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Prediction of Duration Limited Exposure for Participants Wearing Chemical Protective Clothing in the Cold

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The suitability **of** the IREQ (insulation required) index **for** predicting the thermal responses of 6 participants wearing chemical protective clothing was tested during exercise at -20 and -25 °C. IREQ was used to calculate duration limited exposure (DLE). Measured DLE correlated (r= .899, p < .001) with the predicted DLE. In exposures exceeding 40 min, however, the predicted DLE tended to be 10-20 min too short compared to the measured one. During short exposures the prediction was 5-20 min too long. The results show that IREQ overestimated the cold strain in participants wearing chemical protective clothing during cold exposures longer than 40 min. Nevertheless, predicted DLE never exceeded measured times and thus the prediction was always safe from the occupational point of view.

IREQ cold strain heat storage thermal sensation

1. INTRODUCTION

In a cold environment adequate thermal insulation of clothing is required to ensure work ability and provide thermal comfort. In a contaminated

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environment the use of encapsulative protective clothing is also needed to eliminate the interaction of hazardous material with the body surface and the respiratory tract. The overgarment of the protective clothing may be totally impermeable or semipermeable to water vapour. Low vapour transfer properties of the clothing may impede the evaporative heat exchange causing physiological strain in a hot environment (Armstrong et al., 1991; McLellan, Jacobs, & Bain, 1993) and cold strain problems in a cold environment (Cortili, Mognoni, & Saibene, 1996; Rissanen & Rintamäki, 1997).

There are only a few methods to assess cold stress in cold environments. The wind-chill index (Siple & Passel, 1945) is the very classic one. Required Clothing Insulation (IREQ; Holmér, 1984; Standard No. ISO/TR 11079:1999; International Organization for Standardization [ISO], 1999) has been proposed as a method for calculating clothing insulation required in cold environments. The minimal clothing insulation required to maintain body thermal equilibrium at a subnormal level of mean body temperature is termed as $IREQ_{min}$. Insulation required for thermal neutrality is defined as $IREQ_{neutral}$ $IREQ_{niin}$. allows some body cooling and $IREQ_{neutral}$ none or minimal cooling of the body. If clothing insulation is lower than the calculated IREQ, duration limited cold exposure (DLE) has to be determined to prevent progressive body cooling. DLE is defined as the recommended maximum time of exposure. DLE implies the time during which body heat storage is decreased by 40 Wh m^{-2}.

The IREQ index is primarily determined for normal cold-protective clothing and has previously been evaluated in industrial cool stores by Aptel (1988) and O'Leary and Parsons (1994). The purpose of the present study was to test the use of the IREQ method for predicting cold strain during light exercise in the cold while whole body covering chemical protective clothing with a respiratory mask were used.

2. MATERIALS AND METHODS

2.1. Participants

Four men and 2 women participated in the study. Mean values and *SD* for age, weight, height, and subcutaneous fat were 33.2 (8.3) years, 62.8 (9.8) kg, 1.71 (0.1) m, and 16.0 (3.5)%, respectively. Prior to the study the participants signed their informed consent. The experimental protocol was in accordance with the Declaration of Helsinki.

2.2. Environmental Conditions

The experiments were carried out in a wind tunnel at ambient temperature (7_a) of -20 and -25 °C. Mean radiant temperature was equal to T_a. Wind velocity was 2 m s~ and relative humidity 50%.

2.3. Clothing

The participants were dressed in semipermeable chemical (NBC: nuclear, biological, chemical) protective clothing (Saratoga™). The protective layer consisted of impregnated activated carbon spheres. Underneath the over-garment, the participants wore underwear (pants: 50% polyester/50% cotton; a shirt: 50% polyester/28% poIychlaI/22% cotton) and a middle layer (80% polyamid/20% cotton), both with long sleeves and legs. Two pairs of socks, rubber boots with felt liners, cotton gloves, rubber overgloves, mittens with a pile lining, and a full-face respiratory mask (FM12, Avon Ltd, UK) were used. Sleeves and trouser legs were pulled over the gloves and boots and closed by a fastener tape. The hood was pulled over the mask and fixed with a draw-cord. The total mass of the clothing averaged 8.0 and 5.6 kg with and without the boots, respectively.

2.4. Experimental Protocol

After instrumentation at room temperature, the participants entered the climatic chamber (Ta = 18 °C) where they rested for 10 min. Thereafter the participants entered the wind tunnel and started to walk on a treadmill. Ambient temperature and work rate were selected to set the predicted DLE between 30 and 60 min. Walking speeds of 3 and 4 km hr^{-1} were selected to create cool or slightly cool thermal sensation within a 60-min exercise. The exercise lasted 60 min, except in 3 participants who walked 90 min, until their body heat content decreased by 40 W $^{-2}$. Each participant performed two experiments at different metabolic rates at -20 or -25 °C and some of the participants' additional measurements at either temperature.

2.5. Measurements

Rectal temperature (T_{re}.) was measured with a thermistor probe (YSI 401, Yellow Springs Instruments, USA) inserted 10 cm into the rectum. Skin temperatures were measured at 11 sites with thermistor probes (YSI 427) taped on the skin. Dry heat flux from the skin was measured by heat flow discs (HA 13-18-10-P(c), Thermonetics, USA) fixed by double-sided tape at 8 sites on 1 participant. Clothing surface temperature *(T_{cl})* was measured with thermistors (YSI 427, Yellow Springs Instruments, USA) fixed by a porous tape on the overgarment in the front and back side of the body. Temperatures and heat flow were recorded every 1 min by the portable data logger (Squirrel 1200, Grant, UK). Oxygen uptake ($\dot{V}O_2$) was measured continuously by collecting the expired air through ergospirometer (Medikro 919, Medikro Oy, Finland). The collecting tube was fastened to the expiration valve of the NBC mask. Heart rate was recorded using Polar Sport Tester (Polar Electro, Finland) at 1-min intervals. General thermal sensation, thermal sensation of head, hands, fingers, feet and toes (Standard No. ISO 10551:1995; ISO, 1995), and ratings of perceived exertion (RPE; Borg, 1970) were asked at 15-min intervals. The thermal sensation scale ranged from -4 *(very cold)* to +4 *{hot),* 0 being neutral and RPE from 6 *{extremely light)* to 20 *(extremely heavy).* Relative humidity *(RHi_{cl})* and temperature *(T_{icl})* inside the clothing were measured by humidity sensor (Rotronic Hygromer® A2, Rotronic, Germany) placed between middle layer and outergannent at the chest and recorded at 15-min intervals. Nude and dressed body weight was measured before and at the end of the experiment to determine the loss of body weight. The amount of sweat accumulated in the clothing layers was determined by weighing the clothes before and after the experiments.

2.6. Calculations

IREQ and DLE were calculated by using the IREQ software (National Institute for Working Life, Solna, Sweden, version 1.4, 1992).

Mean skin temperature ($\bar{T}_{sk}$) was calculated by weighing 9 local skin temperatures (cheek, chest, lower back, upper arm, lower arm, hand, thigh, calf, foot) with the representative areas (Mitchell & Wyndman, 1969).

Mean body temperature *(T_b)* was calculated as

$$T_b = 0.65 \cdot T_{re} + 0.35 \cdot f_{sk} \qquad ("C),$$

where T_K is the rectal temperature and $\bar{T}_{sk}$ is the mean skin temperature.

Body heat content (Q) was calculated as

$$Q = (0.97 * BW * T_b)'AD'1 \qquad (Wh'irr^2),$$

where 0.97 is the specific heat of body tissue (Wh»kg$^{\#o}$C~'), *BW is* the body weight (kg) and A_D is the DuBois body surface area (nr).

Measured DLE time (mil)) was determined when body heat loss was 40 Wh'irf^2 compared to thermoneutral condition with values of T_{re} = 37 °C and fsk = 33 "C.

Sweat loss was determined from the loss of *BW* corrected for the loss of metabolic mass and evaporative respiratory weight loss.

Mean dry heat flux *(HF* in W*irf^2) was calculated by weighing 8 local heat flow values (cheek, chest, lower back, upper arm, hand, thigh, calf, foot) with the representative areas as in the calculation of *T&.*

Resultant clothing insulation *(/dr)* was calculated according to the equation:

$$I_{clr} = (\bar{T}_{sk} - T_{cl}) \cdot HF^{-1} \qquad (m^2 \cdot {}^\circ C \cdot W^{-1}),$$

where *Ta* is the clothing surface temperature and *HF* is the dry heat flux (W-ITT^2).

Resultant total insulation of the clothing (7$_{Tr}$) was calculated as

$$I \cdot rr = (f_{sk} - 7J - //F-' \qquad (m2«"OW-'),$$

where T_A is ambient temperature.

Metabolic rate (M) was calculated by

$$M - (16.33 + 4.6 \cdot RQ) \cdot VO_2 \cdot 10^3 \cdot (60 \cdot A_D)^{\sim'} \qquad (W«irf^2)$$

(Weir, 1949), where RQ is the respiratory exchange ratio, $\dot{V}O_2$ is the oxygen consumption (L»min~') and A_D is the body surface area (m^2).

Metabolic heat production (//) was estimated from M and from external work *(W),* which was assumed to be zero during the level walking (Havenith, Heus, & Lotens, 1990):

$$H = M - W \qquad (W\text{-}irf^2),$$

where M is the metabolic rate and *W* is the external work (W$^\#$irf^2).

2.7. Statistics

Linear regression was calculated between measured and predicted DLE. Differences between the predicted and measured DLE times were tested with a paired *t* test. Statistical significance was accepted at a $p < .05$ level.

3. RESULTS

3.1. Physiological Responses

Metabolic rate during the exercise varied from 126 to 195 W*nrf2.. Mean *(SD)* relative humidity inside the clothing was 19.7 (13.2)% at the end of the experiment.

3.2. Clothing Insulation

Resultant thermal insulation of the clothing ensemble ($/_{c}i_{r}$) was 1.80 clo (0.279 m^0W"1), measured on a standing human participant at -20 °C and 2 m»s~' of wind. In the same environmental conditions during walking at the speed of 3 and 4 km-hr1, $7_{c,r}$ was 1.76 clo (0.273 ar^0W"1) and 1.59 clo (0.246 m2#CAV~'), respectively. 7_{dr} during walking was regarded as a resultant value for the calculation of the predicted DLE. Resultant total insulation (7_{Tr}) was 1.91 clo (0.296 m^0W'1) and 1.74 clo (0.270 m^0W"1) during walking at the speed of 3 and 4 km#hr~\ respectively.

3.3. Comparison Between DLE and Calculated Changes in Body Heat Content (0

Predicted DLE correlated significantly with the measured DLE (Figure 1). However, measured DLE times tended to be longer than predicted when cold exposure exceeded 40 min and shorter when exposure times were less than 20 min.

Table 1 presents required clothing insulation and the predicted and measured DLE values for the individuals. On average IREQmin was greater

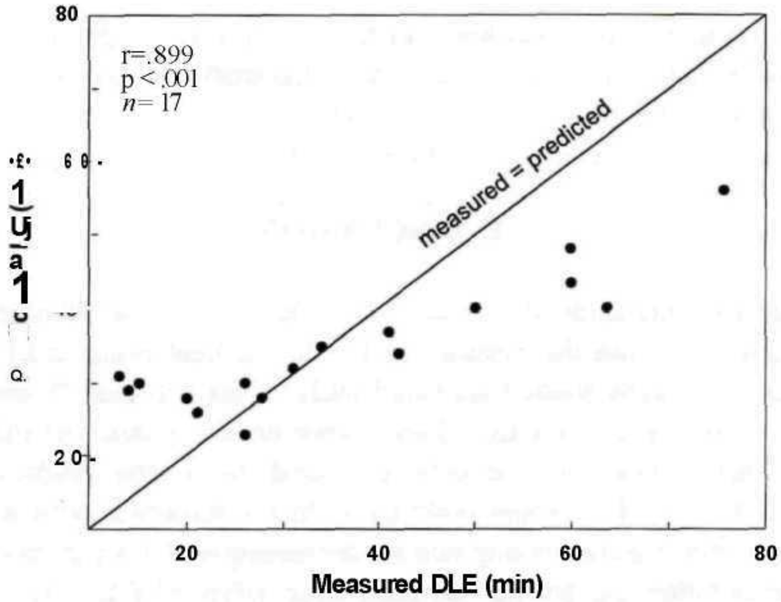

Figure 1. Comparison between predicted and measured DLE.

TABLE 1. Individual Predicted and Measured DLE Times. Clothing Insulation Required ($IREQ_{min}$) at the Given Metabolic Rate and Ambient Temperature Are Presented. Individual $\bar{T}_{sk}$ Values Are Those at the Measured DLE Time. Means *(SD)* Are at the End of the Columns *(N* = 17)

$IREQ_{min}$ (clo)	Predicted DLE Time (min)	Measured DLE Time (min)	$\bar{T}_{sk}$ at Measured DLE Time (°C)
3.00	23	26	29.3
2.62	26	21	29.3
2.79	28	28	29.2
2.11	28	20	29.3
2.45	29	14	29.7
2.59	30	26	29.0
2.41	30	15	29.7
2.06	31	13	29.1
2.30	32	31	29.6
2.14	34	42	28.7
2.01	35	34	29.0
2.32	37	41	29.0
2.63	40	50	29.0
1.91	40	64	29.4
1.80	43	60	29.3
1.81	48	60	28.7
1.71	56	76	29.1
2.27	34.7	36.5	29.2
(0.37)	(8.5)	(19.4)	(0.3)

than the existing thermal insulation of the NBC protective garment. Average mean skin temperature (T_{sk}) was 29.2 °C at the time when body heat content decreased by 40 $W*m^{-2}$.

4. DISCUSSION

The results of this study show that the predicted DLE correlated positively and significantly with the measured DLE during light exercise in the cold. Under the conditions studied predicted DLE values between 25 and 40 min were close to measured DLE times. However, the prediction index gave shorter DLE times than actually measured when the prediction time exceeded 40 min. The whole body cover and a respirator with a full-face mask may decrease the cooling rate by decreasing heat loss, especially from the head and thus explain part of the longer measured DLE. The effect of a respirator on respiratory heat exchange may become marked because the filter device acts as a heat transducer warming the inspired air. Breathing of pre-warmed air is documented to reduce respiratory heat loss and to increase mean body temperatures and thermal comfort during cold exposure (Romet, Prim, Allen, Shephard, & Goode, 1988). Nielsen, Berglund, Gwosdow, and DuBois (1987) showed that the air temperature inside a half-face mask influenced the general thermal sensation. Different methods in determining thermal insulation of the clothing may also cause deviation in DLE times. In this study resultant thermal insulation of the clothing ensemble (I_{clr}) was measured on a walking human participant under the studied conditions. In the instructions of IREQ it is recommended to correct the insulation measured with a static thermal manikin for wind and body movements or to use a moving thermal manikin for determination. Although there appeared differences in predicted and measured DLE times, it should be emphasized that the predicted DLE time was always shorter than the measured one. Therefore prediction always gave a safe limit for the exposure.

During short (less than 25 min) and more severe cold exposures the predicted DLE was too long. In those cases Q decreased during the first 10 min markedly due to the rapid decrease of $\bar{T}_{sk}$. Redistribution of blood from the skin to muscles during the start of the exercise, particularly when I_{clr} was far less than $IREQ_{min}$, could also partly explain the decrease in $\bar{T}_{sk}$. In fact, in the prerequisites of DLE it is assumed that the initial cooling period lasts for 20-40 min during which the body heat content is stabilized to a new and lower level (ISO/TR 11079:1999; ISO, 1999).

Individual variation in the amount of subcutaneous fat, fitness, and cold adaptation may cause differences in thermal responses (Toner & McArdle, 1988). In this study the participants were of average fitness. Gender might affect thermal responses through the smaller body mass in female, although no significant difference could be noticed in the results obtained.

When calculating $IREQ_{min}$ it is assumed that new heat balance is maintained at the $\bar{T}_{sk}$ level of 30 °C. In the present study the $\bar{T}_{sk}$ was 29.2 °C when body heat content was decreased by 40 $W \cdot m^{-2}$. $\bar{T}_{sk}$ reached 30 °C on an average 16 and 18 min earlier than that of predicted and measured DLE, respectively. These results suggest that 30 °C might be too high for estimation of the decrease of body heat content by 40 $W \cdot m^{-2}$.

The factual (resultant) thermal insulation of the clothing (I_{clr}) was used for the calculations of DLE. Resultant clothing insulation was 0.15 clo smaller than the resultant total insulation (I_{Tr}), which also includes the insulation of the boundary air layer. Posture, pumping effect, air movements, and accumulated moisture inside the clothing reduce insulation measured in static situation by 15 to 20% (Havenith et al., 1990; Holmér, 1984). Kuklane, Holmér, and Meinander (1998) reported even a 50% decline in thermal insulation of wetted impermeable protective clothing measured on a sweating thermal manikin. In the present study the amount of accumulated moisture in the clothing was low and also the relative humidity inside the clothing was only about 20% due to the light and rather short exercise as well as cold ambient temperature.

5. CONCLUSIONS

Based on the results following conclusions can be drawn:

1. Predicted DLE correlated significantly with the measured DLE in the participants wearing chemical protective clothing.
2. The predicted DLE times of 25 to 40 min were close to the measured values, whereas during exposures exceeding 40 min the prediction model tended to give shorter maximal recommended cold exposure times.
3. Predicted DLE times never exceeded measured times and thus the prediction was always safe in occupational point of view.
4. The use of a respirator and differences in determine thermal insulation might explain part of the discrepancy between predicted and measured DLE, especially during slow cooling.

5. IREQ method can be used to assess low cold strain if predicted DLE is longer than 25 min when chemical protective clothing with studied thermal insulation is used in a cold environment.

6. FUTURE RESEARCH

The results of the present study leave some questions unsolved. The reasons for underestimation of predicted DLE during long cold exposures need further research. The effects of wearing a respirator with a full-face mask on whole body cooling and thus on shorter predicted DLE times need more specific investigation. Extremities, in particular hands and fingers, often suffer rapid cooling while chemical protective clothing is used in a cold environment. Because extremity cooling is not yet adjusted to IREQ method, the issue needs more research.

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