Physiological Method of Evaluating Protective Clothing for Work in a Cold Environment

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The purpose of this study was to determine the usefulness of physiological studies in the evaluation of protective clothing for work in a cold environment. The study included the examination of the dynamics of changes in chosen physiological parameters (core and skin temperatures, heart rate, pulmonary minute ventilation) as well as physical ones (the temperature and relative humidity under the clothes) during work in protective clothing with unknown thermal insulation. The experiment was conducted in extreme environmental conditions (−10 and −15°C) at a work load defined by the clothing manufacturer as moderate. Results show that thermal equilibrium was achieved and maintained throughout the investigated work time (60 min) and that the protective clothing ensures safety on the time scale of a regular 8-hour work day. It was also shown that the dynamics of thermal stress physiological parameters can be used to determine the maximum duration of exposure for cold protective clothing with unknown thermal insulation.

1. INTRODUCTION

Depending on the work load and environmental conditions, different kinds of protective clothing are used. The clothing is produced from various materials and has different structure designed to optimize thermal insulation (Zembowicz, 1969). Protective clothing should ensure safe work conditions and cannot impede work performance (Lotach, 1972).

The required insulation value (IREQ) can be calculated according to the ISO CD 11079 (1990) procedure. When the insulation of a selected ensemble is known and is smaller than IREQ, the time of exposure to the cold has to be shortened in order to prevent progressive body cooling. The duration of limited cold exposure (DLE) is then determined according to ISO CD 11079 (1990).

When the thermal insulation of protective clothing is unknown, the maximum time of exposure can be determined on the basis of physiological and environmental parameters. The measurements usually include:

- ambient environmental parameters: temperature, relative humidity, and air velocity (Baum, 1986; Baum & Jakubowski, 1987; Lotach, 1972);
- the environmental parameters under the clothes: the temperature and relative humidity of the air under the clothing (Lotach, 1972; Hettinger, Eissing, Herting, & Steinhaus, 1984);
- skin and core temperatures (Grucza, 1990; Lotach, 1972; Parsons, 1988);
- heart rate (Lotach, 1972); and

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predicted thermal sensation of man: (PMV, predicted mean vote) calculated on the basis of
the work load, the kind of clothing, and ambient conditions (ISO 7730, 1984). This value is
used to predict the thermal comfort of clothed men.

In the studies just mentioned, the evaluation of clothing was often based on a single
measurement of physiological variables (Parsons, 1988). In this study, however, the dynamics
of changes in the physiological parameters in young men exercising in the cold is used to
evaluate protective clothing. In order to further characterize the tested clothing, the predicted
thermal sensation was determined and the ratings of the subjective thermal comfort levels
were recorded.

The objective of this study was to determine the maximum length of work time in protective
clothing for a cold environment, using the dynamics of changes in selected physiological
parameters. It was assumed that the tested protective clothing could be used during the whole
shift when the steady state of measured physiological parameters is fixed at levels below
permissible values.

2. METHODOLOGY

2.1. Participants
Six healthy male participants volunteered for these experiments. Their characteristics are
provided in Table 1. Each participant took part in three experiments during which different
clothing was tested. The tests were separated by 3- to 7-day intervals.

2.2. Garment Description
The tested clothing consisted of three layers: (a) 100% cotton short-sleeved/short-legged
underwear, (b) a flannelette shirt and trousers (100% cotton), and (c) protective clothing for
the cold. We tested three kinds of clothing designed for work in a cold environment:

(1) cold-weather clothing for working in a cold store,
(2) cold-weather and rain clothing for airport mechanics, and
(3) cold-weather and rain clothing for construction workers.

All sets of protective clothing were designed for moderate work. Sets 1 and 2 were designed
for use in air temperatures not lower than -15°C, and Set 3 for temperatures not lower than
-10°C.

2.3. Experimental Protocol
After a 15-min rest in the sitting position at 21°C outside the climatic chamber, the participants
entered the chamber and exercised on a bicycle ergometer Monark (Figure 1). The exercise
load was approximately 30% VO2 max and its duration was 60 min.

The ambient air temperature and mean radiant temperature in the climatic chamber were
maintained at stable levels ($T_a = T_r = -15 \pm 0.2°C$ or $-10 \pm 0.2°C$, depending on the intended
application of the tested set of clothing).

<table>
<thead>
<tr>
<th>TABLE 1. Physical Characteristics of Participants ($M \pm SD$)</th>
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<tbody>
<tr>
<td>Age (years)</td>
</tr>
<tr>
<td>-------------------------------------------------------------</td>
</tr>
<tr>
<td>23.5(± 1.6)</td>
</tr>
</tbody>
</table>

Note. $A_D$ = DuBois body surface.
Changes in the following physiological and physical parameters were monitored:

- core temperature measured in the external auditory canal ($t_{ac}$);
- skin temperature ($t_{sk}$) measured in eight sites including forehead, right scapula, left upper chest, right arm/upper location, left arm/lower location, left hand, right anterior thigh, left calf;
- pulmonary minute ventilation;
- heart rate;
- the mass of each participant's body and clothes;
- the temperature and relative humidity under the clothes, measured in five sites, including chest/breast-bone, back/interscapular region, arm/dorsal region, anterior thigh, lateral shank.

### 2.4. Measurements and Calculations

The maximum oxygen uptake of the participants was calculated by the indirect method of Astrand and Ryhming (1954).

The temperature in the external auditory canal ($t_{ac}$) and the skin temperature ($t_{sk}$) were measured with an accuracy of 0.15°C using standard thermocouples, and were recorded on a 10-canal point recorder (Ellab A/S Copenhagen, Denmark). The mean weighted skin temperature was calculated in accordance with the 8-point formula (ISO 9886, 1992). The temperature and relative humidity under the clothes were calculated as an arithmetic mean of the values measured at the five sites listed earlier. Heart rate was estimated on the basis of ECG. The participants and clothes were weighed before and after the experiment (accuracy = ± 5 g).

Heat storage or loss ($\Delta S$) was calculated by the simplified version of the calorimetric equation (PN-92/P-84685, 1992),

$$\Delta S = \Delta T_{ac} c \left( \frac{m}{A_P} \right),$$

where,

- $t_{ac}$ = the external auditory canal temperature (°K s⁻¹),
- $c$ = the specific heat of body tissue (J/g °K),
\[ m = \text{the body mass (kg)}, \]
\[ A_D = \text{the DuBois surface area (m^2)}. \]

All measurements and calculations were carried out every 5 min.

The Required Clothing Insulation (IREQ) and Predicted Mean Vote (PMV) indices were used to characterize the thermal environment and to evaluate the thermal sensation coefficient. They were calculated according to international standards ISO CD 11079 (1990) and ISO 7730 (1984), respectively. After each experiment, the participants' ratings of perceived clothing were assessed according to the procedures of Hettinger et al. (1984).

2.5. Statistical Methods

All results of this study are presented as means ± SE (standard error).

3. RESULTS

The results of this study are presented in Figures 2–7 and in Table 2.

The mean weighted skin temperature \( \bar{t}_{sk} \) was lowest approximately 10 min after the beginning of exercise. The magnitude of the \( \bar{t}_{sk} \) decrease and the time of occurrence of the \( \bar{t}_{sk} \) minimum did not depend on the kind of clothing (Figure 2). Between the 10 and 30 min, \( \bar{t}_{sk} \) increased, and then after approximately 30 min of exercise a gradual decline in the skin temperatures was observed in all cases.

During the experiment, the external auditory canal temperature \( t_{ac} \) was almost constant (Figure 3). Calculated on the basis of body temperature change, the body heat storage and the predicted thermal sensation coefficient PMV at the end of the exercise were \( \Delta S = 16.7 \text{ Whm}^{-2} (± 5.9) \) and 0.5 Whm\(^{-2}\), respectively. When analyzing the temperature dynamics over the first 30 min, a very small decrease of \( t_{ac} (0.43 ± 0.1°C) \) was noted (Figure 3). The corresponding heat loss was \( \Delta S = -5.8 \text{ Whm}^{-2} (± 1.6) \).

![Figure 2. Time course of mean weighted skin temperature (SE = 0.5).](image-url)
The mean sweat loss for all tested clothing was 340 g (± 26.8) and the corresponding heat loss was 119 Whm⁻² (± 4.5, See Table 2). The dynamics of the temperature changes under the clothes (Figure 4) were close to the dynamics of the mean weighted skin temperature. The humidity under the clothes (Figure 5) increased during all experiments but did not exceed 60%. Heart rate stabilized after 10 min of exercise and its mean value was 120.8 beats/min (± 10.6) independent of the tested clothing (see Figure 6). The subjective ratings of perceived clothing are presented in Figure 7.

4. DISCUSSION

The examination of clothing for protection against the cold was conducted under environmental conditions and work load close to those specified by the designer. Under those con-
Figure 4. Time course of temperature under the clothes (SE = 0.4).

Figure 5. Time course of humidity under the clothes (SE = 3.12).
ditions, the dynamics of physiological parameters changes depend on the equilibrium between heat production and dissipation. Only a small decrease of surface tissue temperature and an even smaller core temperature reduction were expected. According to ISO CD 11079 (1990), heat loss should be close to zero (ΔS ≈ 0), core temperature within the 36°C to 37°C range, and the mean skin temperature not lower than 30°C. The sweating rate should also be low (skin wetness, w < 0.6). The predicted thermal sensation should be close to neutral (PMV ≈ 0). In such conditions there would be no need for recovery time.

<table>
<thead>
<tr>
<th>No.</th>
<th>Question</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>is this clothing impermeable for air?</td>
</tr>
<tr>
<td>2</td>
<td>do you sweat in this clothing?</td>
</tr>
<tr>
<td>3</td>
<td>warm are you in this clothing?</td>
</tr>
<tr>
<td>4</td>
<td>does the weight of this clothing load you?</td>
</tr>
<tr>
<td>5</td>
<td>do you feel restricted by this clothing?</td>
</tr>
<tr>
<td>6.1</td>
<td>does this clothing limit the movement of your hands?</td>
</tr>
<tr>
<td>6.2</td>
<td>does this clothing limit the movement of your legs?</td>
</tr>
<tr>
<td>6.3</td>
<td>does this clothing limit the movement of the upper part of your body?</td>
</tr>
<tr>
<td>7</td>
<td>does this clothing deprive of the feeling of safety when you move?</td>
</tr>
<tr>
<td>8</td>
<td>is your breathing disturbed by the clothing?</td>
</tr>
<tr>
<td>9</td>
<td>do you experience occasional difficulty caused by this clothing?</td>
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</table>

Figure 6. Time course of heart rate (SE = 3.8).

Figure 7. Subjective ratings of subjects
The results of this study showed that the thermal equilibrium was indeed achieved for the tested sets of clothing. This was proved by the steady state of body temperatures: \( t_{ac} = 36.7 \pm 0.58^\circ C \), stable \( t_{sk} \) was above \( 30^\circ C \), heart rate was approximately 120 beats/min, and small heat storage \( \Delta S = 16.75 \pm 5.9 \text{ Whm}^{-2} \). Both the predicted thermal sensation (PMV = 0.5) and the subjective rating of thermal comfort indicated that thermal equilibrium was maintained when working in the protective clothing. The subjective ratings of thermal sensation revealed, however, that the evaluated clothing sets were somewhat warmer and less airy, and promoted a marked tendency to greater sweating than individually selected clothing used by participants in thermal comfort conditions.

The overall results indicate that 60-min work time is safe for participants working in the tested clothing at \(-10^\circ C\) and \(-15^\circ C\). However, the subjective and physiological responses of the participants suggest that the tested sets of clothing have a small reserve of thermal insulation. In some work situations this surplus of thermal insulation may be necessary because of the wind chill factor, which was not considered in this study. In outdoor conditions for which the clothing has been designed, for example, for airport mechanics (Set 2) and for construction workers (Set 3), we can expect greater air velocity than assumed in this study.

The results obtained in this study suggest that the tested sets of clothing may be used by healthy young male workers during the whole shift.

5. CONCLUSIONS

The results of this study proved that the dynamics of the thermal stress criteria (body temperatures, heart rate, sweat rate, and heat storage or loss) can be used to determine the maximal time of work when wearing protective clothing with unknown thermal insulation.

REFERENCES


