present study is to clarify the effects of individual variability in sweating rates on thermophysiological responses during the Tcs decrease phase, with subjects wearing C-and P-clothings.

METHODS

Subjects

Seven healthy women agreed to participate as volunteer subjects after being informed of the experimental procedures and procurement of written consent. Their physical characteristics are presented in Table 1. The subjects were asked to refrain from vigorous exercise and alcohol intake on the previous day, and to ingest only a fixed light meal and 200 ml of water 3h prior to the experiment. No fluids were given until the end of the test. The experiments were presented in random order for each subject at the same time of day in the same phase of their menstrual cycle.

Experiment garments

Two different kinds of clothing were selected for the

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Table 1. Physical characteristics of the subjects

Subject	Age (years)	Height (cm)	Weight (kg)	BSA (m^2)	Body fat (%)
A	22	164.0	58.0	1.58	21.8
B	20	165.0	52.0	1.51	20.1
C	24	156.0	46.0	1.38	23.0
D	21	152.0	56.0	1.48	27.7
E	21	156.0	55.0	1.49	20.4
F	24	165.0	57.0	1.57	21.9
G	21	166.0	64.0	1.66	29.3
Means	21.9	160.6	55.4	1.52	23.5
SE	0.6	2.3	2.3	0.1	1.5

BSA: Body surface area according to Fujimoto and Watanabe (1965).

study, one made of 100% cotton clothing(C) and the other 100% polyester clothing (P). Clothing ensembles consisted of short- sleeved no-collar blouses, knee breeches and underwear. The blouses and breeches were made from each material based on the same pattern. C- and P-clothing has similar physical properties in heat conduction and heat transfer. The detailed properties of the fabrics are described in our previous report (Tanaka and Hirata, in press).

Measurements

Skin temperature was measured at four sites (chest, upper-arm, thigh and calf) with thermistors (SXK67, Technolseven, Japan). Mean skin temperature ($\overline{T}sk$) was calculated from these four measurements according to Ramanathan (1964). Core temperature as represented by rectal temperature (Tre) was measured with a precision thermistor probe (401J, Nikkiso-YSI, Japan) inserted 10 cm beyond the anal sphincter. Mean body temperature ($\overline{T}b$) was then calculated as $\overline{T}b = 0.2 \cdot \overline{T}sk + 0.8 \cdot Tre$. Each thermistor was calibrated precisely prior to the experiment.

Cumulative evaporation rate (CER) from the subjects was continuously measured every 30 sec using precision scales (KCC150S, Mettler, Germany). The amount of sweat absorbed in the clothing was determined from the change in clothing weight before and immediately after the experiment. The total sweating rate (TSR) was calculated as the sum of the value of CER at 60 min and the amount of sweat absorbed in the clothing during 60 min heat load.

All temperature and CER data were recorded every 30 sec using a personal computer (PC9870DS, NEC, Japan) via data logger (K722-2005, Technolseven, Japan).

Skin blood flow (SBF) at left dorsal forearm was measured by a laser-Doppler flowmeter (ALF-21, Advance, Japan) and sampled every second by a personal computer (Power Book 190CS, Macintosh, USA) via data logger (MP100WS, BIOPAC systems Inc,. USA).

Clothing microclimate temperature and humidity, Tcs and clothing surface humidity were measured with calibrated temperature-humidity sensors (HMM36UST, Vaisala, Finland) at three sites (chest, upper-arm and thigh) every minute and recorded by a data collector (AM-7052, AM-7102, Anritsu Keiki, Japan). These sensors were fixed on the skin and on the clothing, and there were frame-spacers between the skin and the clothing to maintain a constant degree of space.

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. Each experiment was conducted in a controlled climatic chamber (TBL-15W4YPX, Tabai Espec, Japan) at an ambient

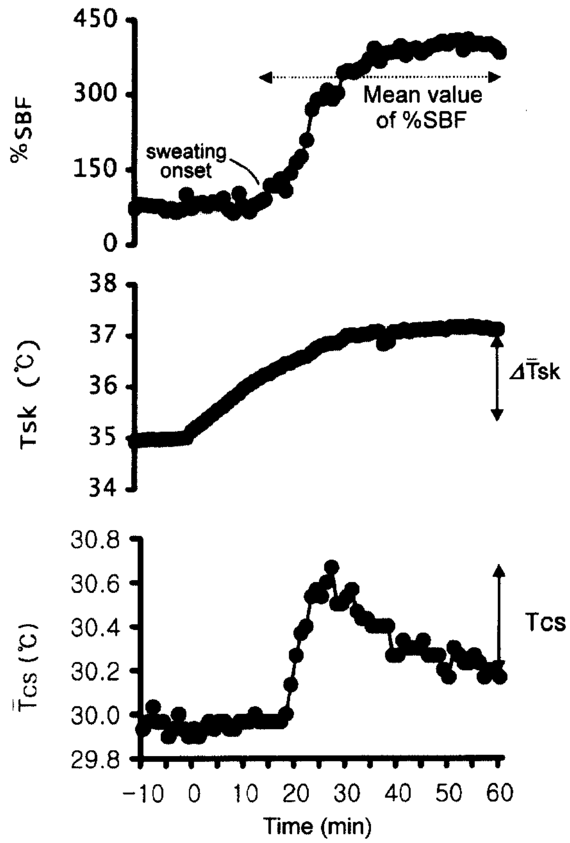

Fig. 1. Example of the time courses of % skin blood flow (%SBF), mean skin temperature ($\overline{T}sk$) and clothing surface temperature (Tcs) during heat load for one cotton clothed subject MK. Dotted line indicates the mean value of %SBF after the onset of sweating to 60 min (%SBF). Vertical arrows show the change in $\overline{T}sk$ ($\Delta\overline{T}sk$) for 0 min to 60min after beginning of the heat load, and in Tcs (ΔTcs) for the peak value to the end of the heat load.

temperature (Ta) of 27.2± 0.5°C, a relative humidity (rh) of 50± 3% and an air velocity of 0.2 m · s^{-1}.The subjects were dressed in either the C- or P-clothing ensemble, which had been suspended in the climatic chamber overnight. After that the subjects entered into the chamber and sat quietly in a chair while instrumentation was attached. Then they immersed their lowerlegs and feet into a water bath of 35°C. The profile of water temperature in the bath (Tw) was as follows: a 10 min baseline period at 35°C, a 15 min thermal transient (35°C to 41°C), and a 45 min at 41°C All clothing was weighed on precision scales before and immediately after the heat load. The methods of the study are provided in more detail in our previous report (Tanaka *et al.*, 2001).

Data analysis

Fig. 1 shows an example of the time course of %SBF, T̄sk and Tcs for one C-clothed subject during a 70 min water immersion. The mean value of skin blood flow (%SBF) was calculated from %SBF after the onset of sweating to the end of the heat load. ΔT̄sk shows the change in T̄sk during a 60 min heat load. The changes in clothing surface temperature (ΔTcs) were determined as the differences between the values at the point when Tcs reaches the highest temperature and at the end of the heat load.

Statistical analysis was carried out by a paired *t*-test and standard linear regression analysis (individual subject plots). The significance level was set at $P<0.05$.

RESULTS

With heat load, sweating occurred in C- or P-clothed subjects, and sweating responses were similar for both types of clothing worn at the end of the water immersion (Table 2). However TSR ranged from 2.42 g · kg^{-1} to 3.63 g · kg^{-1} for C and from 2.38 g · kg^{-1} to 3.29 g · kg^{-1} for P-clothing. ΔT̄sk of C-clothed subjects was significantly higher than P (p<0.05). Conversely, ΔTre was significantly less in C than in P (p<0.05).

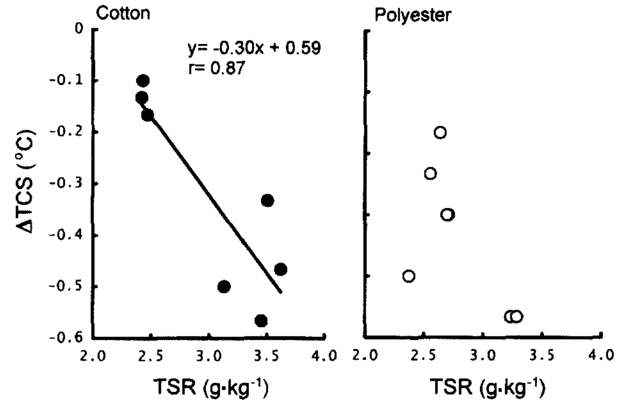

Fig. 2. Relationship between changes in clothing surface temperature after the peak value (ΔTcs) and total sweating rate (TSR) for cotton (●) and polyester (○) clothing. Each data point represents the value for each individual. The regression line was calculated in cotton-clothed subjects.

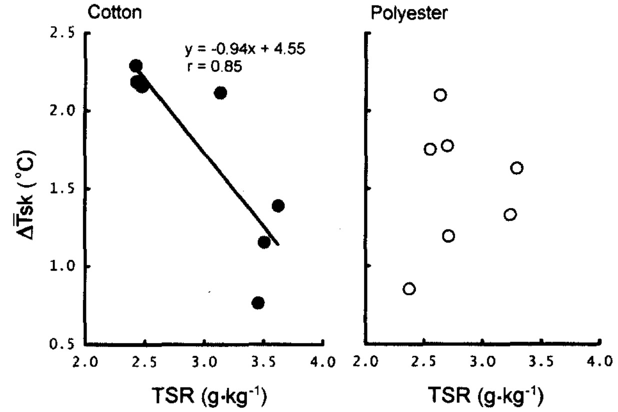

Fig. 3. Relationship between changes in mean skin temperature (ΔT̄sk) and total sweating rate (TSR) for cotton (●) and polyester (○) clothing during 60min heat load. Each data point represents the value for each individual. The regression line was calculated in cotton-clothed subjects.

During water immersion, Tcs in C-clothed subjects rose immediately after the onset of sweating. Subsequently while the subjects were continuously exposed to the heat load, Tcs tended to decrease in each subject. The degree of Tcs decline varied with each individual. ΔTcs significantly correlated with TSR in C-clothing ($y=-0.30x+0.58$, $r=0.87$, $p<0.05$; Fig. 2). No significant relationship

Table 2. Sweating rates and ΔT̄sk, ΔTre and ΔT̄b in cotton and polyester clothed subjects during 60 min heat load

	ESR (g · kg^{-1})	NSR (g · kg^{-1})	TSR (g · kg^{-1})	ΔT̄sk (°C)	ΔTre (°C)	ΔT̄b (°C)
Cotton	2.26±0.14	0.74±0.17	3.01±0.22	1.72± 0.23*	0.35±0.04*	0.63±0.06
Polyester	2.22±0.11	0.57±0.08	2.79±0.14	1.52±0.16	0.45±0.04	0.67±0.05

Values are means±SE. ESR: Evaporative sweating rate, NSR: Non-evaporative sweating rate, TSR: Total sweating rate, ΔT̄sk: Change in mean skin temperature, ΔTre: Change in rectal temperature, ΔT̄b: Change in mean body temperature. *Significant difference between the clothing ensembles, P<0.05.

was present in P-clothing.

$\Delta\bar{T}sk$ was plotted against TSR during heat load in Fig. 3. Correlation of $\Delta\bar{T}sk$ was significant with TSR in C-clothed subjects ($y=-0.94x+4.55$, $r=0.85$; $p<0.05$), however, there was no significant correlation for P-clothed subjects.

The relationship between %SBF and TSR was represented in Fig. 4. It showed a significantly negative correlation between %SBF and TSR in C-clothed subjects ($y = -171.89x+824.96$, $r = 0.82$, $p<0.05$), however it was not significant in P-clothed subjects. The highest %SBF showed 475% at TSR of 2.47 $g \cdot kg^{-1}$ and the lowest %SBF showed 157% at TSR of 3.63 $g \cdot kg^{-1}$ in C-clothed subjects.

DISCUSSION

In C-clothed subjects, ΔTcs decreased directly in proportion to TSR, however no significant correlation was presented in P-clothed subjects (Fig. 2). It is well known that C fabric absorbs water vapor and liquid water (Morton and Hearle, 1975). Thus the more perspiration occurred, the more sweat was absorbed into the C-clothing, and then Tcs was reduced markedly during decrease phase of Tcs since evaporation vapor from the clothing into the environment tends to be greater in heavy sweating subjects. Therefore, changes in $\Delta\bar{T}sk$ and %SBF were attenuated in the C-clothed subjects who has heavy sweating. When P-clothed subjects showed heavy swearing, the transfer of sweat from skin to clothing could be greatly reduced because P-clothing has low water absorbency and moisture regain. Therefore there were no significant correlations between TSR and thermophysiological responses in P-clothed subjects (Figs. 3 and 4).

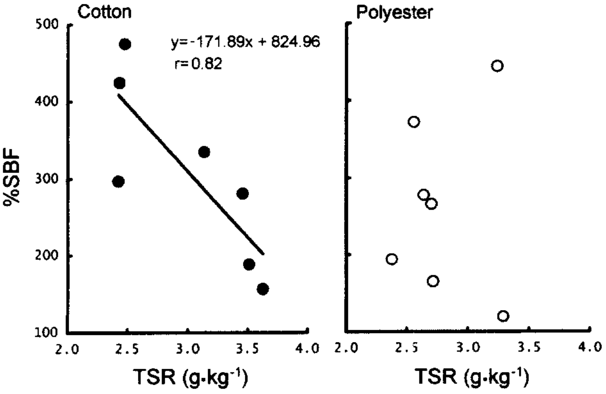

Fig. 4. Mean value of % skin blood flow after the onset of sweating (%SBF) plotted against total sweating rate (TSR) in cotton (●) and polyester (○). Each data point represents the value for each individual. The regression line was calculated in cotton-clothed subjects.

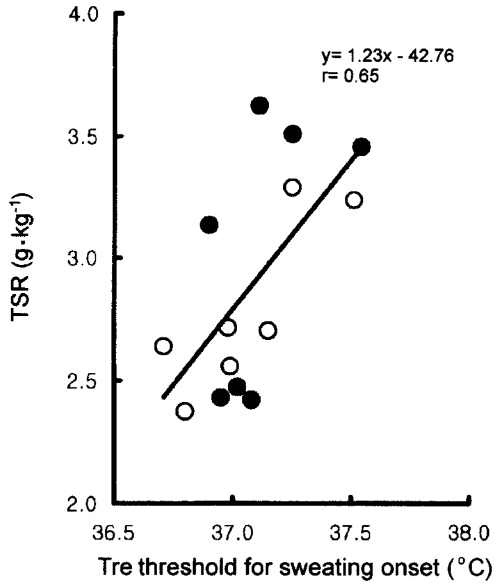

Fig. 5. Correlation between rectal temperature (Tre) threshold for sweating onset and total sweating rate (TSR) for cotton (●) and polyester (●) clothed subjects. Each data point represents the value for each individual. The regression line was calculated in both clothing.

Why was there individual variation in TSR during heat load? Fig. 5 depicts the correlation between threshold Tre for sweating onset and TSR in each experiment. The higher the threshold Tre for sweating onset, the greater the TSR observed in C- and P-clothings. There was significant correlation in C- and P-clothing ($r=0.65$, $p<0.05$). Roberts *et al.* (1977) showed that exercise training increases the slope of the sweating-body core temperature relation, and core temperature threshold for the onset of sweating is diminished by heat acclimation. Several papers also have reported that heat acclimation improved sweating responses (Inoue *et al.*, 1995; Nadel *et al.*, 1974). In the present study, experiments were performed from early November to late December, while the outdoor air temperature gradually declined. Mean ambient temperatures in Kobe city (Japan) reported by Kobe national weather station were 17.1°C at the beginning of November and 7.7°C toward the end of December in 1996 and a temperature decline by 9.4°C was observed during the test period. Therefore it is considered that our subjects were affected by the decrease in natural ambient temperature. Effects of natural seasonal acclimation on thermophysiological sweating responses must not be impossible to ignore in the present study. It is considered that the individual variations in TSR could be influenced by the level of natural heat acclimation rather than the other factors, age, menstrual cycle and circadian rhythm in the present study.

Overall responses to individual difference of TSR in C-

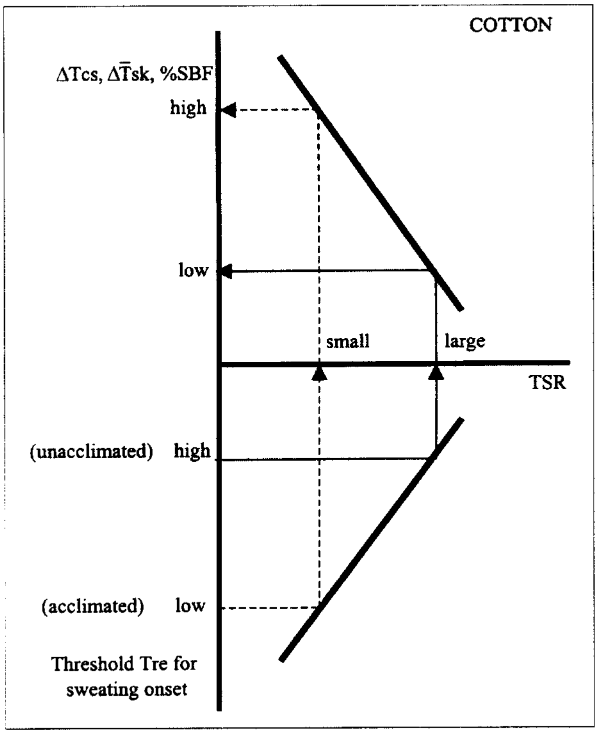

Fig. 6. Schematic representation of the interaction between total sweating rate (TSR) in relation to threshold rectal temperature (Tre) for sweating onset, and changes in clothing surface temperature (ΔTcs), mean skin temperature ($\Delta\bar{T}$sk) and % skin blood flow (%SBF) in cotton clothed subjects during decrease phase of Tcs. Upper oblique line indicates correlation between TSR and ΔTcs, $\Delta\bar{T}$sk and %SBF, respectively. Lower oblique line describes correlation between TSR and threshold Tre for sweating onset. The heat unacclimated subject (unacclimated) shows higher threshold for sweating onset large TSR, and ΔTcs, $\Delta\bar{T}$sk and %SBF are attenuated during heat load (solid arrows). The acclimated subject (acclimated) obtains lower threshold Tre for sweating onset and large TSR, and ΔTcs, $\Delta\bar{T}$sk and %SBF are further enhanced (dashed arrows).

clothed subjects during Tcs decrease phase are summarized in Fig. 6. The relationship between TSR and threshold Tre for sweating onset showed a positive correlation (lower oblique line in Fig. 6) and there were negative correlations (upper oblique line in Fig. 6) between TSR and ΔTcs, $\Delta\bar{T}$sk and %SBF, respectively. Threshold Tre for sweating onset is influenced by the degree of heat acclimation, as mentioned above. The heat acclimated subject showed a lower threshold Tre for sweating onset, and smaller TSR. Furthermore smaller TSR keeps higher ΔTcs, $\Delta\bar{T}$sk and %SBF (dashed arrows in Fig. 6). Conversely the unacclimated subject shows a greater TSR result from higher threshold Tre for sweating onset, so that further attenuations in ΔTcs, $\Delta\bar{T}$sk and %SBF are caused (solid arrows in Fig. 6).

In conclusion, decrease in Tcs was correlated with individual TSR, and attenuated $\bar{T}$sk and SBF in C-clothed subjects. The individual variation in TSR was affected by threshold Tre for sweating onset. On the other hand, there was no effect of TSR on thermoregulatory responses in P-clothed subjects. The present study shows that individual TSR had significant effects on not only Tcs but also on thermoregulatory responses during the Tcs decrease phase in C-clothed subjects.

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