

# Heat Strain in Cold

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**Abstract:** In spite of increased environmental cold stress, heat strain is possible also in a cold environment. The body heat balance depends on three factors: environmental thermal conditions, metabolic heat production and thermal insulation of clothing and other protective garments. As physical exercise may increase metabolic heat production from rest values by ten times or even more, the required thermal insulation of clothing may vary accordingly. However, in most outdoor work, and often in indoor cold work, too, the thermal insulation of clothing is impractical, difficult or impossible to adjust according to the changes in physical activity. This is especially true with whole body covering garments like chemical protective clothing. As a result of this imbalance, heat strain may develop. In cold all the signs of heat strain (core temperature above 38°C, warm or hot thermal sensations, increased cutaneous circulation and sweating) may not be present at the same time. Heat strain in cold may be whole body heat strain or related only to torso or core temperature. Together with heat strain in torso or body core, there can be at the same time even cold strain in peripheral parts and/or superficial layers of the body. In cold environment both the preservation of insulation and facilitation of heat loss are important. Development of clothing design is still needed to allow easy adjustments of thermal insulation.

**Key words:** Cold exposure, Exercise, Heat production, Thermal insulation, Clothing, Protective garment

## Introduction

Heat strain in cold conditions is a common phenomenon and depends usually on the difficulty or inability to change the clothing insulation according to the needs of changed heat production<sup>1–5</sup>. Anecdotal stories tell even about heat exhaustion during military exercises in cold, when maximal amount of clothing is worn and exercise intensity has increased to high levels. However, published results on heat strain in cold are rare.

Heat strain in cold is equally hazardous as in warm environment, although all the signs of heat strain (warm or hot thermal sensations, discomfort, sweating, high core and/or skin temperatures, increased cardiac work) may not be present at the same time. The additional feature in heat strain in cold is that during the periods of heat strain, sweating will be accumulated in clothing which impairs the thermal insulation and increases the risk of cold strain in subsequent phases of work with lower heat production.

This paper focuses on heat balance in cold, with observations on heat strain in outdoor and indoor cold exposures, and observations from exercise with whole body covering chemical protective garments in cold.

## Heat Balance in Cold

In a given ambient thermal condition, body heat balance depends on metabolic heat production and heat loss/gain by radiation, conduction, convection and evaporation. The thermal insulation of the clothing is in the main role in adjusting different forms of heat loss. Metabolic heat production is composed of basal metabolism and regulated heat production. Basal metabolic rate can be changed very little, mainly by thyroid hormones. Eating can increase heat production by 15% for a couple of hours. The main source of variation in metabolic heat production is the variation in muscular work either by physical activity or cooling induced shivering. Basal metabolic rate (BMR) is ca. 58 W/m<sup>2</sup>,

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and physical exercise can increase metabolic rate, depending on individual's physical fitness, maximally 10–13 times BMR, while shivering can increase the metabolic rate ca. 3 times BMR. Almost the whole metabolic rate is converted to heat while resting and shivering. During physical exercise the proportion of external work is ca. 0–20% from metabolic rate, leaving 80–100% of metabolic rate to be converted to heat<sup>6</sup>.

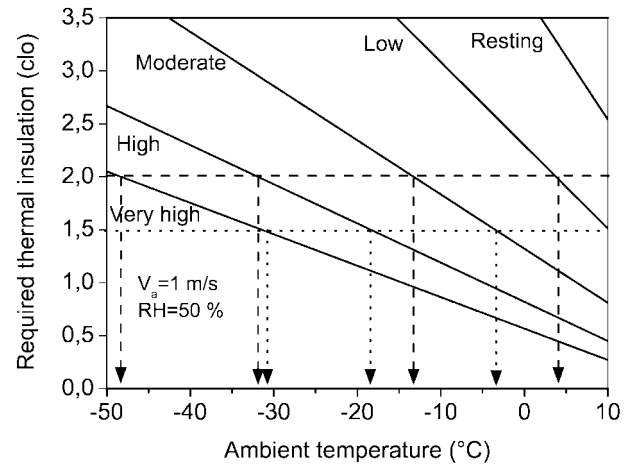
If the ambient thermal conditions are stable, the variation in metabolic heat production is the main factor causing imbalance in body heat balance. There can be at least two reasons for this imbalance: level of physical work may vary largely during the work and pauses, or the clothing may be worn for the initial conditions with low heat production and later on, when exercise starts to produce heat, the thermal insulation of the clothing is exaggerated.

Both whole body heat balance and local protection against cooling should be taken care in the cold. Even with torso heat strain it is usually not practical to uncover large areas of body to facilitate heat loss, as unprotected areas may suffer from a local cold strain. Therefore, a certain level of whole body thermal protection should be maintained in most conditions.

Usually the thermal insulation of work clothing in cold environment is around 2 clo. Such kind of clothing could be composed, e.g., from underwear with short sleeves and legs, shirt, trousers, jacket, heavy quilted outer jacket and overalls, socks, shoes, cap, gloves<sup>6</sup>. It may also be consisted of protective components, like helmet, safety boots and special gloves, against non-thermal hazards, which also increase the thermal insulation. Figure 1 shows the thermal insulation required for maintaining good heat balance at different levels of physical work at ambient temperatures between  $-50$  and  $+10^{\circ}\text{C}$ <sup>7,8</sup>. The figure shows, that with a 2.0 clo clothing the risk for accumulation of heat starts above  $+4^{\circ}\text{C}$  with low level of work, above  $-13^{\circ}\text{C}$  with moderate work, above  $-32^{\circ}\text{C}$  with high level of work and above  $-49^{\circ}\text{C}$  with very high level of work. The figure shows also the risk limits of starting of heat accumulation for 1.5 clo clothing, which could be consisted of, for example, underwear with short sleeves and legs, shirt, trousers, jacket, thermo jacket and trousers, socks and shoes<sup>6</sup>.

## Experiences from Field and Laboratory

Budd<sup>2</sup> studied the members of the International Biomedical Expedition to the Antarctic. He recorded their thermal comfort, clothing, and activity for 60 d while travelling by motor toboggan and living in tents on the Antarctic plateau. Air temperature averaged  $-14^{\circ}\text{C}$  (range



**Fig. 1.** Required thermal insulation of the clothing calculated for different ambient temperatures and work levels: resting ( $65 \text{ W/m}^2$ ), low ( $100 \text{ W/m}^2$ ), moderate ( $165 \text{ W/m}^2$ ), high ( $230 \text{ W/m}^2$ ) and very high ( $290 \text{ W/m}^2$ ).

External work has been assumed to be 0% at the two lowest activity levels and 5% at the other levels of exercise. Air velocity is 1 m/s and relative humidity 50%. The arrows point the ambient temperature, above which heat load is possible to develop with a given thermal insulation<sup>7,8</sup> of 2.0 clo (dashed line) and 1.5 clo (dotted line).

$+2$  to  $-29^{\circ}\text{C}$ ) and wind speed 11 m/s (range 0 to 22 m/s). Men were outdoors for 7.6 h of the 12 h sampling period on travel days and for 3.6 h on camp days. Bulky down-filled clothing, typical of that used by present-day polar expeditions, adequately protected the trunk from cold at the cost of overheating during exercise. Face, hands, and feet were less well protected, and they experienced cold-induced numbness and pain in 33%, 19%, and 12%, respectively, of the observations made in the coldest weather. Because men could not conveniently reduce clothing insulation to the extent required, sweating and discomfort from warmth increased with energy expenditure and were present in 60% of the observations made during heavy work.

In military field training body heat balance was studied in 64 conditions at ambient temperatures between 0 and  $-29^{\circ}\text{C}$ , and the duration of the training sessions varied from 55 min to 9.5 h<sup>9,10</sup>. The results showed that marked cold strain (mean skin temperature ( $T_{\text{sk}}$ )  $< 27^{\circ}\text{C}$ /thermal sensation "cold–very cold") was common over the whole ambient temperature range. A common reason for cooling was low physical activity. However, cold strain was evident only in the superficial and peripheral parts of the body. Rectal temperature ( $T_{\text{rect}}$ ) was dependent on the level of physical activity, and when  $T_{\text{rect}}$  exceeded  $37.6^{\circ}\text{C}$  (corresponding moderate work level) feet, hand and cheek temperatures, as well as  $T_{\text{sk}}$ , started to increase. That level of  $T_{\text{rect}}$  corresponds

to moderate work level (60% of maximal metabolic rate)<sup>11</sup>.

During the training sessions, where long transportations were mainly done by all-terrain vehicles,  $T_{\text{rect}}$  exceeded 38.0°C (which is regarded as a limit of heat strain<sup>6</sup>) for 5% of time and 37.8°C (associated with increased skin temperatures) for 14% of time. Thermal sensations of “slightly warm” or warmer were recorded in 17% of cases. Thermal sensations of “warm” or “hot” were recorded in 3% of cases. Different thermal sensations were recorded with lower skin temperatures than measured in laboratory, probably because of cold acclimatisation: warm thermal sensation was recorded when  $T_{\text{sk}}$  was 31.5°C (SD 0.2) and hot sensation at 32.0°C (SD 0.4)<sup>9, 10</sup>.

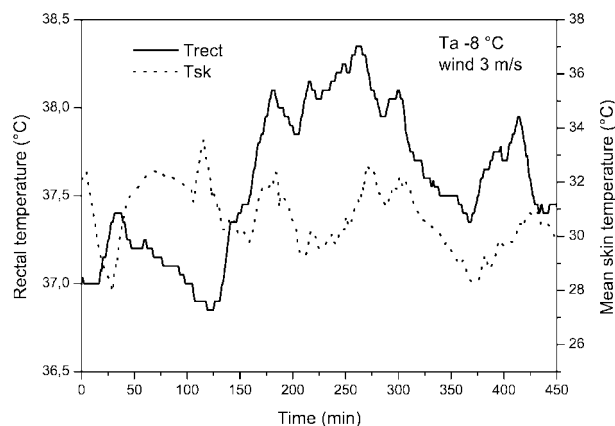
Figure 2 shows an example of long (7.5 h) patrol skiing at -8°C, where  $T_{\text{rect}}$  vary with levels of activity, occasionally increasing above 38.0°C. Because physical activity was variable but almost continuous,  $T_{\text{sk}}$  stayed on a quite high level throughout the training session<sup>9, 10</sup>.

The length of the exercise bouts affects the development of heat strain as shown in 2 h laboratory test sessions at -15°C, where exercise/rest bouts lasted either for 20 min (10 min exercise/10 min rest) or 60 min (30 min exercise/30 min rest). During the longer sessions  $T_{\text{rect}}$  increased to a considerably higher level than during the shorter sessions (Fig. 3). In both occasions,  $T_{\text{sk}}$  decreased during the whole test period from ca. 33.0 to 30.0°C<sup>12, 13</sup>.

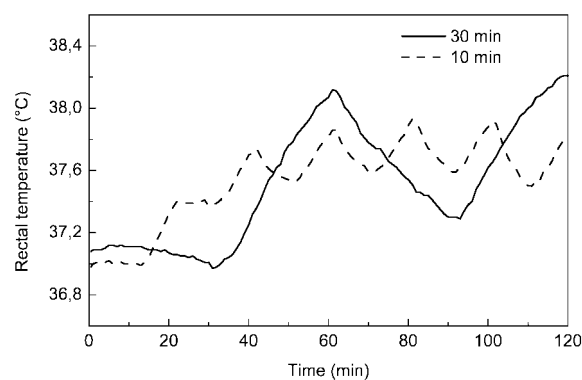
Sweating is evident for active individuals in the cold even though the rate of sweat production may remain low<sup>14–16</sup>. Sweating depends both on core and skin temperatures. During exercise with core temperatures above 37.6°C marked sweating is possible even at low skin temperatures like 26°C<sup>14</sup>. Sweating has been observed during running 10–11 km/h even when  $T_{\text{sk}}$  has been as low as 20°C (Rintamäki *et al.* unpublished).

## Chemical Protective Clothing in the Cold

Chemical protective (CP) garment is used to protect its wearer from a contaminated environment. Low water vapour permeability and increased thermal insulation are characteristics for the most CP garments. Thus CP garment, together with the respirator and rubber gloves and boots, severely constrains body's normal heat dissipating mechanisms, most markedly the evaporation of sweat<sup>17, 18</sup>. Consequently, body heat storage is increased and the user is exposed to heat stress conditions which may lead to inability to continue the performance<sup>19</sup>. The weight and bulk of encapsulating overgarments as well as the loose fit increase energy requirements for most tasks<sup>20, 21</sup>. Energy



**Fig. 2. Rectal and skin temperatures during military patrol skiing with variable work levels<sup>9, 10</sup>.**



**Fig. 3. The effect of the length of the exercise bouts on rectal temperature.**

Exercise/rest bouts lasted either for 20 min (10 min exercise/10 min rest) or 60 min (30 min exercise/30 min rest). Exercise (walking on treadmill 6 km/h, slope 2°) was performed at -15°C (air velocity 2.5 m/s) and rest at 10°C (calm). During walking the subjects had a 12 kg rucksack. The thermal insulation of the three-layer clothing was ca. 2.0 clo<sup>12, 13</sup>.

cost of walking increases about 3%/clothing kg, when multilayered clothing ensembles are worn<sup>22</sup>. Also, hobbling effects of the clothing<sup>23</sup> and increased stiffness of the overgarment due to cooling of the material<sup>24</sup> increase energy cost. The full-face mask furthermore decreases evaporation from skin and increases thermal and physiological strain by increasing respiratory resistance<sup>25</sup>. The heat strain associated with wearing the CP garment at high ambient temperatures is well documented (e.g. <sup>26–28</sup>).

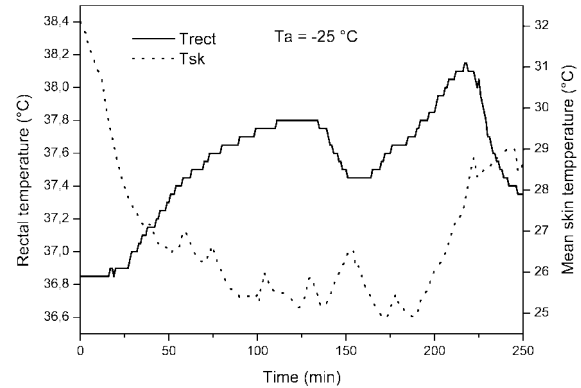
The use of CP clothing is not limited only to warm or hot conditions. The preparedness to use CP is also required in cold environments. Additional clothing layers further

increase the bulkiness of the protective clothing system. Adjustment of the thermal insulation of the clothing by donning or doffing clothing layers according to activity level is not possible in the contaminated area<sup>29</sup>. It has been shown that wearing CP protective clothing during heavy activity may cause performance decrements due to the heat strain at wide range of ambient temperatures<sup>30, 31</sup>.

The increase in  $T_{\text{rect}}$  is mainly dependent on the level of physical activity<sup>11</sup> rather than ambient temperature during physical activities. Furthermore, increase of  $T_{\text{rect}}$  is time dependent. During moderate to heavy work  $T_{\text{rect}}$  can easily exceed 38°C (Fig. 4) and may thus put the individual at risk of hyperthermia and heat exhaustion when the CP overgarment and two layers of underwear are worn even at as low as -25–-30°C. In the cold it is typical that individuals wearing CP garment experience a decrease in  $T_{\text{sk}}$ , irrespective of whether they are inactive<sup>30</sup> or active<sup>16, 30, 32</sup> although core temperature increases and sweating occurs. In the Fig. 4 it is illustrated how  $T_{\text{sk}}$  decreases during moderate activity level while  $T_{\text{rect}}$  increases.  $T_{\text{sk}}$  is also affected by the duration of the exposure to cold. In the study of Cortili *et al.*<sup>32</sup>  $T_{\text{sk}}$  was 26.8°C after 120 and 56-min exercise at the moderate workload at the ambient temperatures of 0°C and -20°C, respectively. Decrease in  $T_{\text{sk}}$  is mainly caused by skin cooling in peripheral parts of the body. Skin temperature at the upper body is maintained at higher level than  $T_{\text{sk}}$ .

Because the heat dissipation by evaporation is diminished due to the low moisture penetration through the clothing system, warm and humid microclimate is developed inside the clothing. Sweating is thus worsening, not relieving, the heat strain while CP clothing is worn. Sweat accumulation within clothing during work may degrade clothing insulation and disrupt thermal balance during subsequent periods of rest or low intensity activity<sup>30</sup>. Moreover, excessive cooling of fingers and hands is often resulted from poor thermal insulation of the protective glove system coupled with sweat accumulation in them<sup>30, 33</sup>.

The results of several studies<sup>15, 24, 31, 32</sup> concerning heat and cold strain in the cold while wearing CP clothing is summarized in Table 1. In the table thermal strain is assessed at different activity levels and at different ambient temperatures while CP clothing is worn<sup>31</sup>. The activity level is classified as light, moderate and heavy and thermal strain is classified to three categories: discomfort, performance decrement and tolerance according to Lotens<sup>34</sup>. In the Table 1 heat strain is based on both  $T_{\text{rect}}$  and  $T_{\text{sk}}$ . If only  $T_{\text{rect}}$  above 38°C is taken as a criterion for heat strain, risk of heat strain would be evident during heavy work or higher activity even at -30°C.



**Fig. 4.** Rectal and mean skin temperature during moderate (25–125 min) and heavy (150–220 min) exercise at ambient temperature of -25°C while wearing chemical protective clothing<sup>31</sup>.

## Conclusions

The results from field and laboratory measurements show that heat strain is possible in cold during periods of increased physical activity, if the adjustment of clothing insulation is not possible. Moreover, there can be heat strain in torso even when there is no heat strain in peripheral parts of the body, or even when there is cold strain in the periphery. During exercise in cold with adequate clothing, skin temperatures start to increase when  $T_{\text{rect}}$  exceeds 37.6°C, and there can be heat strain judged from core temperature and sweating even when skin temperatures are low. Therefore, in cold environment both the preservation of insulation and facilitation of heat loss are important. Development of clothing design is still needed to allow easy adjustments of thermal insulation according to the changes in physical activity.

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**Table 1. Probability of heat strain or cold strain (within 60 min) of whole-body and fingers as a function of physical activity level and ambient temperature, when wearing chemical protective clothing.**

Activity level	Risk of thermal strain							Body
Heavy	0/-	0/-	0	0	+	+	+	Whole body
	-	-	-	0	0	0	0	Fingers
Moderate	-	-	0/-	0/-	0	+	+	Whole body
	—	—	-	-	0	0	0	Fingers
Light	—	-	-	-0	0	0	0	Whole body
	—	—	—	-	-	-	0	Fingers
Very light/ rest	—	—	—	-	0	0	0	Whole body
	—	—	—	-	-	0	0	Fingers
	-30	-25	-20	-15	-10	-5	0	
	Ambient temperature (°C)							

0 (neutral); heat strain: + (discomfort); cold strain: - (discomfort), - (performance decrement), — (tolerance)<sup>31</sup>.

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