Chapter 11

Working in Cold Environment: Clothing and Thermophysiological Comfort

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Additional information is available at the end of the chapter

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Abstract

The chapter presents an in-depth discussion over the occupational activities in a cold environment, which can be performed both outdoors and indoors. It explores the differences between working in natural and artificial cold environment. The thermophysiological comfort, the reactions of the thermoregulatory system during cold exposure, and cold-related injuries are presented and discussed in detail. Clothing as the only insulating barrier between the body and the cold environment is discussed, and hi-tech solutions for development of cold protective clothing are presented. The particular application of standards for the indoor environment is considered, and their input for the proper management of the occupational activities in the cold is analyzed.

Keywords: cold environment, thermophysiological comfort, protective clothing, cold-related injuries

1. Introduction

Being warm-blooded creatures, humans can maintain a stable temperature of their bodies despite the large temperature fluctuations of the surrounded environment. The thermophysiological comfort is one of the aspects of the human comfort both indoors and outdoors. It is preconditioned by the functioning of the thermoregulatory system of the body and its reactions to the temperature of the surrounding air, the activity performed, and the used clothing insulation. Body's thermoregulation is very sophisticated and tries to maintain the temperature of the core body around 37°C while balancing between the heat, gained or produced, and the heat, released by the body to the surroundings.

According the definition in [1], cold is any environment, where people are exposed to a temperature below 15°C. The British standard BS7915 (1998) [2] determines that "cold environment" is the one with an air temperature below 12°C. People are working in a risky cold environment, which can be natural (outdoor) or artificial (indoor) cold environment. It is the clothing only (in the past) and special protective clothing (at present) that is the only barrier between the human body and the cold environment. Clothing, activity, and proper management of the occupational activities help and maintain the thermophysiological comfort of people, working in the cold.

The purpose of this chapter is to present details about the human thermoregulatory system and the thermophysiological reactions of the body in a cold environment. Natural cold environment and artificial cold environment are compared to the light of their different effects on the occupational activities and management of the cold exposure. Cold-related injuries as part of the thermoregulatory reactions of the body and the risk from cold exposure are summarized. Clothing and hi-tech garments for protection from extreme temperatures are discussed. Practical advices and standards for the management of the occupational activities in the cold are presented.

2. Thermophysiological comfort and thermoregulation

2.1. Thermophysiological comfort

Comfort is a relative and subjective category, which depends on individual reactions and perceptions. Hatch [3] defines the comfort as a neutral state, where there is no pain or discomfort. The *thermophysiological comfort* is a part of the *physiological comfort*, related to the reactions of the thermoregulatory system [4]. It is based on the sensors for warmth and cold in the body, susceptible to thermal environment, air velocity, temperature asymmetry, etc. and the consecutive reactions of the thermoregulatory system, which increases either the heat, produced by the body, or the heat losses to the surrounding environment. When the heat production is equal to the heat losses, the body is considered to be in a state of a thermophysiological comfort [4].

2.2. Basics of human thermoregulation in the cold

The main goal of the thermoregulatory system is to maintain the temperature of the core body (the brain and organs in the torso) around 37°C. The sensation of cold is initiated by the reaction of cold receptors: specialized nerve endings in the skin. They send signals to the central nervous system together with signals, coming from the brain (**Figure 1**). The two signals are processed in the hypothalamus: the gland in the brain that is responsible for the reactions of the thermoregulatory system. Actually, the spinal cord also controls the thermoregulation in case of cold exposure [5].

When the hypothalamus is activated, it sends electrical signals that trigger different thermoregulatory mechanisms, related to the decrement of the heat losses from the body (skin and lungs) to the surrounding air and increment of the heat production (in muscles and liver) [6–10]. **Figure 2** summarizes the basic physical and physiological reactions of the human body to the cold.

One of the first reactions of the body in cold environment is to provoke vasoconstriction: a decrement of the cross section of the blood vessels in the surface zones of the skin and the

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extremities. The vasoconstriction appears due to signals from the hypothalamus to the smooth muscles in the arterioles. The aim of the vasoconstriction is to impede the transfer of hot blood out of the core body, thus preserving as long as possible the accurate functioning of the heart, brain, and lungs. This process can increase the body temperature of 1–2°C, due to the reduction of heat losses through the three mechanisms of heat transfer: conduction, convection, and radiation.

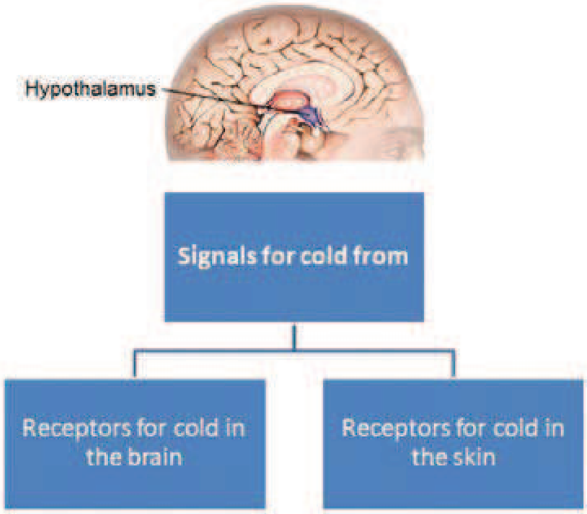

Figure 1. Signals sent to the hypothalamus.

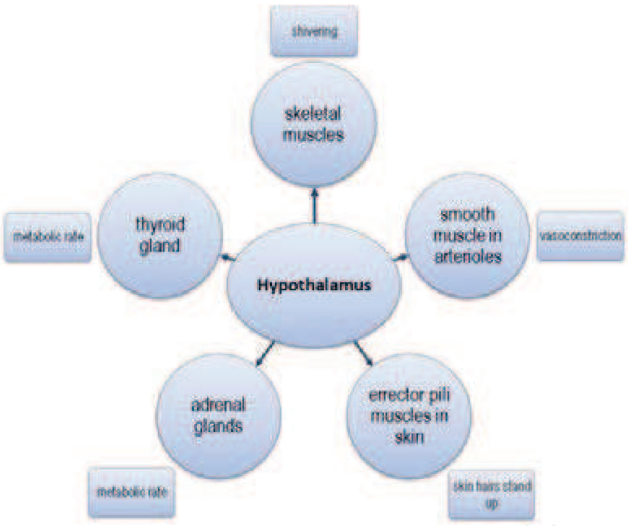

Figure 2. Thermoregulatory mechanisms in cold environment.

Figure 3 presents thermograms of a human hand, before and 3 min after the exposure to a cold environment of −10°C. The isolines clearly show the vasoconstriction process that has started. Vasoconstriction creates a feeling of cold, causing muscle tremors and increased heat production. Heat production from the liver also adds to the process. Cold hands and feet are the most frequent complaints of people in low ambient temperatures. Many of cold-related injuries are referred to fingers, nose, ears, and extremities, due to the decreased blood flow to them.

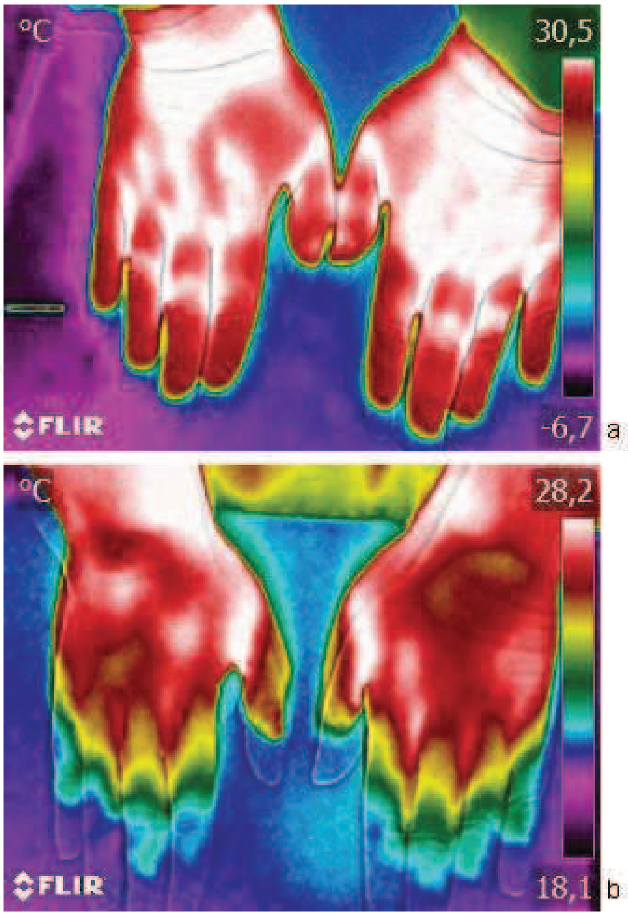

Figure 3. Thermograms of human hand: (a) before the cold exposure and (b) after a cold exposure to −10°C.

The behavioral reaction of the person to add an additional layer(s) of clothing (or bedding) also contributes to the augment of the core body temperature and the reduction of heat losses from the skin. Thus, when exposed to cold environment, the body maintains its internal temperature via vasoconstriction, increased heat production, and behavioral changes.

Signals to the erector pili muscles in the skin provoke pricking of the skin. Though small as an effect, the reaction is related to the detention of motionless air as close to the skin surface as possible. The air near the skin can be an additional insulation layer for the clothed body, as the thermal resistance of the air is almost twice higher than the thermal resistance of the natural fibers, for example, used in textile and clothing production.

The skeletal muscles are triggered to shivering: a spontaneous movement of the muscles, aiming to increase the heat production. This reaction to the cold is temporary and depends on the glycogen, the “fuel” of the muscles. The glycogen depletion stops the heat production by shivering.

The signals from the hypothalamus to the thyroid and adrenal glands have to increase the metabolism, which is another source of heat production for the body. The metabolic reactions are performed on a cell level.

2.3. Body reactions to cold

Despite its complex and sensitive mechanism for thermoregulation, the human body is coping with the aggressive impact of the environment in a relatively narrow range. The decrement of the core body temperature has an adverse effect on the function of the body and can lead to severe disability and even death.

Out of these threats, however, even in cases, when the protective mechanisms of the body are sufficiently effective and thermoregulatory processes are able to maintain the core body temperature at about 37°C, the cold environment can cause a sequence of events, associated with the so-called thermal discomfort (**Figure 4**). The low environmental temperature causes delay in reaction time, fatigue, and increased sleepiness of the individual [11].

These effects are, to their nature, pure physiological processes, i.e., the accelerated heart rate causes fatigue, and the lack of irrigation in the brain tissue causes sleepiness. All these can result in a larger number of subjective errors, compared to the occupational activities in thermal comfort environment (20–22°C).

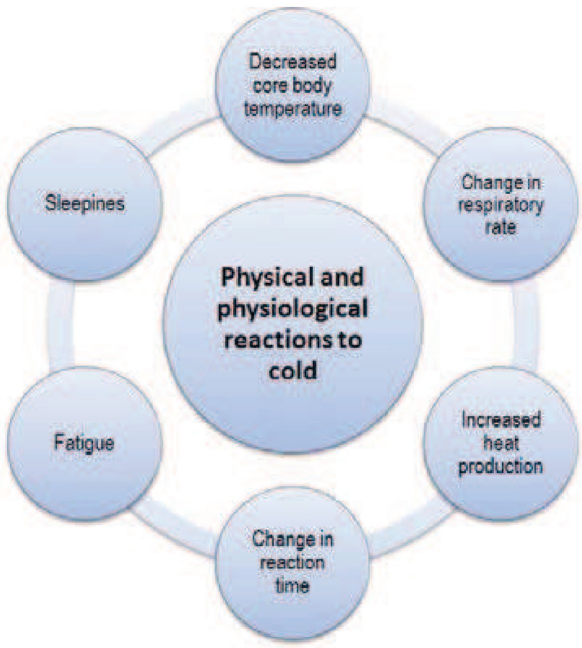

Figure 4. Body's reactions to cold environment.

3. Particularities of working in cold environments: natural vs. artificial cold

The work in natural and artificial cold has very similar features: in both cases the impact of the low and sub-zero temperatures could be dangerous for the human body. However, the majority of the workplaces in the cold are related to an outdoor exposure [12]. In winter time, in mountain, arctic and subarctic regions, different logistic activities for the society (road maintenance, transport) involve cold exposure. Tourism and winter sports also are associated with occupational activities that require cold exposure. Different industries like construction industry, fishery, farming, reindeer breeding, mining, metallurgy, forestry, horticulture, etc. involve work in outdoor conditions with low temperatures. In Sweden over 30% of the employed persons, for example, work in cold conditions repeatedly, for shorter or longer time [13].

The artificial cold workplaces can be found mainly in the food industry and fishery. Fresh food is usually preserved at a temperature below 6°C; frozen food is handled and stored at a temperature around −25°C. The work in food processing departments of big supermarkets is also related to cold exposure. It is reported that cold-related diseases and discomfort complaints are more frequently observed among workers, exposed to artificial than to outdoor cold [14, 15].

In any case, to protect the human body from the cold-related hazards, workers must be provided with protective clothing during their cold exposure. The comparison between the occupational activities in natural and artificial cold shows, however, some differences, which influence the thermophysiological comfort of the workers.

On the first place, the indoor, artificial cold, is more stable in temperature, air velocity, and humidity fluctuations, which is preconditioned by the application of systems for chilling and air conditioning. This helps the proper selection of protective clothing, which does not need changing during the exposure. In the natural cold environment, the air temperature changes during the 24-hour period. This requires the use of clothing, which allows adding or removing of layers within some limits, in order to protect the worker from overheating or freezing.

In addition, the climate conditions have to be considered together with the geographical features: activities in mountain regions (road construction, logging, tourism) increase the negative effect of the low temperatures and the solar load; activities in the flatlands or seas (agriculture, fishing, oil platforms) increase the severity of the wind effect.

In the food processing industry, static work is frequently observed. Some outdoor activities (transportation or work with heavy machinery) also require a sitting posture of the worker, but it is performed in the protective indoor environment of the vehicle (track, bulldozer, etc.). In any case the immobility of the body in cold environment is harmful and has to be avoided. Protective gloves and boots must be used, but they cannot replace the need of blood circulation in the extremities. At the same time, indoor cold work may require fine motor skills activities, which is in contradiction with the application of heavy protective gloves and mittens.

Another difference between the occupational activities in artificial and natural cold is that workers in an artificial cold environment move more frequently between colder and warmer environment. The temperature difference provokes higher strain on the thermoregulatory system of the body. At the same time, continuous cold air flows in the artificial cold facilities lead to appearance of body temperature asymmetry (asymmetric cooling), which adds to the thermal discomfort of the workers.

Last but not least, the protective clothing in an artificial cold environment may need to combine different protective abilities, i.e., against chemical or mechanical hazards, because of the occupational safety regulations.

4. Cold-related injuries

Cold-related injuries may occur in any environment, which temperature is around the freezing temperature. However, the thermoregulatory reactions to cold start at any air temperature, which is below the temperature of the body, and signals for cold are received by the cold sensors in the skin. Hypothermia may occur even in deserts if it is preconditioned by the body state and environmental conditions.

The major injuries, related to cold exposure, are frostbite, trench foot, immersion foot, hypothermia, and cold allergy. The reactions of the thermoregulatory system against the cold start when the core body temperature decreases below 37°C (**Figure 5**). The shivering, which is a way for heat production, reaches its peak at 35°C [16]. Below this temperature the body starts to demonstrate signs of hypothermia. At a temperature of 34°C, muscle rigidity appears, and the person is not anymore able to perform manual operations due to a loss of manual dexterity [17]. At 32°C the consciousness is clouded and around 30°C it is lost. If the core body temperature decreases below 30°C, the risk of death becomes extremely high if the cold exposure continues. The data from [16] show that cardiac arrhythmia appears at 29°C, and at 27°C the person appears dead. The drop of the core body temperature to 24°C leads to the development of pulmonary edema, and around 20°C the heart stops beating. However, it has to be mentioned that the lowest core body temperature, from which a person has been recovered, is 18°C [16].

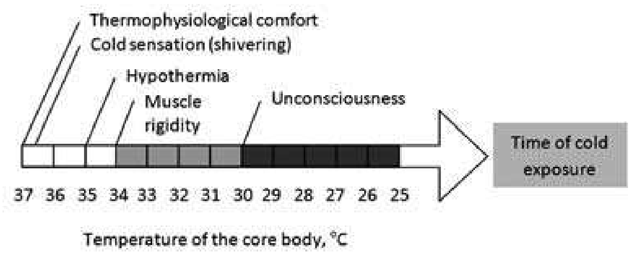

Figure 5. Effect of the time of cold exposure on core body temperature and hypothermia.

Frostbite is an injury that affects mainly the extremities in the cold, especially fingers and toes, as well as unprotected parts of the face (nose, lips, ears). It appears due to the crystallization of the liquids in the cells of the skin and deeper tissues of the body shell. The severity of the injury depends on the speed of freezing. Temperatures below 0°C and low relative humidity of the air precondition the appearance of frostbite.

Trench foot and immersion foot are classified as a nonfreezing cold injury [16]. Trench foot may appear at temperatures above 0°C and high relative humidity of the air. Its severity depends on the time of cold exposure. Immersion foot occurs as a result of prolonged static work in upright posture or as a consequence of immobilization of the extremities. It is related with wet environment, including cold water exposure.

Hypothermia appears after prolonged cold stimulus, but other environmental factors like wind, contact with cold objects, or immersion in water can favor it. Three types of hypothermia are classified in [18]: primary, secondary, and clinically induced (the last being out of the scope of cold-related injuries).

Primary hypothermia is diagnosed when the thermoregulation responses to the cold exist, but they cannot beat the symptoms of hypothermia. Primary hypothermia can appear in any cold environment, when the low temperature overwhelms the body thermoregulatory system.

Secondary hypothermia differs from the primary as the thermoregulatory reactions of the body are impaired [17]. Symptoms of hypothermia appear again, but their severity is not proportional to the cold induced. Secondary hypothermia is due to additional peculiarities of human physical or physiological state: fatigue, illness, or injury. Insufficient clothing insulation, poor nutrition or dehydration, and short sleep are also reasons for secondary hypothermia. The onset of the secondary hypothermia can hardly be predicted, being dependent of several factors: clothing insulation, metabolic rate, body size, nutrition status, hydration, and physiological and even psychological status.

Cold allergy, expressed in red and itchy pimples on uncovered skin, exposed to cold air, is also frequently observed as cold injury. It usually disappears after warming. Severe cases of cold allergy are associated with fever, seizures, fever, increment of the heartbeat, and swelling of the torso or extremities.

5. Textiles and clothing for protection from cold

Clothing plays the role of a passive insulation layer between the body and the environment. Both the textile layers and the layers of air between them in the clothing system perform this role. The adjustment of the passive insulation to the changing thermal conditions of the environment may be done through adding or removing textile layers. However, sometimes this is not possible to be done, or the textile layers, necessary to guarantee the body thermal comfort, are so thick that the movements will be limited.

The textiles, in the form of layers in clothing garments, headwear, handwear, or footwear, are of crucial importance for the survival and healthy work of people in the cold environment, as they are the only barrier between the human body and the cold. The ability of the textile layers to transfer the moisture from the body to the environment, while keeping the heat next to the skin and preventing the moisture transfer from the surroundings to the body, determines to a great extent the thermophysiological comfort of humans in the cold [19].

The main aim of the cold protective clothing is to entrap as much as possible air between the textile layers; at the same time, the clothing ensemble has to be as light as possible to assure proper activities and unimpeded movements. Therefore, different layers of clothing have to be worn—besides the better air encapsulation, the number of layers gives the advantage to remove one or more of them if the body’s heat production increases (during activity) or the solar radiation heats the body in outdoor conditions.

At least three layers of loose-fitting clothing must be worn [19]. The inner, closer to the body layer, is usually made of polyester, polypropylene, or other synthetic fibers that draw moisture

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away from the skin and keep it dry. The middle layer is the most insulating one; it is made of down, wool, nonwoven webs of synthetic fibers, etc. and holds the body's heat. The outer layer aims to protect the body from wind and precipitation; it is made of "breathable" waterproof fabrics that allow some ventilation (like Gore-Tex® or polyamide). This layer may frequently need to be resistant to oil, fire, chemicals, or abrasion.

The fitting of each clothing item in the ensemble is extremely important. The tight clothes may press the body tissues and decrease the blood flow, thus increasing the risk of cold injuries. Any additional layer(s) of clothing should be large enough not to compress the inner layers and decrease the insulation properties due to omitting the insulating air layer between two consecutive textile layers.

Proper selection of footwear and handwear has to be done to prevent hands and feet from the cold. Mittens are better solution than gloves, as four of the fingers share one and the same "thermal environment," but gloves are needed if hands' finer movements are a key to the performed activity in the cold. The head has to be obligatory protected by a cap, as the heat may be seriously lost through the head to the environment when the other parts of the body are well insulated. The chicks and nose may be protected from the cold by a mask. In case of obligatory use of a helmet, a wool knit cap has to be worn beneath.

Insulated boots with removable felt liners are mostly used for protection in the cold. The liners and the socks are an important part of the footwear. They have to be kept dry so as to perform best in the cold environment as an insulating layer. Inner socks, made of polypropylene that helps keep feet dry and warm, are best to be combined with outer thicker socks. The boot liners have to be removed daily for complete drying. The socks have to be also changed if they get wet or damp.

The incorporation of phase change materials (PCMs) in textiles for cold protection adds an active thermal insulation effect to the passive insulation, performed by the clothing [20]. PCMs, applied in cold protective clothing, are mostly paraffins from different types, used in several combinations. PCMs can experience the process of change from one state to another, i.e., from liquid to solid and back; thus, they are able to absorb, store, or discharge heat, following the fluctuations of the surrounding temperature.

The paraffin is incorporated into microcapsules, which has to prevent its dissolution during the liquid phase. Outlast Technologies Inc., which is the leader in production of textiles with PCMs, have developed Thermocules microcapsules, which can be added in the structure of the synthetic fibers in the wet spinning process or can be incorporated in flat textiles (woven, knitted, and nonwoven) as part of surface coating.

Classical cold wear garments can hardly ensure the thermophysiological comfort of the body in extreme cold conditions for a long time. The application of PCMs can help the process of avoiding thermal stress and hypothermia during occupational activities, thus increasing the work performance under high thermal stress.

Heated clothing and accessories are an alternative of the classical cold protective clothing. They are wired and use different technologies to provide warmth to the body parts that need it with priority: core body, feet, and hands.

The Microwire™ technology of Gerbing uses thin conductive filaments, coated with Teflon® that form heating panels, incorporated in clothing items. In jackets the panels are placed on the back, chests, and collar. Incorporated in gloves, the Microwire™ heating panels help sustaining the finer finger movements as long as possible. PrimaLoft® microfibers are applied for insulation, while a breathable Aquatex™ membrane assures the waterproofness of the system. A heating panel can reach a temperature of 57–63°C, powered by a 7 V or 12 V batteries. Wireless heat control can be used, adjusted by a smart phone application.

Smart clothing for cold protection is also produced by Venture Heat: heated jackets, gloves, and basic line shirts and pants. The incorporated heating panels are made of micro-alloy fibers, powered by rechargeable Li-ion battery. Highly breathable layers from inside and breathable waterproof layers from outside the heating panels are used to assure the body's thermophysiological comfort. The heated gloves of Venture Heat can protect the hands from the cold up to 5 h, depending on the temperature, the applied heating power, and the body's activity. A heated scarf, which can be added to the clothing ensemble, may ensure cold protection from 2 to 6 h. The scarf is made of 100% polyester fibers, and a carbon fiber heating source is placed at the center of the scarf (in the neck zone).

The heated jacket of Flexwarm uses a technology that can add to the efforts of the body's thermoregulatory system to ensure the thermophysiological comfort. Two types of sensors are placed in the jacket: sensors that control the temperature of the body and sensors that detect the temperature of the surrounding air. The heating panels can be separately controlled. Their thickness is equal to the thickness of cotton fabrics, 0.5 mm. The wearer can control the temperature of the panels, which can be heated up to 65°C. Due to the flexible Flexwarm® heating layer, the cold protection garments can be rolled or twisted without a risk of damage.

6. Management of the occupational activities in the cold

The International Standard ISO 15743 [21] deals with the risk assessment and management in a cold environment. It gives both theory and practical tools (checklists, guidelines, examples) to manage the occupational activities in the cold, minimizing the risk of appearance of cold-related injuries. The International Standard ISO 12894 [22] gives details and recommendations on the medical supervision of people, exposed to extreme cold.

The management of the occupational activities in a cold environment helps people to perform their work. Preliminary and regular screening, made by professionals in occupational health, helps to avoid the risk of cold-related injuries due to health limitations of the workers or accumulation of cold strain. Information and training of the workers for activities in a cold environment are inseparable parts of their occupational training. All employees of the company/organization, carrying out activities in the cold, should be trained to identify, access, and manage the risks at work, related to the cold exposure [21].

There are three groups of factors, which are important for the management of the occupational activities in the cold:

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- Environmental factors: air temperature, air humidity and wind speed
- Individual factors: activity and cold protective clothing
- Organizational factors: work-rest schedule and adequate shelter

Actually, the second and the third groups of factors have to counterbalance the environmental factors, so as to minimize the cold-related health problems of the workers.

One of the approaches to estimate the severity of the environmental factors is to assess the windchill temperature. It is very appropriate for application in outdoor environment and indoor freezers with fast-moving cold air [23]. The wind speed increases the effect of the low ambient temperature, and the cold, felt by humans, is stronger than supposed for the given air temperature.

The International Standard ISO 11079 [24] gives a tool for designing and management of the activities in cold environments. It defines required clothing insulation (IREQ) index, which allows to predict the necessary clothing insulation to protect the human body in a given cold environment, assessing all environmental factors together with the activity. The IREQ index determined the cold stress at two levels: neutral, which corresponds to the thermophysiological comfort of the human body, and minimal, related to the situation when cold strain already appears, the body is constantly cooling, but the thermoregulatory system of the body still can react and maintain the core body temperature within the desired limits.

Activity is very important in a cold environment, as it produces the necessary heat for warming the core body. However, the contact with cold surfaces increases the heat losses from the body: these can be either handling materials or tools or work in a sitting or kneeling posture on cold surfaces. The exposure to wet environment or precipitation increases the heat losses through the clothing layers as they lose their insulation abilities faster when wet. The inside clothing items and especially the underwear to stay dry during the cold exposure is therefore important: an overheating of the body due to activity in the cold may be likewise dangerous.

The duration of the cold exposure is of crucial importance for the seamless occupational activities in the cold. The American Conference of Governmental Industrial Hygienists (ACGIH) has adopted a schedule for periods of work and breaks, developed by the Saskatchewan Department of Labor in Canada [25]. However, the “work warm-up schedule” is based on the environmental factors only and does not account with the individual factors (clothing and activity). The International Standard ISO 11079 [24] introduces the Duration of Limited Exposure index, which allows to calculate the time of the cold exposure, based on the environmental and personal factors. The Recovery Time index is used to predict the time needed for sheltering, which is enough for the body to warm up before continuing the cold exposure.

7. Conclusions

A number of occupations involve substantial exposure to cold environment, natural or artificial. Working in the cold is related to many adverse effects for the human body, health, and productivity. The knowledge about the thermoregulatory reactions of the body in a cold environment and the associated risks of thermal discomfort, cold strain, and injuries helps workers and employers to make a stand against the cold. The selection of the proper insulating clothing, maintenance of continuous activity, and regular shelter for heating the body are the keys to the comprehensive management strategy for protection of people during occupational activities in the cold.

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