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This study was designed to find the effects of two kinds of dust-free garments with (A) and without (B) frozen gel strip (FGS), and half-naked clothing (brassiere and shorts; C) on thermophysiological parameters and on temperature and humidity within clothing. The heart rate, rectal, and skin temperatures as well as sweat rate and clothing microclimate were measured during 140 min in 9 healthy females. Inquiries were also made into the subjective rating of thermal, humidity, and comfort sensations. The main findings in our experiments are as follows: (a) Physiological parameters such as rectal and skin temperatures (chest and forehead), heart rate, and sweat rate were clearly lowest in garb C, intermediate in garb A, and highest in garb B throughout the experiment; (b) Temperature and humidity within clothing were lower in garb A than in garb B; (c) More than half of the 9 participants decreased thermal sensation by wearing garb A. These results suggest that the usage of FGS could improve the heat load in lightly working participants wearing dust-free garments.

dust-free garment   frozen gel strip   skin temperature   heart rate   clothing microclimate

1. INTRODUCTION

There are two types of cleanrooms: an industrial cleanroom designed against floating dusts and a biological cleanroom against microorganisms. The U.S. Federal Standard No. 209 D prescribes that there should be less than 100 particles/ft^3 of dust particles smaller than 0.5 μm in diameter for cleanness to be of Class 100. Even cleanness lower than of Class 100 has been known to be enough in all industries except the semiconductor industry (Brandt & Cory, 1989). It is estimated that dust from the human body and garments is responsible for 15–20% of the inferior goods produced

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in semiconductor and microelectronic manufacturing (Tolliver, 1988). Therefore, in order to minimize inferior goods production, it is very important to prepare garments free of dust from the human body and from the garments themselves.

The dust-free garments used generally in semiconductor production are designed to safeguard the products from dust or static electricity. They consist of protective coveralls, a hood, mask, gloves, and boots for dust resistance and elimination of static electricity. The hood and mask are worn to wrap released particles because the head is a significant source of particles. However, workers wearing a hood and mask feel uncomfortable due to accumulated heat, because 70–80% of the body-generated heat is released from the head (Siekmann, 1983).

Furthermore, workers wearing dust-free garments often suffer from a general uncomfortable feeling caused by impermeable properties of the clothing, indicating that an improvement of dust-free garments is necessary.

A few studies have been carried out on the development of better dust-free garments (Brinton & Swick, 1984; Swick & Vancho, 1985; Webber & Wieckowski, 1982). However, the studies focus mainly on the development of better materials, and methods for the evaluation of the dust-free garment performance, whereas thermophysiological properties of this garment were not investigated.

With these in mind, we endeavored to compare the effects of two kinds of dust-free garments with and without frozen gel strip (FGS), and half-naked clothing (brassiere and shorts) on thermophysiological parameters and clothing microclimate (temperature and humidity).

2. MATERIALS AND METHODS

2.1. Participants

Nine healthy females volunteered as participants. As shown in Table 1, their characteristics (mean $\pm$ *SD*) were 19.4 $\pm$ 1 years (age), 159.4 $\pm$ 5.1 cm (height), 54.0 $\pm$ 5.4 kg (body mass), and 1.48 $\pm$ 0.08 m^2 (body surface area, calculated according to Fujimoto, Watanabe, Sakamoto, Yukawa, & Morimoto; 1968). The participants arrived at the laboratory at the same time of day and in the same menstrual phase to avoid differences due to circadian and menstrual effects on thermal physiological parameters.

TABLE 1. Physical Characteristics of Participants

Participants	Age	Height (cm)	Body Weight (kg)	Body Surface Area (m^2)
BA	19	152	61.8	1.5246
HA	22	159	51.0	1.4435
HD	19	156	47.3	1.3789
HN	19	164	58.1	1.5604
MK	20	160	58.2	1.5362
TH	19	158	50.0	1.4250
US	18	170	59.9	1.6196
WD	20	158	49.1	1.4137
WT	19	158	51.0	1.4375

2.2. Experimental Garments

Two kinds of dust-free garments with (A) and without (B) FGS, and half-naked clothing (brassiere and shorts, C) were used in this study. The dust-free garment ensemble was composed of a hood, mask, boots, gloves, dust-free inner wear, and coveralls garb.

The dust-free garment was made of a polyester/carbon conductive woven fabric with a standard front zipper and snap closing at wrists and ankles. The dust-free garment with FGS was designed to have two 9-by-6-cm pockets in its inner chest part. These pockets were made of nonwoven polyethylene materials with excellent air-keeping and bulkiness not only to maximize the cooling performance after inserting the FGS, but also to minimize the infiltration of water into both inner wear and outwear by the defrosting of the FGS. The characteristics of the clothing materials are presented in Table 2.

TABLE 2. Characteristics of Experimental Garments

Garb	Description of Clothing	Material	Weight (g/piece)
A	Dust-free garment with FGS	Polyester/carbon (96.5/3.5%) woven fabric	365.90
	Dust-free inner wear	Polyester/carbon (92/8%) knitted fabric	266.00
	Accessory		
	Hood	Polyester/carbon (96.5/3.5%) woven fabric	67.92
	Socks	Polyester 100% knitted fabric	42.19
	Mask	Polyester/carbon (92/8%) knitted fabric	18.10
	Gloves	Polyester/carbon (92/8%) knitted fabric	52.60
	Boots	Polyurethane with woven fabric	423.10
B	Dust-free garment	Polyester/carbon (96.5/3.5%) woven fabric	361.45
	Dust-free inner wear	Polyester/carbon (92/8%) knitted fabric	266.00
A	Accessory: same as garb		
C	Shorts	Cotton 100% knitted fabric	39.10
	Brassiere	Nylon/polyurethane	41.70

Notes. FGS—frozen gel strip.

2.3. Measurements

Rectal temperature (T_{rectal}) was measured with a thermistor probe. A rectal probe was inserted into the anus to a depth of 12 cm by the participants themselves. Skin temperatures (T_{skin}) were measured at eight sites (forehead, forearm, hand, chest, back, thigh, leg, and foot) with adhesive surgical tape. Clothing microclimate (temperature and humidity) was measured using a thermistor and humidity sensors at chest and back levels between skin and inner wear (first layer), and between the inner wear and outer wear (second layer). Heart rate was recorded every minute by Sport Tester (Polar Electro Ky, Finland). The body mass of the participants and the garments was measured at the beginning and at the end of the experimental protocol. Body weight loss was measured by using a balance (Sartorius) with an accuracy of 1 g.

All parameters were recorded continuously by a recorder, and also sampled every minute by a computer through an analog-to-digital (A/D) converter. Inquiries were also made into the thermal sensation with a 9-point scale (1—very hot; 2—hot; 3—warm; 4—slightly warm; 5—neutral; 6—slightly cool; 7—cool; 8—cold; 9—very cold), humidity sensation with a 7-point scale (1—very wet; 2—wet; 3—slightly wet; 4—neutral; 5—slightly dry; 6—dry; 7—very dry), and comfort sensation with a 4-point scale (1—comfortable; 2—slightly uncomfortable; 3—uncomfortable; 4—very uncomfortable) at scheduled time as shown in Figure 1.

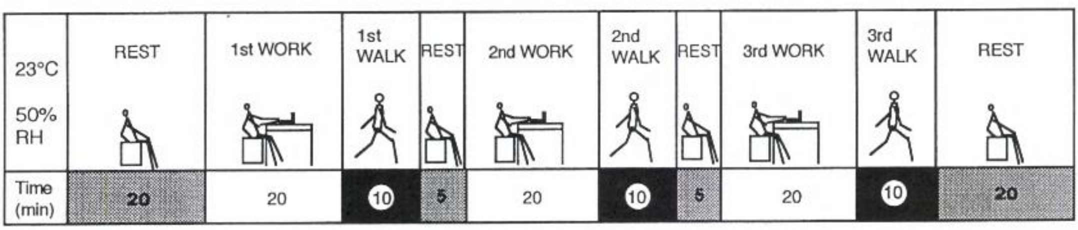

Figure 1. Experimental schedule.

2.4. Experimental Protocol

Tests were carried out in a climatic chamber at an air temperature of 23 °C, relative humidity of 50%, and air velocity of 0.1 $m \cdot s^{-1}$.

The total time of measurements was 140 min. After a 20-min rest, 20 min of simple work (the participants were assembling electronic products), a 10-min walk (5 $km \cdot h^{-1}$ on a horizontal treadmill), and a 5-min rest (a 20-min rest in the final trial) were repeated three times (Figure 1).

2.5. Calculation and Statistical Analysis

Mean skin temperature ($\overline{T}_{skin}$) was calculated by the following modification of the Hardy-DuBois equation:

$$\overline{T}_{skin} = 0.07\ T_{head} + 0.14\ T_{arm} + 0.05\ T_{hand} + 0.18\ T_{chest} + 0.17\ T_{back} + 0.19\ T_{thigh} + 0.13\ T_{leg} + 0.07\ T_{foot}$$

The statistical significance between the parameters was assessed using a two-factor analysis of variance. A p-value smaller than .05 was considered statistically significant.

3. RESULTS

3.1. Rectal and Skin Temperatures

Rectal temperature tended to slowly drop after entry to the climatic chamber, and then sharply rose after the first walk in garb A and garb B (Figure 2a). However, rectal temperature was clearly lowest in garb C, intermediate in garb A, and highest in garb B. The rectal temperatures after the first walk were significantly different among the three kinds of garb ($p < .01$).

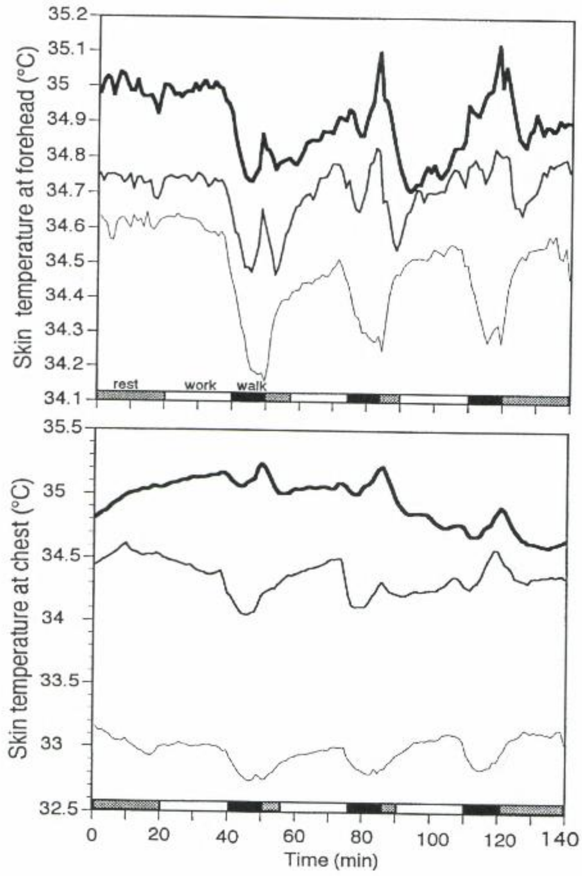

Figure 2a. A comparison of the effects of three kinds of clothing on rectal (upper) and mean skin (lower) temperature. *Notes.* A—dust-free garments with frozen gel strip (FGS), B—dust-free garments without FGS, C—half-naked clothing (brassiere and shorts).

Mean skin temperature was lowest in garb C, intermediate in garb A, and highest in garb B throughout the whole experiment (Figure 2a, $p < .01$). The mean skin temperature during the 140-min experimental period was 35.9 ± 0.04 °C in garb A, 36.4 ± 0.04 °C in garb B, and 31.7 ± 0.02 °C in garb C.

There was no remarkable difference in the temperature of the limbs such as leg,

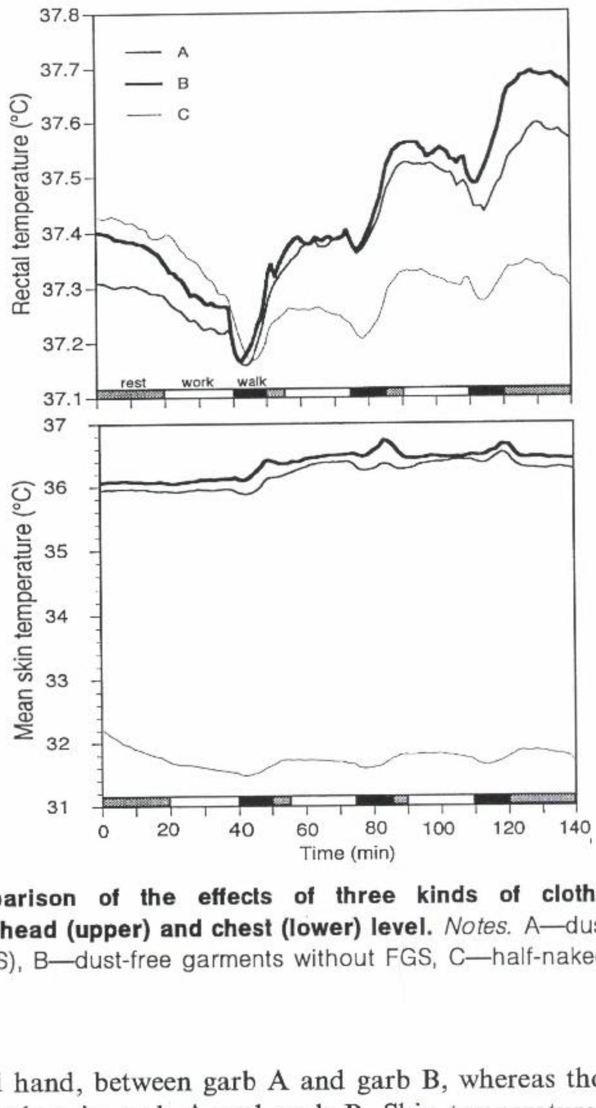

Figure 2b. A comparison of the effects of three kinds of clothing on local skin temperature at forehead (upper) and chest (lower) level. *Notes.* A—dust-free garments with frozen gel strip (FGS), B—dust-free garments without FGS, C—half-naked clothing (brassiere and shorts).

foot, forearm, and hand, between garb A and garb B, whereas those in garb C were significantly lower than in garb A and garb B. Skin temperatures of leg, foot, and hand decreased or did not change during working in garb A, garb B, and garb C, whereas those in forearm increased in garb A, garb B, and garb C. Skin temperatures in forearm and hand decreased during walking in garb A, garb B, and garb C, whereas those in leg and foot increased mostly in garb A, garb B, and garb C.

Figure 2b shows a comparison of forehead and chest skin temperatures among garb A, garb B, and garb C throughout the experimental period. As seen in the figure, both skin temperatures were highest in garb B, lowest in garb C, and intermediate in A ($p < .01$). Forehead and chest skin temperatures fell conspicuously during walking in garb C only ($p < .01$).

Local skin temperatures at chest and forehead were 34.4 ± 0.02 °C and 34.5 ± 0.01 °C in garb A, 35.0 ± 0.03 °C and 35.0 ± 0.01 °C in garb B, and 33.0 ± 0.01 °C and 34.5 ± 0.02 °C in garb C, respectively (see Table 3).

TABLE 3. Comparison of Physiological Parameters Among Three Kinds of Garb

Parameter	Garb A	Garb B	Garb C	F-value by ANOVA		
				A×B	A×C	B×C
T_{rectal}	37.4 ± 0.02	37.5 ± 0.02	37.3 ± 0.01	10.09**	97.07**	101.05**
$\overline{T}_{skin}$(°C)	35.9 ± 0.04	36.4 ± 0.04	31.7 ± 0.02	46.43**	475.43**	527.40**
$T_{forehead}$ (°C)	34.5 ± 0.01	35.0 ± 0.01	34.5 ± 0.02	308.25**	541.28**	993.15**
T_{chest} (°C)	34.4 ± 0.02	35.0 ± 0.03	33.0 ± 0.01	103.55**	109.53**	130.46**
$T_{micro\text{-}chest}$ (°C)	32.6 ± 0.09	33.3 ± 0.06	—	369.31**	—	—
$T_{inner\text{-}chest}$ (°C)	30.4 ± 0.10	30.8 ± 0.07	—	130.45**	—	—
$T_{micro\text{-}back}$ (°C)	32.1 ± 0.03	32.2 ± 0.06	—	5.17*	—	—
$T_{inner\text{-}back}$ (°C)	29.6 ± 0.04	30.1 ± 0.05	—	5.04*	—	—
$H_{micro\text{-}chest}$ (kPa)	2.52 ± 0.56	2.67 ± 0.59	—	4.53*	—	—
$H_{inner\text{-}chest}$ (kPa)	1.94 ± 0.16	2.14 ± 0.24	—	6.67*	—	—
$H_{micro\text{-}back}$ (kPa)	2.40 ± 0.51	2.48 ± 0.47	—	4.16*	—	—
$H_{inner\text{-}back}$ (kPa)	2.28 ± 0.32	2.46 ± 0.28	—	5.98*	—	—
Heart Rate (beat/min)	80.5 ±11.4	88.9 ±13.6	77.6 ±17.8	10.90*	75.79**	69.08**
Boy Mass Loss (g)	126.3 ± 0.04	145.4 ± 1.11	83.2 ± 0.34	6.25*	5.41*	5.77*

Notes. T_{rectal}—rectal temperature, $\overline{T}_{skin}$—mean skin temperature, $T_{forehead}$—forehead skin temperature, T_{chest}—chest skin temperature, $T_{micro\text{-}}$—temperature between skin and inner wear on chest or back level, $T_{inner\text{-}}$—temperature between inner wear and outer wear on chest or back level, $H_{micro\text{-}}$— humidity on chest or back level between skin and inner wear, $H_{inner\text{-}}$—humidity on chest or back level between inner wear and outer wear, *—significant at 5% level ($p < .05$), **—significant at 1% level ($p < .01$).

3.2. Heart Rate

Heart rate sharply increased during walking and during rest it returned to its original condition, which was lowest in garb C, highest in garb B, and intermediate in garb A (Figure 3).

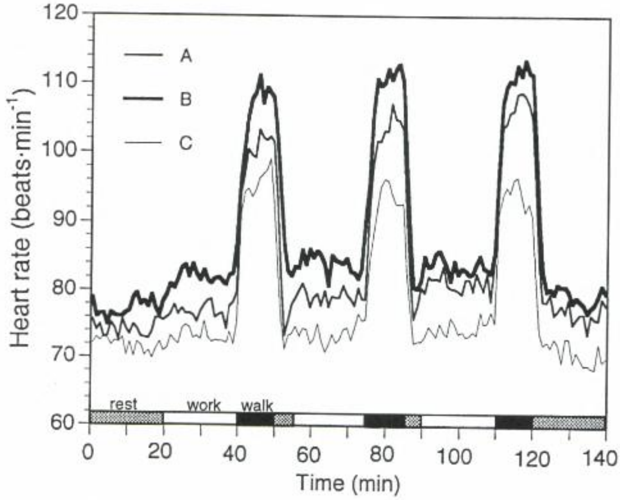

Figure 3. A comparison of the effects of three kinds of clothing on heart rate.
Notes. A—dust-free garments with frozen gel strip (FGS), B—dust-free garments without FGS, C—half-naked clothing (brassiere and shorts).

The mean heart rate (beats·min^{-1}) during the 140-min experimental period were 80.5 ± 11.4 in garb A, 88.9 ± 13.6 in garb B, and 77.6 ± 17.8 in garb C. The values were significantly different among the three kinds of garb in accordance with walking and rest ($p < .01$).

3.3. Body Mass Loss

Body mass loss by evaporation during the 140-min test was 126.3 ± 0.04 g in garb A, 145.4 ± 1.11 g in garb B, and 83.2 ± 0.34 g in garb C, which was significantly different ($p < .05$).

3.4. Temperature and Humidity Within Clothing

Temperature and humidity were measured at chest level between skin and inner wear ($T_{micro\text{-}chest}$), and between the inner wear and outer wear ($T_{inner\text{-}chest}$). A comparison of

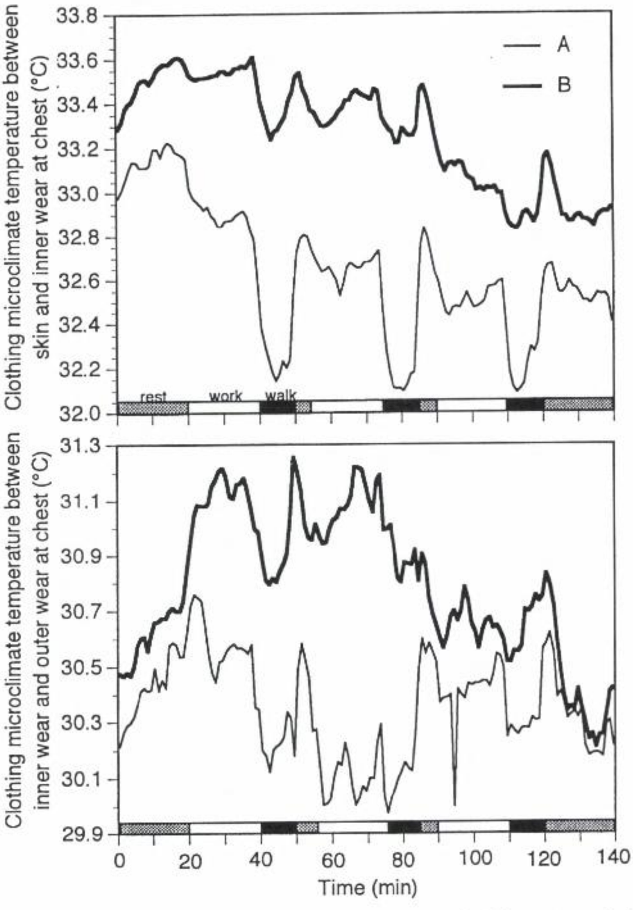

Figure 4. A comparison of the effects of three kinds of clothing on clothing microclimate temperature at chest level between inner wear and outer wear (upper) and between skin and inner wear (lower). *Notes.* A—dust-free garments with frozen gel strip (FGS), B—dust-free garments without FGS, C—half-naked clothing (brassiere and shorts).

changes in clothing microclimate temperature at chest level between garb A and garb B is shown in Figure 4.

As seen in Figure 4, $T_{micro\text{-}chest}$ and $T_{inner\text{-}chest}$ were significantly lower in garb A than in garb B ($p < .01$). $T_{micro\text{-}chest}$ and $T_{inner\text{-}chest}$ were 32.6 ± 0.09 °C and 30.4 ± 0.1 °C in garb A, and 33.3 ± 0.06 °C and 30.8 ± 0.07 °C in garb B, respectively.

Humidity within clothing was about 1.5–1.7 kPa. It slowly rose at the beginning of walking, and then it rose rapidly (Figure 5). After the third walk, the humidity between skin and inner wear ($H_{micro\text{-}chest}$) both in garb A and garb B rose to about 4 kPa, whereas the humidity between inner wear and outer wear ($H_{inner\text{-}chest}$) in both kinds of garments increased to about 3.1 kPa at chest level.

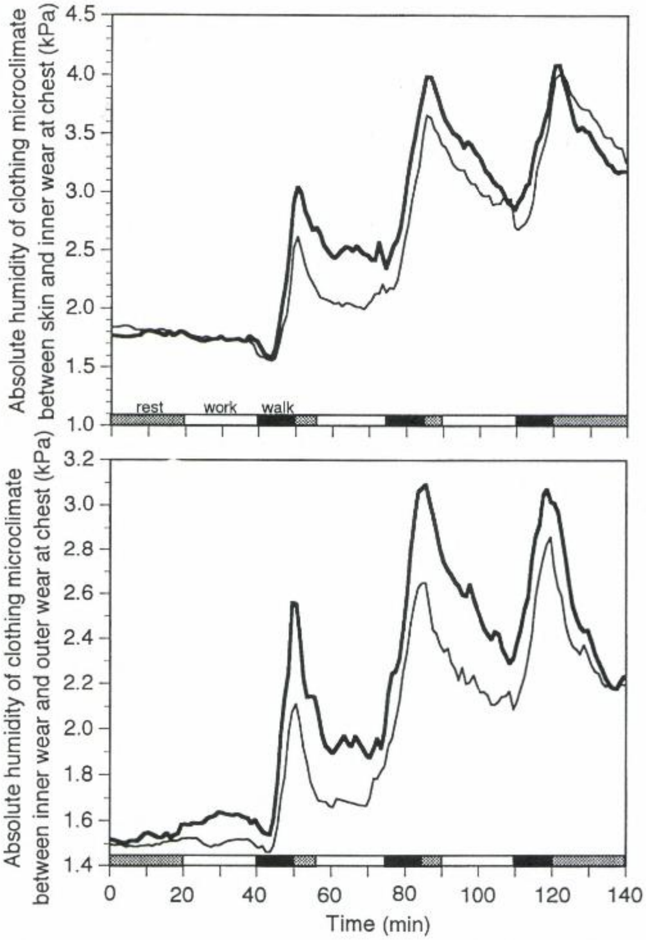

Figure 5. A comparison of the effects of three kinds of clothing on clothing microclimate humidity at chest level between inner wear and outer wear (upper) and between skin and inner wear (lower). *Notes.* A—dust-free garments with frozen gel strip (FGS), B—dust-free garments without FGS, C—half-naked clothing (brassiere and shorts).

The humidity between skin and inner wear, $H_{micro\text{-}chest}$ and $H_{inner\text{-}chest}$ was lower in garb A than in garb B. $H_{micro\text{-}chest}$ and $H_{inner\text{-}chest}$ were 2.52 ± 0.56 kPa and 1.94 ± 0.16 kPa in garb A, and 2.67 ± 0.59 kPa and 2.14 ± 0.24 kPa in garb B, respectively.

3.5. Subjective Ratings

Although the humidity sensation and thermal sensation of this study tended to be higher in garb A than in garb B, there was no significant difference between garb A and garb B. Comfort sensation was not significantly different between garb A and garb B.

However, most participants (6 out of 9) answered that they felt more comfortable and cooler in garb A than in garb B. The participants felt equally "wet" in garb A and garb B 1 hr after the start of the experiment. "Head" and "hands" felt particularly uncomfortable in both garbs, because the head was covered by a hood and mask, and hands by impermeable vinyl gloves.

4. DISCUSSION

The most interesting findings in these experiments were (a) physiological parameters such as rectal and skin temperatures (chest and forehead), heart rate, and sweat rate were clearly lower in garb A than in garb B throughout the experiment; (b) temperature and humidity within clothing were lower in garb A than in garb B; (c) more than half of the 9 participants reported improved thermal sensation in garb A in comparison with garb B.

Frontal chest skin temperatures were clearly lower in garb A than in garb B (Figure 2b). This is due to a direct cooling effect of FGS located the near frontal chest area. Thus, the reduced chest temperatures may help the heat flow from inner trunk to its surface, and hence, also from chest skin through clothing to surrounding air. Greater heat flow in garb A seems to be responsible for lower level of rectal temperature in garb A throughout the latter half of the experimental period. Although tympanic temperature was not measured in our experiment, it is presumed to be kept also lower in garb A, as rectal and tympanic temperatures generally run parallel (Hayashi & Tokura, 1996). Heart rate is positively correlated with tympanic temperature (Cabanac & Caputa, 1979). Therefore, reduced heart rate in garb A is considered to be due to lowered tympanic temperature in garb A. Core and skin temperatures are the driving force toward the sweating center located in the hypothalamus (Ogawa, 1986). Reduced core and skin temperatures in garb A are responsible for decreased amounts of body mass loss in garb A and, hence, for lower clothing microclimate humidity in garb A (Figure 5). Lower level of core and skin temperatures, sweating, and clothing microclimate humidity in garb A might have improved the thermal sensation in garb A. Hayashi and Tokura (1994) also found similar effects of cooling the upper torso on thermophysiological responses and clothing microclimate in participants wearing protective clothing for pesticide.

It is concluded that local cooling of the upper torso could physiologically reduce the thermal strain in participants wearing dust-free garments.

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