Effects of Two Kinds of Underwear on Metabolic Heat Production during 60 Min Recovery after 30 Min Severe Exercise in the Cold

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Abstract. The purpose of this study is to investigate the thermophysiological significance of hydrophilic and hydrophobic properties of underwear materials under the influences of profuse sweating produced during severe exercise in the cold. Two kinds of underwear were used: two layers of cotton underwear with two-piece long-sleeved shirt and full-trousers (C), and two layers of polypropylene underwear with two-piece long-sleeved shirt and full-trousers (P). In addition, the subject put on a two-piece ski suit of 100% polyester including 100% polyester padding. Eight adult females volunteered as subjects in this study. The test was performed in a climatic chamber at an ambient air temperature of 2°C and an air velocity of 0.26 m·s⁻¹. The subject exercised on a cycle ergometer at an intensity of 65% maximal oxygen uptake for 30 min and followed by 60 min recovery. The major findings are summarized as follows: 1) The fall of rectal temperature tended to be greater in P during the recovery. 2) The absolute humidity of innermost layer and middle layer was significantly higher in C than in P during the recovery, but the absolute humidity of middle layer and outermost layer was significantly higher in P than in C during the exercise. 3) Clothing microclimate temperature of innermost at back was significantly higher in C during the exercise and recovery. 4) Metabolic heat production for last 30 min during recovery was significantly higher in P. 5) The degree of skin wettedness sensation and sweating sensation for whole body was significantly higher in P during the exercise. It was concluded that the slower evaporation behavior by absorbing of underwear material in the clothing system has a beneficial influence on thermophysiological responses during severe exercise and its recovery in the cold, although the differences were very small.


Keywords: cotton, polypropylene, clothing microclimate, metabolic heat production

Introduction

Although there are several studies dealing with the effects of clothing on thermophysiological responses and subjective sensations in the cold (Vokac et al., 1972, 1976; Holmér, 1985; Nielsen et al., 1988; Nielsen and Endrusick, 1990 a, b, Gavhed et al., 1991; Bakkevig and Nielsen, 1994), the physiological significance of clothing for metabolic heat production has not been understood systematically so far.

Ha et al. (1996) reported that the metabolic heat production tended to be higher in the cold during the recovery after 30 min walking for the subjects wearing two layers of polypropylene with two-piece long-sleeved shirt and long-legged trousers (P) than in those wearing two layers of cotton underwear with two-piece long-sleeved shirt and long-legged trousers (C). The authors discussed these different levels of metabolic heat production from the viewpoint of different moisture absorbency of the underwear materials in P and C. Briefly to say, as C absorbs moisture and P not, moisture transport is higher from the skin through underwear to the outer clothing in P than in C, resulting in a greater decrease in the thermal insulation of the outer clothing in P, hence, in the flow of dry heat loss in P to a greater extent and finally in higher metabolic heat production in P in order to compensate for the greater dry heat loss. If these discussions were the case, the metabolic heat production would be predicted to behave more differently between P and C under the influences of more vigorous sweating conditions. With these in mind, the present paper is aimed at finding the effects of the two kinds of underwear, i.e., polypropylene and cotton underwear on thermophysiological responses, especially metabolic heat production during 30 min severe exercise with vigorous sweating and 60 min recovery in the cold.
Materials and Methods

Experimental garments
The same garments used in our previous paper (Ha et al., 1996) were used in our present experiment.

Subjects
Eight adult females volunteered as subjects in this study. The subjects were 22.1 ± 0.9 years in age (means ± SE), 163.3 ± 1.6 cm in height, 57.2 ± 3.1 kg in weight and 1.56 ± 0.04 m² in body surface area (as calculated by the equation of Fujimoto et al., 1968). The experimental procedure was explained to the subjects, and each subject carried out a pre-test.

Measurements
The same parameters used in our previous paper (Ha et al., 1996) were measured with some additional parameters as shown. Thermography for the measurement of clothing surface temperature at the back level in a subject was taken by a thermal video system (TVS-8100, AVIO, Japan, accuracy: ± 0.4%). Before the experimental sessions, the maximal oxygen uptake (Vo₂max) was estimated using a cycle ergometer (Ergociser, model EC-1500 Cateye Co) by measuring pulse rate. Loss of body mass was measured continuously using a balance (Sartorius, accuracy: ± 1 g, Germany).

Experimental protocol
The same protocol used in our previous paper (Ha et al., 1996) was employed, including the following ones. The test was performed in a climatic chamber at an ambient air temperature of 2°C and an air velocity of 0.26 m·s⁻¹. The subject exercised on a cycle ergometer at an intensity of 65% maximal oxygen uptake for 30 min and followed by 60 min recovery. The average Vo₂max value was 33.5 ± 2.21 ml·kg⁻¹·min⁻¹ and the average exercise intensity was 103.1 ± 4.23 W in this study.

Calculations and statistical analysis
The same method used in our previous paper (Ha et al., 1996) was adopted.

Table 1 Physical properties of underwear fabrics

<table>
<thead>
<tr>
<th>Fabrics</th>
<th>Weight (g·m⁻²)</th>
<th>Thickness (mm)</th>
<th>Density wale, course (no·inch⁻¹)</th>
<th>Moisture regain (%)</th>
<th>Moisture transfer (g·m⁻²·24 hr⁻¹)</th>
<th>Air permeability (cc·cm⁻²·s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cotton</td>
<td>242.2</td>
<td>1.83</td>
<td>29, 24</td>
<td>6.8</td>
<td>4647.7</td>
<td>147.4</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>138.3</td>
<td>1.01</td>
<td>30, 23</td>
<td>0.5</td>
<td>4733.1</td>
<td>378.0</td>
</tr>
</tbody>
</table>

Results

Body temperature
A comparison of temporal changes in Tₑ (top) and Tₛ (bottom) between cotton and polypropylene underwear is shown in Fig. 1. These parameters decreased temporarily at the beginning of exercise, but increased to the end of exercise and decreased gradually during the recovery. Tₑ and Tₛ were not significantly different between the two types of clothing during exercise and recovery. However, the fall of Tₑ tended to be greater in P underwear condition during recovery; 0.79 ± 0.09 for C and 0.94 ± 0.06 for P.

Temperature and microclimate temperature at the back and chest level
A comparison of skin temperature on the back and chest, and clothing microclimate temperature at the back and chest level between C and P is shown in Fig. 2. Skin temperatures on the back and chest (top) did not differ between C underwear and P underwear. Clothing microclimate temperatures of innermost at the back level (middle, left) were significantly higher in C underwear than in P underwear during the exercise (F=45.69, p<0.01) and recovery (F=17.05, p<0.01). Clothing microclimate temperature of innermost at the chest level (middle, right) was significantly higher (F=10.74, p<0.01) in C underwear than in P underwear during the exercise, but it was not significantly different during the recovery. Clothing microclimate temperature of outermost at back level (bottom, left) was not significantly different between C underwear and P underwear during the exercise and recovery.

Absolute humidity of clothing microclimate
The absolute humidity of the clothing microclimate of each layer at the back level is shown in Fig. 3. The humidity of each layer quickly increased with the onset of sweating (about 10 min of exercise), the increase continued until the stop of exercise, and it gradually decreased during the recovery. The absolute humidity of innermost layer between skin and underwear (top) was not significantly different during exercise, but it was significantly higher (F=9.05, p<0.01) in C underwear during recovery. The absolute humidity of middle layer
between underwear and outer wear (middle) was significantly higher (F=19.61, p<0.01) in P underwear during the exercise, but it was significantly higher (F=4.19, p<0.05) in C underwear during the recovery. The absolute humidity of outermost layer inside ski suit (bottom) was significantly higher (F=20.52, p<0.01) in P underwear during the exercise, but it was not significantly different during the recovery.

Parameters on the weight change
A comparison of the cumulative decrease in whole body mass losses by evaporation between C and P is shown in Fig. 4. As seen in the figure, the whole body mass losses by evaporation during exercise and recovery tended to be greater in P underwear than in C underwear.

The changes in underwear weight between the beginning and the end of experiment tended to be greater in C underwear than in P underwear. However, the weight change of ski suit was not significantly different. Total body mass loss during the experimental periods was not significantly different. These values were listed in Table 2.

Metabolic heat production
Metabolic heat production for the last 30 min during recovery was compared between C underwear and P underwear in Fig. 5. As seen in the figure, metabolic heat production was significantly higher in P (F=8.90, p<0.01) underwear than in C underwear during the last 30 min recovery.

Pulse rate
Pulse rate had average values of 153.2 ± 2.64 beats·min⁻¹ in C underwear and 154.6 ± 2.62 beats·min⁻¹ in P underwear during the exercise, and those of 89.8 ± 3.26 beats·min⁻¹ and 91.3 ± 3.72 beats·min⁻¹ in C and P during the recovery, respectively. These values were not significantly different between the two kinds of underwear condition throughout the exercise and recovery.

Subjective ratings
The rating of thermal sensation of whole body changed from ‘slightly cool’ to ‘hot’ during the exercise and changed from ‘hot’ to ‘cold’ during the recovery. There was no significant difference in thermal sensation.
of whole body between the two kinds of underwear condition throughout the exercise and recovery. The rating of shivering/sweating sensation of whole body changed from ‘not at all’ to ‘moderately sweating’ during the exercise and changed from ‘slightly sweating’ to ‘slightly shivering’ during the recovery. Sweating sensation of whole body was significantly higher (F=11.33, p<0.01) in P underwear than in C underwear during exercise, but shivering sensation of whole body was not significantly different during the recovery between the two kinds of underwear condition. At the start of exercise, the subjects judged skin wettedness sensation to be ‘normal dryness’ for both C and P underwear conditions. After the start of sweating, it changed into ‘main part of the body wet’. The degree of skin wettedness sensation was significantly higher (F=4.50, p<0.05) in P during the exercise, but it was not significantly different between C and P underwear during the recovery. Clothing wettedness sensation showed a similar pattern to skin wettedness sensation. It changed from ‘dry’ to ‘wet’. The degree of clothing wettedness sensation was not significantly different between the two kinds of underwear condition throughout the exercise and recovery.

**Discussion**

In this study, we obtained that the metabolic heat production was higher in P than in C during the last 10 min recovery period. One probable reason for this is that the rectal temperature tended to drop more greatly during the recovery in P than in C. This decreased rectal temperature might have stimulated the thermoregulatory center in the brain, having probably resulted in an elevation of metabolic heat production in P (Aschoff et al., 1971).

Higher metabolic heat production during the recovery in P suggests that the heat loss might have occurred more greatly during the recovery in P than in C, since the human body could control to keep the balance between metabolic heat production and heat loss physiologically (Hensel, 1981). The facts that the dry
Table 2 A comparison of total body loss, evaporative body mass loss and clothing weight change between cotton and polypropylene

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Cotton</th>
<th>Polypropylene</th>
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<tbody>
<tr>
<td>Total body mass loss (g)</td>
<td>245.6 ± 25.23</td>
<td>247.1 ± 17.90</td>
</tr>
<tr>
<td>Evaporative body mass loss (g) during exercise</td>
<td>202.6 ± 14.32</td>
<td>217.3 ± 13.23 (p&lt;0.1)</td>
</tr>
<tr>
<td>Evaporative body mass loss (g) during recovery</td>
<td>116.6 ± 6.70</td>
<td>124.1 ± 7.75</td>
</tr>
<tr>
<td>Clothing weight change (g)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ski suit</td>
<td>13.9 ± 4.35</td>
<td>13.9 ± 1.65</td>
</tr>
<tr>
<td>Underwear</td>
<td>27.5 ± 6.68</td>
<td>13.8 ± 2.75 (p&lt;0.1)</td>
</tr>
</tbody>
</table>

Fig. 3 A comparison of clothing microclimate humidity of innermost layer (top), middle layer (middle) and outermost layer (bottom) between C and P during rest, exercise and recovery. Solid line: C. Dashed line: P. Values are means ± SE. n=8.

Fig. 4 A comparison of cumulative decrease of whole body mass losses between C and P during rest, exercise and recovery. Solid line: C. Dashed line: P. Values are means ± SE. n=8.

Fig. 5 A comparison of metabolic heat production between C and P underwear during the last 30 min recovery. Solid line: C. Dashed line: P. Values are means ± SE. n=8.
heat loss might have been greater during the recovery in P are indirectly evidenced from smaller differences of clothing microclimate temperature between innermost and outermost at back in P (Fig. 2, left). Actually, dry heat loss is greater in P than in C, according to the results of clothing surface temperature on the back by the thermography for one subject (Fig. 6, top; at 25 min after the exercise, bottom; at 55 min after the recovery, left; cotton, right; polypropylene). These mean values (17 cm width) were 16.0 °C and 15.0 °C in C, and 17.2 °C and 15.8 °C in P 25 min after the exercise and 55 min after the recovery, respectively. The higher clothing surface temperatures during the exercise and recovery in P underwear condition are direct evidence for the greater dry heat loss, although these results are obtained from one subject.

Why could the dry heat loss probably occur more greatly from skin through clothing to surrounding in P? The mechanisms for this were fully discussed elsewhere (Ha et al., 1996). Shortly to say, the higher clothing microclimate humidity might be involved with the flow of dry heat from skin through clothing to surrounding. The ski wear, especially its outermost part was cooled at T_a of 2 °C, resulting in the probable occurrence of the higher moisture of ski suit into liquid water droplet, hence, in the lowering of its thermal insulation.

Heat transfer is complex to analyze since both dry heat and mass (moisture) transfer are involved. One possible explanation for the difference between C and P may be as follows. C underwear absorbs more moisture by direct absorption from wet skin, thereby reducing its thermal insulation. However, in P more humid air reaches the outer layers (ski suit) and part of it condenses. Heat is released and local temperature is increased. In addition, the local thermal insulation of parts of the ski suit layers may decrease due to wetting and furthermore contributing to dry heat loss and higher temperature in comparison with C. The final outcome appears to be a slightly higher clothing surface temperature with P. This may also explain the more
rapid fall in rectal temperature during rest in P. Apparently, heat balance is achieved by controlling moisture accumulation in the underwear in C at the risk of getting wet close to the skin. In P heat balance is controlled by keeping dry underwear at the risk of getting condensation in the ski suit.

Why was the clothing microclimate (temperature, humidity) at the back of the ski suit not consistent during recovery between our previous paper (Ha et al., 1996) and our present paper? Although the mechanisms for these discrepancies remain to be known, the findings that the thermal gradient between innermost microclimate and outermost microclimate at the back seemed to be greater in both papers in cotton underwear, suggesting that the heat flow from inside to outside clothing might have been smaller in cotton underwear.

The innermost microclimate temperature was significantly higher in cotton underwear than in polypropylene one during recovery, which the reverse occurred in our previous paper (Ha et al., 1996). In our present paper, a greater amount of sweating occurred, and produced more heat liberated by absorbing the moisture.

More detailed examination of the actual heat and mass transfer is required to fully explain the different behaviour of cotton and polypropylene materials.

References


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Received: August 12, 1996
Accepted: June 22, 1998
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