

NR 2003:4

Human responses to cold and wind

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ARBETE OCH HÄLSA | VETENSKAPLIG SKRIFTSERIE

ISBN 91-7045-669-0 ISSN 0346-7821



Arbetslivsinstitutet
National Institute for Working Life

Arbete och Hälsa

Arbete och Hälsa (Work and Health) is a scientific report series published by the National Institute for Working Life. The series presents research by the Institute's own researchers as well as by others, both within and outside of Sweden. The series publishes scientific original works, dissertations, criteria documents and literature surveys.

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ARBETE OCH HÄLSA

Editor-in-chief: Staffan Marklund

Co-editors: Anders Kjellberg, Birgitta Meding, Bo Melin, Gunnar Rosén and Ewa Wigaeus Tornqvist

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National Institute for Working Life
S-113 91 Stockholm
Sweden

ISBN 91-7045-669-0
ISSN 0346-7821
<http://www.niwl.se/>
Elanders Gotab, Stockholm

List of papers

This thesis for a doctor's degree is based on the following papers referred to by numbers.

- I. Gavhed, D, Holmér, I. Thermal responses at three low ambient temperatures - validation of the Duration Limited Exposure index. *International Journal of Industrial Ergonomics* 1998; 21, 465-474.
- II. Gavhed, D, Mäkinen, T, Holmér, I and Rintamäki, H. Face temperature and cardiorespiratory responses to wind in thermoneutral and cool subjects exposed to -10 °C. *European Journal of Applied Physiology* 2000; 83, 449-456.
- III. Mäkinen T, Gavhed D, Holmér I, Rintamäki H. Effects of metabolic rate on thermal responses at different air velocities in -10 °C. *Comparative Biochemistry and Physiology* 2001; Part A: 759-768.
- IV. Gavhed, D, Mäkinen, T, Holmér, I, and Rintamäki, H. Face cooling by cold wind in walking subjects. *International Journal of Biometeorology*, *in press*.
- V. Gavhed, D, Mäkinen, T, Holmér, I and Rintamäki, H. Effects of cold, wind and light exercise on cardiovascular responses. *Submitted*.
- VI. Gavhed, D, Ohlsson, G, Holmér, I. Face cooling and cardiovascular responses to wind at -10 °C. *Submitted*.

Paper I was reprinted with kind permission from the publisher Elsevier in the Netherlands.

Paper II and III were reprinted with kind permission from the publisher Springer Verlag, Heidelberg, Germany.

Papers IV-VI were reprinted as manuscripts.

Abbreviations and definitions

A_b	the total surface area of a nude person, m^2
C	convective heat flow, the heat exchange by convection between the boundary surface (clothing or skin) and the environment ($W \cdot m^{-2}$)
CIVD	Cold-induced vasodilatation
DLE	Duration Limited Exposure, the recommended maximum time of exposure. (min, (h)) with available or selected clothing
$DLE_{neutral}$	DLE calculated for defined criteria (low strain)
DLE_{min}	DLE calculated for defined criteria (high strain)
E_{res}	evaporative heat loss from the respiratory tract to the environment ($W \cdot m^{-2}$)
f_{cl}	clothing area factor, the ratio between the surface area of the clothed body, including unclothed parts, and the surface of the nude body (ND)
HR	heart rate ($beats \cdot min^{-1}$)
H_{res}	respiratory heat loss, the non-evaporative and evaporative heat loss from the respiratory tract to the environment ($W \cdot m^{-2}$)
h_c	convective heat transfer coefficient, the net dry heat transfer per unit area between a surface and a moving medium per unit temperature difference between the surface and the medium ($W \cdot m^{-2} \cdot K^{-1}$)
h_r	radiative heat transfer coefficient, the net rate of heat transfer per unit area by radiation between two surfaces, per unit temperature difference between the surfaces ($W \cdot m^{-2} \cdot K^{-1}$)
h	total heat transfer coefficient, the ratio of total heat transfer per unit area by radiation, convection and conduction to the temperature difference between the surface and operative temperature of the environment ($W \cdot m^{-2} \cdot K^{-1}$)
I_a	boundary layer thermal insulation, the thermal resistance at the outer boundary (skin or clothing) for the whole body (clo, $m^2 \cdot K \cdot W^{-1}$)
I_{cl}	the basic clothing insulation, that is the resistance of a uniform layer of insulation covering the entire body that has the same effect on sensible heat flow as the actual clothing under standardized (static, wind-still) conditions (clo, $m^2 \cdot K \cdot W^{-1}$)
$IREQ$	required clothing insulation, the resultant clothing insulation required during the actual environmental conditions to maintain the body in a state of thermal equilibrium at acceptable levels of body and skin temperatures, an index of cold stress (clo, $m^2 \cdot K \cdot W^{-1}$)

$IREQ_{neutral}$	neutral required clothing insulation, the clothing thermal insulation required to provide conditions of thermal neutrality, i.e. thermal equilibrium maintained at a normal level of mean body temperature. This level represents none or minimal cooling of the human body (low cold strain) (clo, $m^2 \cdot K \cdot W^{-1}$)
$IREQ_{min}$	minimal clothing insulation required to maintain body thermal equilibrium at a subnormal level of mean body temperature. This level represents a defined body cooling (high cold strain criteria) (clo, $m^2 \cdot K \cdot W^{-1}$)
I_T	total insulation, the total equivalent uniform thermal resistance between the body and the environment under standardised (static, wind-still) conditions (clo, $m^2 \cdot K \cdot W^{-1}$)
I_{Tr}	total thermal resistance between the body and the environment under dynamic conditions (clo, $m^2 \cdot K \cdot W^{-1}$)
M	metabolic rate, the rate of transformation of chemical energy into heat and mechanical work by aerobic and anaerobic metabolic activities within an organism, expressed in terms of unit area of the body surface ($W \cdot m^{-2}$)
M_h	rate of metabolic heat production ($M-W$) ($W \cdot m^{-2}$)
p	air permeability of clothing ($l \cdot m^{-2} \cdot s^{-1}$)
$P_{w,ex}$	water vapour pressure in expired air (kPa)
$P_{w,a}$	water vapour pressure in ambient air (kPa)
Q	body heat gain or loss, the increase (+) or decrease (-) in the heat content of the body caused by an imbalance between heat production and heat loss, expressed in terms of unit area of total body surfaces ($Wh \cdot m^{-2}$)
Q_{lim}	limit value of body heat loss ($Wh \cdot m^{-2}$)
R	radiative heat flow, the heat loss by radiation from the boundary surface (clothing or skin) to the environment ($W \cdot m^{-2}$)
RQ	respiratory quotient, the ratio of carbon dioxide production to oxygen consumption as measured from analysis of expired gases (ND)
t_a	air temperature, the dry-bulb temperature of the air surrounding the occupant ($^{\circ}C$)
t_{ex}	expired air temperature ($^{\circ}C$)
t_{nose}	local nose skin temperature
$t_{forehead}$	local forehead skin temperature
t_{cheek}	local cheek skin temperature
t_{ear}	local ear skin temperature
t_{chin}	local chin skin temperature
t_{sk}	mean skin temperature, averaged from 10-14 sites distributed on the body ($^{\circ}C$)
t_{re}	rectal temperature ($^{\circ}C$)

TPR	total peripheral resistance
T_{pref}	preferred ambient temperature
TS	thermal sensation of whole body
V_{O_2}	oxygen consumption, the rate at which the body consumes oxygen ($l\ O_2 \cdot \text{min}^{-1}$)
w	skin wettedness, the equivalent fraction of the skin surfaces which can be considered as fully wet (ND)
WCI	Wind Chill Index, the rate of heat loss from an unprotected skin surface area ($W \cdot m^{-2}$)
v_a	average velocity of the air ($m \cdot s^{-1}$)
v_{walk}	walking speed ($m \cdot s^{-1}$)
W	effective mechanical power, the energy spent in overcoming external mechanical forces on the body ($W \cdot m^{-2}$)
W_b	body mass (kg)

Codes for the experimental conditions

CO	Preconditioning in cold, $-5\ ^\circ\text{C}$, giving <i>cool</i> sensations
LOW	“ <i>Low</i> intensity”: walking on the level at $2.8\ \text{km} \cdot \text{h}^{-1}$ at air temperature $-10\ ^\circ\text{C}$
LOW0	LOW and $0.2\ \text{m} \cdot \text{s}^{-1}$ air velocity
LOW1	LOW and $1.0\ \text{m} \cdot \text{s}^{-1}$ air velocity
LOW5	LOW and $5.0\ \text{m} \cdot \text{s}^{-1}$ air velocity
MOD	“ <i>Moderate</i> intensity”: walking at $2.8\ \text{km} \cdot \text{h}^{-1}$ 6° uphill at air temperature $-10\ ^\circ\text{C}$
MOD0	MOD and $0.2\ \text{m} \cdot \text{s}^{-1}$ air velocity
MOD1	MOD and $1.0\ \text{m} \cdot \text{s}^{-1}$ air velocity
MOD5	MOD and $5.0\ \text{m} \cdot \text{s}^{-1}$ air velocity
SIT BARE	<i>Sitting</i> at $-10\ ^\circ\text{C}$ without hat
SIT BARE2	SIT BARE and $2.0\ \text{m} \cdot \text{s}^{-1}$ air velocity
SIT BARE4	SIT BARE and $4.0\ \text{m} \cdot \text{s}^{-1}$ air velocity
SIT BARE6	SIT BARE and $6.0\ \text{m} \cdot \text{s}^{-1}$ air velocity
SIT HAT6	<i>Sitting</i> at $-10\ ^\circ\text{C}$ with winter hat and $6.0\ \text{m} \cdot \text{s}^{-1}$ air velocity
ST	<i>Standing</i> at air temperature $-10\ ^\circ\text{C}$
TN	Preconditioning at normal temperature, $+20\ ^\circ\text{C}$, giving <i>thermoneutral</i> sensations

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Introduction

Cold can be uncomfortable, distracting, incapacitating and dangerous. Cold is also a risk factor for a number of diseases. Numerous scientists and adventurers on expeditions in cold environments have been defeated by cold and wind during their struggle to make new discoveries. Many military manoeuvres have failed due to cold, one of the most disastrous being the trial of the Swedish carolines to take Trondheim during the winter of 1718. About 3,700 men died, unable to protect themselves in the cold strong winds. Recently, in 2000, an experienced Swedish adventurer had to stop a ski expedition from Severnaja Zemlja in the Arctic Ocean to the North Pole and leave for hospital treatment of a cold injury.

More than 3.5 millions of people living above the Arctic circle and an additional number in subarctic regions have to handle problems with cold and wind every day. Many of them are exposed to cold only occasionally, especially those living in urban areas, while others spend long time in cold conditions more frequently. During the winter season several workers are exposed to cold and wind for many hours a day. About 350,000 people in Sweden are exposed to cold for more than 50% of their working time (64). Among common occupational activities performed in cold environments are construction work, repair and maintenance. Moreover, cold store workers are exposed to low air temperatures, commonly $-25\text{ }^{\circ}\text{C}$, the whole year around. The average occupational cold exposure time in Finland has been reported to be about five hours per day (64). During leisure time average cold exposure was one hour on weekdays and two hours on weekends or vacation (64). Other outdoor activities at which people at times are exposed to cold are military activities, winter sports and recreation activities, such as hunting and ski touring. Increasing numbers of people spend their winter holiday in cold areas and more participate in “adventure” activities related to snow and ice. It is easier today for inexperienced people to access cold areas than before, due to the development of snow mobiles and helicopter transportation, which increases the number and risk for cold injuries.

Cold adds to other physical and mental loads on the individual at work. The reasons for the additional load are both of physiological and physical origin. The bulkiness of cold-protective clothing both increases the energy consumption and restricts the body movements. Low tissue temperature impairs the nerve-motor function. Finally, cold sensations are very unpleasant and may distract and disturb the worker.

Cold stress can be general and/or local. If the body is exposed to cold and the cold protection is insufficient, body temperatures will decrease, starting with peripheral parts of the body and gradually progressing to deeper tissues and the body core. When the body core is less than $35\text{ }^{\circ}\text{C}$, it is defined as hypothermia. Hypothermia is rare at occupational work, since the work is commonly done under controlled situations. Some work, such as surveillance, implies inactivity with low heat production and may lead to low body temperature. Another example of a difficult work arena is rescue work in the arctic regions, in which the conditions may be difficult to control.

Most cases of hypothermia occur during recreational exposure to cold and many cases occur every year in connection with accidents. Even in homes with low indoor temperature elderly people may suffer from hypothermia.

Local cold stress is predominant at cold exposure and frostbite is most common in peripheral parts of the body, especially fingers, toes, nose and ears. The skin blood flow in these areas becomes very low when blood vessels constrict due to a temperature decrease. Heat supply to the hands, fingers, feet, toes, face and ears reduces accordingly, accelerating the cooling process. The temperature of the skin approaches the ambient temperature. At subzero temperatures the tissue may freeze. Frostbite is a local injury that may have serious consequences. It forces the victim to interrupt his/her activities and may also lead to troublesome sequelae (63). The total number of frostbite victims in Sweden has not been reported. However, the Swedish military force reports about 150 cold injuries yearly. In Finland 4-68% of the adults (depending on latitude of residency, age and occupation) have had frostbite at least once (63), the highest incidence reported being among reindeer herders. A recent investigation on admissions to hospital in Finland reported an annual incidence of frostbite to be 2.5 per 100,000 (94). The risk of frostbite is increased by wind, which carries heat away from the skin rapidly by convection. This is especially evident when the skin is unprotected. At tissue temperatures above freezing highly undesirable effects of cold, which are not compatible with occupational work may be present. Already at hand and finger temperatures of about 20 °C manual dexterity may be affected (74) and pain may be experienced (35).

It is both desirable and necessary to prevent cold stress. For this purpose a number of indices have been developed. The most used methods to assess the risks of cold work are a cold stress index for general body cooling, IREQ/DLE (Insulation required/Duration limited exposure) and a local cold stress index, WCI (Wind Chill Index). If the clothing insulation provided is insufficient for the actual conditions the DLE, can be calculated to limit the cold exposure. Experimental data that validate DLE and WCI are limited. WCI is mainly based on physical experiments, which were supplemented with a small number of field experiments on humans. The use and validity of WCI has recently been extensively discussed.

This thesis will examine the physiological and subjective responses at the risk limits for cold and wind exposure in the currently used cold indices and will have both physiological and occupational hygiene aspects. The physiological focus will be on the skin temperature and cardiovascular responses, which may lead to cold injury and cardiovascular health problems. The other dominating part is the validity of the cold indices used for occupational risk assessment.

Aim

The aim of the thesis was

- to increase the knowledge about the effects of cold and wind on human thermal, physiological and subjective responses during rest and exercise,
- to validate the prediction models for cold work, Insulation Required/Duration limited exposure (IREQ/DLE) and Wind Chill Index (WCI) and
- to investigate the specific criteria for setting limit values for cold occupational work.

The specific purposes of Paper I was

- to test the validity of the DLE calculation of ISO TR 11079 with subjects walking at low intensity at subzero temperatures and
- to examine the subjective and physiological effects at these conditions.

The specific purposes of Paper II, IV, V and VI was

- to examine the effects of cold wind at an air velocity just below and clearly below frostbite risk level according to the Wind Chill Index,
- to examine the combined effects of physical activity and wind on face, skin and body temperature, cardiovascular, respiratory (only Paper II) and subjective responses of healthy subjects,
- to study the heat balance in cold wind (Paper III) and
- to investigate if headgear may change the thermal and physiological responses (Paper VI) to wind.

Background

The temperature-regulating system

The temperature-regulating system may be divided into temperature sensors and afferent neural pathways, integration of thermal inputs, and effector pathways for autonomic and behavioural regulation.

The body (core) temperature is regulated within a narrow range around 37 °C in order to maintain optimal physiological function. The control function is similar to a thermostat, but the target value for the thermostat is probably better described as a temperature interval, which may shift slightly upwards and downwards, widen and narrow depending on diurnal variation, ovulation in women and other factors, such as exercise and fever. Outside the interthreshold range (the temperature between the sweating and vasoconstriction thresholds), which is only a few tenths of a degree at rest, thermoregulatory responses are elicited (119).

Thermal reception

The skin is innervated with around a million afferent nerve fibres. They are part of the sensory system and vasomotor action. The cutaneous nerves contain axons with cell bodies in the dorsal root ganglia. Most terminate in the face and extremities.

Numerous thermoreceptors, located in the skin and in deeper tissues (91), provide the thermoregulatory centre with peripheral information.

The receptors for temperature and pain are free nerve endings. They appear to be derived from non-myelinated fibres and occur in the superficial dermis and in the overlying epidermis. There are both heat and cold sensitive receptors, which fire at different temperature intervals. At constant temperature the receptors have a static discharge and a dynamic response to temperature changes (73). The discharge pattern of the cold fibre is characterised by large onset and quick decay (quick adaptation). Cold fibres discharge from an approximate temperature of 10 °C, (see (72)). Specific cold fibres (153) and various cutaneous cold-receptor populations (see (72) fire maximally between 25-30 °C and above 45 °C. Above approximately 45 °C paradoxical discharge of cold fibres occurs. It may also be mentioned that there are slow-adapting mechanoreceptors which are cold-sensitive. Neurons in the trigeminal nucleus respond to both temperature and mechanical stimuli (72), but the role of the specific cold sensitivity of the mechanoreceptors is not known.

The hypothalamic thermoregulatory center contains neurons with specific temperature sensitivity (see (92)). Not only the preoptic anterior area contain thermosensitive neurons, but also ventromedial and posterior hypothalamus (83). Thermosensitive neurons have also been found along the internal carotid artery, the medulla oblongata and skeletal muscle (see (132)). They respond to changes in the blood temperature (72). The extra-hypothalamic thermosensitive neurons are able to sense and modulate thermal signals (16).

Afferent neural pathways

Afferent signals from peripheral and central thermoreceptors are transferred by neurons that collect in the anterior hypothalamus and in the reticular formation (22, 130). The signals of the cold receptors are mediated by A δ myelinated fibres. The nucleus raphe magnus and the subcoeruleus area appear to be important relay stations in the transmission of thermal information from skin to hypothalamus (12, 75). Thermosensitive afferent fibres from the face are connected to second-order neurons in the trigeminal nucleus of the medulla oblongata via the trigeminal ganglion. Thermoreceptive neurons in the trigeminal complex (Nervus caudalis) are predominantly cold neurons.

Integration of thermal inputs in the central nervous system

The dominant thermoregulatory controller of body (core) temperature and integrator of temperature signals is located in the preoptic region of the anterior hypothalamus in the central nervous system. The neurons carrying afferent signals collect in the anterior hypothalamus and in the reticular formation. The link between the sensory input and the effector output is complex and it is not clear how the signals are processed. However, there is experimental support for that thermal signals are partly integrated at several levels within the spinal cord and brain to provide a co-ordinated pattern of defence responses (see (186)).

Inhibitory and excitatory thermoregulatory neurons at many levels below the hypothalamus, which participate in thermoregulation, seem to exist. Modifications of the signals shift the thresholds and slopes for thermoregulatory responses (186). These responses include behavioural responses and autonomic responses such as sweating, vasodilatation, vasoconstriction and shivering.

Efferent signals

The efferent signals reach the effector system of thermoregulation, vascular smooth muscle in the blood vessels and skeletal muscle via alfa-motor neurons. The effector systems are described below under "Physiological effects of cold".

Perception of temperature and pain

Sensory spots in the skin from which electrical stimuli elicit thermal sensations were investigated most intensively between the years 1920-1950. The investigators reported that the number of cold spots in the face and nose were between 5.5 and 9.0 per cm² of skin, which is similar to many other body regions, but higher than in legs, feet and palm of the hand (73). Single specific fibres innervate one single spot in the skin (73). Receptive fields of the cold units are strictly ipsilateral, (sensed on the same side of the body as stimulated) (72). Bilateral cold stimulation shows spatial summation indicating neural integration of thermal afferents in the spinal cord (see (73)).

Cold sensations may appear both from cooling of the skin and from lowering of the body core temperature. All body regions are more sensitive to cold than to warm (171). Thermal sensitivity is highest in the face and lowest in the lower extremities (23, 171). However, in a study of suprathreshold cold sensitivity of different body

areas, low and moderate cold stimulation levels were estimated to feel least cold in the face than in other areas (170). High levels of cold were felt as nearly the same in all body regions. It is important to note that the degree of cold experience also depends much on the size of the stimulated area (169). The reaction time of a cold stimulus has been measured to be 334-660 ms (see (73)).

At skin temperatures below about 15 °C and over 45 °C, pain is experienced. Thermal sensations may be characterised as low-threshold responses, whereas pain a high threshold sensation. Cold signals and sharp, pricking pain are mediated by A δ thick myelinated fibres, whereas thin unmyelinated C fibres convey signals from warmth receptors and mediates slow burning pain. The fibre population is heterogeneous and convey different thermal information. Some fibre populations of nociceptive fibres respond both to intense mechanical and thermal stimuli, others are only thermally responsive, still others are low-threshold mechano-receptive fibres. The segregation of thermal and pain sensation is not clear.

Cold sensitivity (temperature threshold) of the face does not change much with age in contrast to some other body areas, e.g. toes and fingers (171). Chronic underperfusion of the thermal receptors has been put forward as an explanation for the decline of thermal sensitivity (171).

Physiological effects of cold

The major physiological protective mechanisms in cold are peripheral vasoconstriction and cold-induced thermogenesis by shivering. The most significant effects of cold and wind on humans and risks for diseases are illustrated in figure 1.

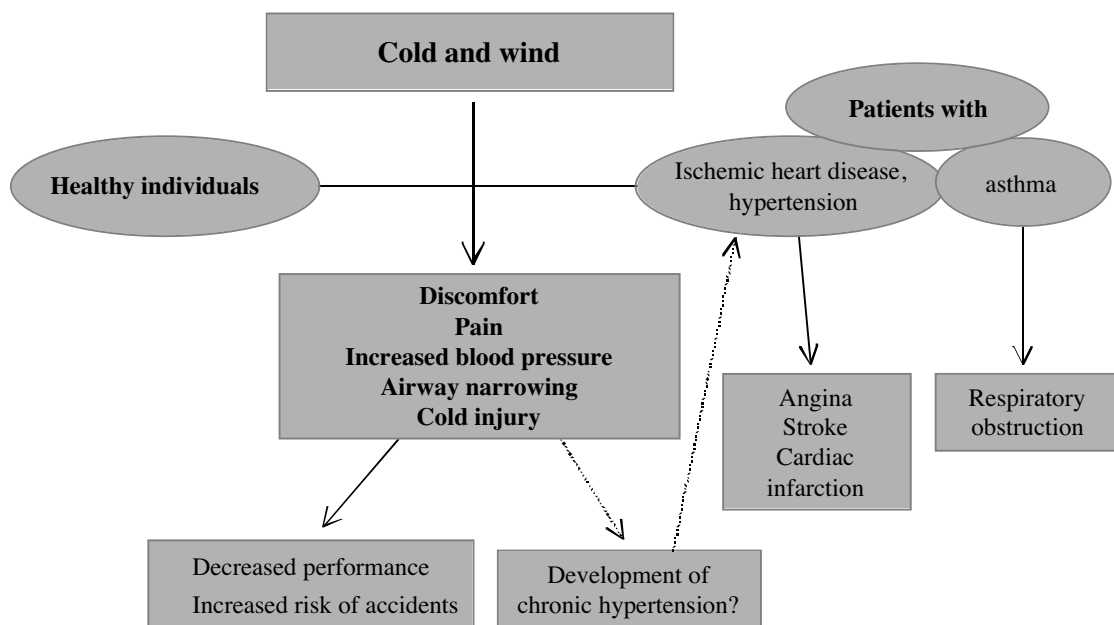


Figure 1. Established and possible (dashed lines) effects of cold and wind on human individuals.

Whole body effects

Cold stress is recognised in many ways (Figure 1). First a feeling of cold appears, then manual dexterity is reduced and may be lost, behaviour becomes unsafe, accidents may happen as a partial result of cooling and shivering may occur.

The accident rate has been reported to increase at cold ambient temperature compared to normal temperature (see (147)). Factors behind unsafe behaviour may include distraction from cold discomfort, cold pain and speeding up work to reduce the exposure time. The higher risk for accidents is also due to clumsiness, which may cause losing the grip and slipping.

Cold also affects locomotion. At low temperatures nerve and motor function (141) are impaired. Cooling slows the signal conduction in the nerves (177). Cold joints become stiff (20), which increases the resistance to movements. Muscle power, force and endurance are decreased by cold (141). The impaired nerve-motor function may have negative effects on work performance. Manual dexterity is the most apparent and important decrement of performance at work in the cold. The magnitude of impairment is influenced by body thermal state, cooling rate and type of task (36, 67). Slow cooling has been shown to have larger effect on performance than rapid cooling, probably because the temperature of deeper tissues becomes lower (17).

The energy cost of exercise is increased by 10-40% by a 0.5 to 1.5 °C decrease in core temperature, most likely due to lower mechanical efficiency (151). Multi-layer clothing systems further increase the energetic cost of body motion due to additional weight and friction (173) and restrict the range of movements.

Shivering is an involuntary response to reduced temperature of the preoptic area in the hypothalamus and/or peripheral temperature (see (70)). This defence mechanism is activated only when behavioural compensations and maximal arterio-venous shunt vasoconstriction are insufficient to maintain core temperature. The benefit of shivering is an increased heat production, up 5-6 times above basal level (see (53)), which may prevent further cooling. Alpha motoneurons are activated (71) and coordinated in an oscillatory mode (70). The core and peripheral stimuli for shivering onset work independently (see (117)). It is initiated at core temperature about 36 °C (12) and is maximal at 35 °C (62). Finally, if the thermoregulatory defence mechanisms are insufficient to maintain the body temperature steady above 35°C, hypothermia develops.

Cardiovascular responses

Increased blood pressure is associated with cold exposure. The total peripheral resistance (TPR) is increased in cold due to the skin vasoconstriction and at rest about 20% of the cardiac output is redistributed from the skin to more central part of the body. TPR may account for a great part of the pressure rise. In normal temperature baroreceptor reflexes are elicited in response to the increased venous return and bradycardia follows. The reflex bradycardia is of parasympathetic origin (176). Cold stimulation of the face at by convective and conductive cooling of the face has been shown to have the same effect, i.e. bradycardia, increase of blood pressure and increased peripheral resistance (18, 33, 69, 109, 110, 176). Bradycardia caused by cold

face test correlates well with that produced by the diving reflex (100). It is notable that total peripheral resistance and blood pressure does not increase in response to cold air blown on the abdomen (68).

Receptors in the nasal mucosa and face innervated by the trigeminal nerve initiate bradycardia and increase total peripheral resistance at cold stimulation (18). The ophthalmic division of the trigeminal nerve is the most sensitive pathway for eliciting the diving reflex and no additional effect of covering the whole face with ice packs were found (100). The forehead region has been shown to be the most sensitive area for cold induced bradycardia (165).

The peripheral vasoconstriction and venoconstriction in response to cold together result in an increase in end-diastolic volume and cardiac output (164). However, by inotropic adjustments (increase of contractility of the heart muscle) of the heart (stroke volume increased), cardiac output seemed to be maintained during exercise at cold exposure (see (151)).

Many observations on cardiovascular responses have been done with cold pressor tests on both healthy subjects and patients with cardiovascular diseases. Cold pressor tests are used to test the autonomic function of individuals. (28). The type of stimulation and protocols vary. In most cold pressor tests the hand or foot is immersed in cold water, but in some tests the face is exposed to wind or ice packs are applied to the face (4, 18, 100, 109, 148, 160). The cold stimulus at cold pressor tests is normally applied for only 30 s to 3 minutes and the test is performed with subjects at rest. Hence, a large part of the existing knowledge base on cardiovascular responses to cold stimuli is limited to the happenings of a few minutes. Differences between cold ice stimulation of hand and face have been shown. Stroke volume decreased and blood pressure increased during hand cooling in ice water, while stroke volume increased and blood pressure was unchanged during facial cooling with an ice bag (4). Moreover, the cold pressor response to the immersed hand or foot differs slightly from cold air stimulation of the face. It is evoked from peripheral cutaneous cold and/or pain receptors and leads to an increased muscle nerve sympathetic activity and tachycardia (18, 181). The role of the catecholamines at cold exposure is not clear. Most studies of plasma noradrenaline have shown increased levels (155) while others have observed different responses among the subjects (24) during cold stimulation of the hand or face.

In the normal living situation the face is exposed to cold air (or water in the case of diving). Thus, face cold stimulation is important to study. Few studies on face fanning at subzero temperature with simultaneous measurements of face temperature and cardiovascular responses longer than about 10 minutes have been reported. It is not clear from short experiments if the initial responses observed are short-term reflexes, if the responses last if the cold exposure continues or if there may be an initial response followed by a lasting response. Further, the importance of skin temperature on the cardiovascular responses has not been investigated. Studies of very short duration may show reflexes elicited by cold wind, but not reveal sustained effects as is important in occupational settings.

Respiration

Cold air blown on the skin or other cold stimulation of the face elicits reflex bronchoconstriction in both patients with respiratory diseases and in non-asthmatic subjects (101, 102, 126). Sensory receptors in the nasal cavity, pharynx, larynx, face and trunk may mediate these reflexes (see (52)). Cold also has direct effect on airway smooth muscle (108). At a lung ventilation rate of 60 l min⁻¹ (isocapnic hyperventilation at rest) at -17 °C, the airway temperature was shown to fall and the tracheal mucosal blood flow seemed to decrease (127). Further, a significant reduction of upper esophageal temperature has been observed in subjects breathing -40 °C air during moderate exercise (93). An increase of evaporative heat loss from the airways to the environment may contribute to the symptoms observed in asthmatics after breathing cold air. The air is capable to contain only very small amounts of water at low temperature. Saturated air contains 2.4 g water per m³ air at -10 °C, which is about 10% of the water content of air at body temperature. Inhaled air is humidified by evaporation from the mucosal surface. It is thus a probable risk that the mucosal osmolarity increases. Inhalation of nebulized hyperosmolar solutions has been shown to induce bronchospasm (see (52)). Inhalation of cold dry air would be a problem especially at higher lung ventilation rates in normal subjects and patients with respiratory diseases.

Cold diuresis

In addition to the mentioned effects of cold, the water balance is affected. With a cold-induced increase of systolic blood pressure, the renal artery perfusion pressure increases. A secondary rise in capillary pressure increases the hydrostatic gradient and results in a reduced sodium resorption. Sodium losses in the urine are accompanied by fluid losses (57).

Local effects

Peripheral skin circulation. Thermoregulatory vasoconstriction decreases cutaneous heat loss. The blood vessels of hands and feet are richly innervated by sympathetic fibres which may participate in an extensive restriction of the blood flow and heat supply to the hands, fingers, feet, toes, face and ears. The blood vessels of the extremities constrict when the body is cooled or/and skin is cooled locally (152). The sympathetic tone of the peripheral vessels is increased (164, 181). Both peripheral vasoconstriction and venoconstriction occur during exposure to cold air. (see (151)). The vasoconstriction response occurs by direct action of cold on the vessels (181) and by central or spinal cutaneous reflex vasoconstriction (152). The skin vasoconstriction in response to local cooling is mediated mainly via alfa-2-receptors in the blood vessel walls (34, 41, 187), but also to a smaller extent via alfa 1-receptors (60), while beta-2-receptors are not much involved in the mediation of skin vasoconstriction (159).

The decrease in limb blood flow begins at core temperature of 37.5 °C and is completed at 36 °C. Arteriovenous anastomoses, specialised shunt vessels, permit blood to be shunted directly from the arterial side to the venous vascular bed. The smooth muscles coating these structures are richly innervated by sympathetic fibres.

The size of arteriovenous anastomoses can be changed greatly according to the need. With a six-fold increase of diameter of the shunts at opening 1,000 times more blood could pass through the arteriovenous anastomoses per unit of time. In some skin areas the density of arteriovenous anastomoses is high. These are fingers, toes, ear lobes and nose (133).

As mentioned, frostbite may occur at low ambient temperature. The most vulnerable parts of the body in this respect are fingers, toes, face and ears. In some situations hands and fingers are unprotected, for example at outdoor repair/service work when the worker takes off the gloves to be able to better handle small details, such as screws and bolts. The face is commonly bare and therefore the frostbite risk here is high.

Face skin circulation. Rasch and Cabanac concluded that the face vessels (forehead, cheek and infraorbital area) were generally constricted during normothermia, since they did not further constrict at hypothermia (157). Blair failed to find skin temperature decrease in forehead, cheek, chest (part exposed to air) or ear during body cooling in a water bath of 18-19 °C, filled to the middle of the torso (xiphisternal level) and explained this by absent vasoconstriction, but large decreases in finger and nose were observed (9). With cutaneous nerve block, the ear temperature increased during body cooling. The vasoconstrictor tone in the ear was suggested to be near maximal already in normal conditions, but that the tone of the cheek skin vessels was not appreciable. Thus the control of skin blood flow seems to differ between the more extensively studied fingers and the less studied face.

Exercise in cold wind

At exercise onset, an increased sympathetic tone leads to a generalised vasoconstriction (164). The tachycardia that is observed at exercise onset is initially a result of withdrawal of vagal tone. After 10 to 30 seconds a strong sympathetic action follows (121, 123).

The ambient temperature in most studies of exercise and cold wind has most often been above 0 °C, but in combination with wind the cooling effect may have corresponded to calm conditions at subzero temperature. Furthermore, the exercise intensities used have been quite high in the published studies.

There is an interaction between cold and exercise stimuli. The bradycardic effect of trigeminal stimulation of the face is overcome by stronger inhibitory input during muscle contractions (3, 95). When the dynamic exercise level corresponds to 60-65% of maximal oxygen consumption, the depressor effect on the heart by face cooling is decreased and sympathetic activation dominates (33, 156). The heart rate may decrease down to 15 beats·min⁻¹ by cold facial ventilation at submaximal exercise (161), but the heart rate is not decreased at maximal levels (33). From these studies it seems that the sympathetic activity dominates during exercise, which eliminates bradycardia.

Heat balance and heat exchange

The metabolism of the body produces heat as a by-product to energy transformation and utilisation. The efficiency of muscular work in the human body spans from 0% to about 25%. The rest is converted to heat. The body loses heat by convection, radiation, conduction and evaporation. Convection is dependent on the temperature gradient between the body and the ambient air and is increased by wind. Radiation is dependent on the gradient between the body surface and the environment radiation temperature (temperatures and emissivity of the surfaces). Thus convection and radiation are the main avenues for heat loss in the cold.

In addition to convective cooling, the hands and feet may be cooled by conduction of heat between the body and materials in contact. This may lead to a rapid local heat loss for example at handling of cold materials and standing on cold ground. In normal situations evaporative heat loss constitutes a small part of the total heat loss, but during heavy work, sweating may increase evaporation. Wettedness of the clothing increases the heat loss by reducing insulation and increasing evaporation.

Heat loss is normally regulated without the major responses of sweating or shivering because cutaneous vasodilatation and vasoconstriction usually suffice with appropriate use of clothing.

Occupational work in the cold

Many factors of the occupational work are fixed, such as:

- Time for a task to be completed
- Nature of the work task
- Personal protective equipment required
- Environmental conditions

Thus, the degrees of freedom to adjust to the environment are few. The work tasks and the time they have to be done are essentially fixed, for example repair of broken telephone lines. Some workplaces require special personal protective equipment besides the cold protective clothing, such as helmets. And finally, the focus of this thesis, the temperature and air velocity at which outdoor work is to be performed is naturally beyond personal control.

Even though theoretically possible to regulate, the air temperatures of cold/refrigerated indoor workplaces, typically cold stores and food-processing industry, are stated by law or determined by the activity of the workplace and cannot be increased to meet the comfort requirements of the workers.

In cold the temperature gradient between the body and the environment is large. Therefore the body may lose a large amount of heat by convection and radiation to the environment. Clothing protects the body in the cold by reducing the heat transport from the body. The insulation properties of clothing *in wear* are decisive for an individual's comfort, safety and health in cold climate. The clothing insulation may be the main factor that can be adjusted to reduce the thermal stress on the individual. In

situations where also this factor is fixed for example due to uniform protective clothing provided by the employer, the working time or the organisation of the work must be adjusted to protect the worker from cooling.

This is the main reason that the outputs/results of a method to prevent body cooling, namely the IREQ index, is the clothing insulation required (79).

Methods for evaluating cold stress

The risk for cold stress and cold injuries at work must be assessed. A few methods to predict the effects of cold have been developed and are in use. The major physiological concerns at work in cold environments are *whole-body* cooling, which may lead to hypothermia and *local* cooling, which may render cold injury. A milder problem is cold sensations and pain accompanied by discomfort, which may be serious since it has implications on safe behaviour. Two methods deal with these problems: IREQ (Insulation required) for whole-body cooling and WCI (Wind Chill Index) for local cooling.

IREQ (Insulation required) and DLE (Duration limited exposure)

IREQ is a method that is used to prevent cooling of the body core and hypothermia of people exposed to cold (90). It has mainly been used for occupational purposes. The calculated output of IREQ indicates how much insulation would be needed at a certain physical activity level (metabolic rate) and thermal climate (air and radiant temperature, air velocity and air humidity) to maintain heat balance during a working day (Figure 2). IREQ can be used for air temperatures below +10 °C.

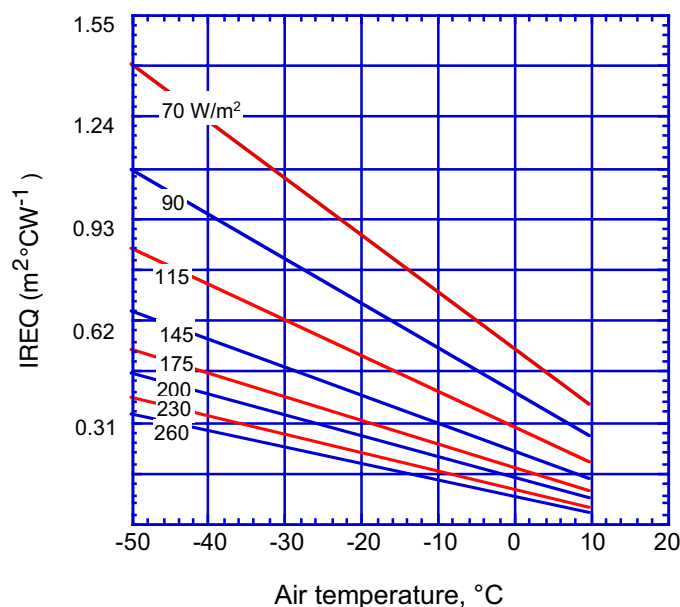


Figure 2. Clothing insulation required (IREQ) for various metabolic rates (lines) at a range of air temperatures. A subject at these conditions is predicted to feel thermoneutral and have a comfortable mean skin temperature. Air velocity is assumed to be $0.2 \text{ m}\cdot\text{s}^{-1}$, the relative humidity 50% and the mean radiant temperature equal to air temperature. Modified from (90).

The concept of IREQ is that the body is allowed to cool only to a certain extent for a period of eight hours, which is a normal workday. Two levels of thermal state may be calculated by IREQ, “IREQneutral” and “IREQmin”. IREQneutral is a level at which a person would be able to maintain thermal equilibrium at a normal level of mean body temperature and IREQmin is a lower level at which a person maintains thermal equilibrium at a subnormal level of mean body temperature and peripheral cooling. Cold exposure starts with a cooling period of 20–40 min when the heat content of body tissues, particularly skin and extremities, is reduced. Thermal equilibrium is then restored for the values of mean skin temperature. This corresponds to a heat debt of approximately 40 Wh·m⁻² compared to the low strain of IREQneutral.

It is not always that the clothing insulation available is sufficient to give heat balance for a full workday. Then a time limit for cold exposure may be calculated. DLE (Duration limited exposure) gives the recommended maximum time of exposure with available or selected clothing at the given conditions to prevent significant body cooling (when a certain amount of tissue heat, 40 W·m⁻² h⁻¹ has escaped from the body). DLE is calculated as:

$$DLE = \frac{Q_{lim}}{S} \text{ (h, min)}$$

Q_{lim} is the limit value of body heat loss (Wh·m⁻²) and S is the rate of change in body heat content (W·m⁻²). DLE may be calculated both for IREQneutral (low strain conditions) and IREQmin (high strain conditions). The calculations of IREQ and DLE are described in detail in the standard document ISO TR 11079 (90). The DLE index in the valid standard had not been validated at the time of the study Paper I. Since then, one validation study on chemical protective clothing has been reported (163).

The insulation of the clothing is mainly dependent on the thickness of still air in fibres, between fibres and between clothing layers. In still air there is also an insulating air layer at the clothing surface, provided there are no body movements. During physical activity the clothing insulation is reduced compared to during standing at ease (129, 142). The actual insulation during a real wearer situation may be up to 57% lower than measured on a standing thermal manikin (82). The reduction is due to stirring or elimination of the still air volumes, due to ventilation of the clothing (‘pumping effects’) produced by extremity movements, due to deformation of the clothing at certain body positions, and under certain circumstances due to sweat absorption and adsorption in/by the clothing fibres (59, 78). In wind, the boundary air layer is reduced and at high wind speeds it is negligible (82). The reduced insulation of the clothing in wind may, in addition to the mentioned factors, be due to deformation of the clothing (compression by the air pressure of wind) and penetration of air through the clothing material and through openings of garments (neck, sleeves and waist).

Clothing insulation is measured on a stationary thermal mannequin or moving with 45 steps·min⁻¹ (37) at an air velocity between 0.3 and 0.5 m·s⁻¹. For the calculation of IREQ in a work situation, the insulation value measured at standing is reduced by a coefficient 0.1 when the metabolic rate (M) is 70-100 W·m⁻², and 0.2 when $M > 100$ W·m⁻² to correct for the effects of movements. If wind is present a correction for the

reduction of the boundary layer and the increased convection is calculated by the index. However, a revision of the IREQ method was recently done (Ingvar Holmér, personal communication). Two major corrections are considered. The first is introduction of the effect of wind and body movements on the clothing insulation and the other is the criterion for mean skin temperature, which will be described below.

Wind Chill Index, WCI

The Wind Chill Index, WCI, has for almost sixty years been a widely used tool for predicting the cooling effect of bare skin and predicting the risk for frostbite. It was invented by Siple and Passel based on a series of physical experiments in arctic conditions (166). They used a plastic (pyroline) cylinder container, about as large as a human head. The container was attached to a pole on a rooftop of one of the wooden huts where scientists worked. For each of the multiple experiment they filled the container with water at 33 °C and measured the heat loss from the container at combinations of different ambient temperatures and air velocity and observed when the water froze. Siple and Passel also observed the time for a frostbite to occur in subjects exposed to different combinations of temperature and wind in the field and collected reports on frostbite occurrence, temperature and wind conditions during field activities. The subjective data was used to verbalise the “wind chill temperature” values of WCI and to validate the frostbite risk limits. However, the validation was not done under controlled conditions and the climatic parameters during the activities were only estimated from one measurement, not monitored specifically the time before the frostbite occurred. In summary, WCI combines two important climatic physical parameters to give a measure of the cooling effect of the bare skin and provides a risk assessment method for frostbite of the skin.

A modification of the WCI table was published in 1995 by Osczevski, based on measurements of heat loss from a thermal head model (145). The Wind Chill Index is currently being revised with data from human experiments (31, 32).

Table 1. Cooling power of wind on exposed flesh expressed as a chilling temperature under almost calm conditions ($1.8 \text{ m}\cdot\text{s}^{-1}$) according to the Wind Chill Index (166).

Wind speed	Actual thermometer reading, °C						
$\text{m}\cdot\text{s}^{-1}$	0	-5	-10	-15	-20	-25	-30
1,8	0	-5	-10	-15	-20	-25	-30
2	-1	-6	-11	-16	-21	-27	-32
3	-4	-10	-15	-21	-27	-32	-38
5	-9	-15	-21	-28	-34	-40	-47
8	-13	-20	-27	-34	-41	-48	-55
11	-16	-23	-31	-38	-46	-53	-60

Values given in bold type (shaded area) correspond to $\text{WCI} \geq 1600 \text{ W}\cdot\text{m}^{-2}$, which is the level where exposed skin freezes.

However, an accurate assessment/prediction of the clothing insulation required at work in the cold should be based on data from experiments with human subjects in cold-protective clothing. Further, mathematical models must be validated on humans. The models do not consider the physiological responses that may drastically change the outcome of the model, for example cold-induced vasodilatation.

Criteria for cold work

In both scientific studies and in practice limiting factors of cold work have been found to be a) low local skin temperatures limiting manual function and causing frostbite, b) body temperature limiting body function and c) low inspiration temperature that may cause problems with respiratory function. In addition to physiological and performance limitations, strong discomfort is not acceptable at occupational work.

IREQ is based on data obtained from resting subjects and subjects exercising at constant work rates and at a constant ambient temperature without wind. The comfort criteria used in IREQ to physiologically define thermal neutrality were developed from studies in moderate ambient temperatures and still air. The comfort criteria comprise certain mean skin temperature levels and rate of evaporative heat loss levels as functions of the metabolic rate (Table 1a). Equations for prediction of mean skin temperature conform to results from cold environments. A modified set of "comfort criteria" in terms of skin wettedness is used for the calculations. The mean skin temperature criterion used by IREQ for maximal accepted peripheral cooling /minimal clothing (IREQ minimal) accepted is 30 °C (90). This mean skin temperature and the skin wetness criteria (ratio between skin evaporation and the maximal possible evaporation in the actual condition) (Table 1a) coincide with subjective thermal sensations of in the range of "cool" to "comfortable" (6). This state of body has also shown to be tolerated for extended exposures (7, 15, 44, 77, 85, 114). The individual's thermal sensation and thermal comfort has been reported to correlate with the peripheral vasomotor activity and the sweating intensity (40). Thermal comfort and 'neutral' sensations can be maintained even at low temperatures with an appropriate combination of clothing insulation and physical activity (8, 50). For local cooling, criteria are recommended for wind chill, hand temperature and temperature criteria for the respiratory tract (Table 1b). As mentioned, a new criterion for mean skin temperature has been suggested for high strain. It will be described in the "Discussion" part.

Table 1a. Physiological criteria for whole-body cooling in IREQ/DLE (90)

	For IREQmin "high strain"	For IREQneutral "low strain"
Predicted thermal sensation	Cold	Neutral
Criteria		
mean skin temperature (°C)	30.0	$t_{sk} = 35.7 - 0.0285 \cdot M$
DLE, Q_{lim} body heat content change (Wh·m ⁻²)	-40	-40
wettedness (n.d.)	0.06	$w = 0.001 \cdot M$

Table 1b. Physiological criteria for determination of local cooling in (90)

Local cooling	"high strain"	"low strain"
Wind Chill Index, WCI (W·m ⁻²)	1600	1200
Hand temperature (°C)	15	24
Respiratory tract, air temperature (°C)	-40	-20

Methods

The thesis is based on four experimental series (Table 2). The results from the studies are described in six papers (I-VI).

Experimental design

The experimental conditions of all studies are summarised in table 2. The conditions were selected to be under the risk levels established by the current indices, Insulation required (IREQ) and Wind Chill Index (WCI).

Table 2. The conditions of the studies described in Paper I-VI. The studies A-D will not be referred to separately in the Results part of the thesis. TN: thermoneutral, CO: cold. 0, 1 and 5 refers to air velocity.

Code	Activity	n	Ambient temperature (°C)	Air velocity (m·s ⁻¹)	Duration (min)
Study A (PAPER I)					
A	Walking, 2.0 km·h ⁻¹	10	-6	0.2	90
B	Walking, 2.0 km·h ⁻¹	10	-14	0.2	90
C	1) Walking, 2.0 km·h ⁻¹ , then insulation added	5	-22	0.2	50+50
	2) Walking, 2.0 km·h ⁻¹ , then walking, 6.0 km·h ⁻¹	5	-22	0.2	50+50
Study B (PAPER II and V^B)					
<i>Preconditioning at +20 °C (TN) and -5 °C (CO)</i>					
TN+ST0	Sitting ^A ,	8	+20 ^A , -10	0.2	60 ^A +30
TN+ST1	then	8	+20 ^A , -10	1.0	60 ^A +30
TN+ST5	Standing	8	+20 ^A , -10	5.0	60 ^A +30
CO+ST0	Sitting ^A ,	8	-5 ^A , -10	0.2	60 ^A +30
CO+ST1	then	8	-5 ^A , -10	1.0	60 ^A +30
CO+ST5	Standing	8	-5 ^A , -10	5.0	60 ^A +30
Study C (PAPER III, IV and V^B)					
TN+LOW0	Sitting ^A , then walking	8	+20 ^A , -10	0.2	60 ^A +60
TN+LOW1	at 2.8 km·h ⁻¹	8	+20 ^A , -10	1.0	60 ^A +60
TN+LOW5	(LOW intensity)	8	+20 ^A , -10	5.0	60 ^A +60
TN+MOD0	Sitting ^A , then walking	8	+20 ^A , -10	0.2	60 ^A +60
TN+MOD1	at 2.8 km·h ⁻¹ , 6° uphill	8	+20 ^A , -10	1.0	60 ^A +60
TN+MOD5	(MODerate intensity)	8	+20 ^A , -10	5.0	60 ^A +60
Study D (PAPER VI)					
SIT BARE2	Sitting, bare-headed	10	-10	2.0	10 ^C
SIT BARE4	Sitting, bare-headed	10	-10	4.0	10 ^C
SIT BARE6	Sitting, bare-headed	9	-10	6.0	10 ^C
SIT HAT6	Sitting, with hat	9	-10	6.0	10 ^C

^A pre-conditioning

^B only with pre-conditioning at 20 °C.

^C not completed by all subjects (see “Results”, Table 13).

The first study (Paper I) was designed to examine the thermal responses at different low ambient temperatures and to validate the IREQ/DLE index (79). The experimental conditions (combination of climate, thermal insulation and activity level) were selected to give a reduction of the body heat content below 40 Wh·m⁻² at certain time limits.

IREQ/DLE predicted mild peripheral cooling and heat balance at -6 °C. The time limits for accepted cold exposure would be reached in the -14 and -22 °C. The conditions were calculated by IREQneutral/DLE to allow work for approx. 2 h at -6 °C, 1 h at -14 °C and 40 min at -22 °C. With IREQmin/DLE the corresponding time limits were approx. 4 h at -6 °C, 90 min at -14 °C and 50 min at -22 °C. The total clothing insulation value used for calculation was reduced by 20% to correct for the convection increase during walking.

All conditions in Study B and one in Study C, “TN+LOW” (Paper II-V) (for explanation see Table 2) were selected to be cold, “TN+MOD0” and “TN+MOD1” (see Table 2) aimed to be “slightly warm” and finally, TN+MOD 5 aimed at thermal neutrality.

In Study B (Table 2), Paper II, the subjects were “preconditioned” for 60 minutes at -5 °C and +20 °C, respectively. The preconditioning at -5 °C aimed to produce high degree of skin vasoconstriction before entering the climate chamber, while +20 °C would be thermoneutral, giving a normal skin temperature at the start of wind exposure. The selected walking speed and treadmill inclinations (and their corresponding predicted metabolic rates) during walking in Paper III-V (Study B and C in Table 2) aimed to trigger skin vasodilatation (treadmill inclined by 6°) and give normal skin temperature (treadmill on the level), respectively. In Paper VI (Study D in Table 2) the subjects were exposed to three air velocities while sitting. The air velocities were selected to be below predicted risk for frostbite according to the Wind Chill Index, WCI (Table 3). At a heat loss rate of 1625 W·m⁻² frostbite would occur within an hour. In addition, 1.0 m·s⁻¹ was specifically selected because it is outside the range of WCI (2.8 m·s⁻¹ to 25 m·s⁻¹).

The experiments were arranged in a factorial design with three to six repeated measurements for each subject at random order within the series of experiments (sitting, standing and walking, respectively). The subjects were not informed in advance about precisely which ambient conditions they were exposed to avoid expectations and comparisons with previous exposure. However, for ethical reasons

Table 3. Correspondence of the experimental conditions of Paper II-VI and the Wind Chill Index, WCI

Air velocity (m·s ⁻¹)	WCI (W·m ⁻²)	Predicted subjective sensation
0.2	outside range	-
1.0	outside range	-
2.0	1127	very cold
4.0	1319	bitterly cold
5.0	1387	bitterly cold
6.0	1444	bitterly cold

Table 4. Physical characteristics of the subjects, average and range (within brackets)

Study code	A, Paper I (n=10)	B-C, Paper II-V (n=8)	D, Paper VI (n=10)
Age (years)	22.4 (20-25)	23.5 (21-25)	48.5 (44-54)
Body mass (kg)	75.4 (64-93)	73.2 (64-85)	Not measured
Height (m)	1.81 (1.74-1.88)	1.79 (1.72-1.85)	Not measured
Relative body fat (%)	Not measured	13.6 (10.3-17.9)	Not measured

they were informed that they were going to be exposed to cold and wind and what type of responses that could be expected.

Subjects

Eight to ten healthy voluntary subjects participated in each of the studies after giving their informed consent (Table 4). All subjects were young (20-25 years old), except for Paper VI, in which the subjects were 44-54 years old. The same eight subjects participated in Paper II-V. The subjects were non-smokers and had never suffered from cold injury. All subjects were male, except for two in Paper VI. However, only one of the two women fulfilled all experiments.

Table 5. Description of clothing systems used in the experiments and their insulation properties.

Clothing layer	Study A, Paper I	Study B-C, Paper II-V	Study D, Paper VI
Inner layers: (same in all)	Briefs Long-sleeved crew-neck undershirt and ankle length underpants (Long Johns)		
Middle layer: (same in all)	Fibre pile jacket and pants		
Outer layer:	Overall and jacket, unlined	Insulated trousers and jacket, quilt-lined	Insulated overall and parka, quilt-lined
Additional:	Balaclava, scarf, heavy insulated leather gloves, fibre pile mittens, socks and light boots, Insulated parka during one condition	Hat with insulation lining and earflaps, heavy insulated mittens, wind protective mittens, socks and wool-lined knee-high rubber boots	Hat with pile lining and earflaps (in one condition), high insulation mittens, socks and boots
Total insulation (m ² ·C·W ⁻¹) (clo)	0.42 2.7	0.42 2.7	0.51 3.3

Clothing

In all studies three-layer cold-protective clothing ensembles were used, a military ensemble was used in Paper II-V (Table 5). The occurrence of the different ensembles in the respective studies is indicated in the table. The same military winter hat was used in Paper II-VI. The clothing insulation was measured with a standardised method on a standing thermal mannequin (37). During pre-conditioning in Paper II-V hat, gloves, jacket and boots were not worn in order to avoid heat load.

Experimental protocol

The subjects gave their informed consent to the tests, which were approved by the local Medical Ethics Committee. Before the experiments started the subjects were medically examined and were proven healthy. The preparations for the tests were standardised. The day/hours before the test the subjects were asked to follow restrictions concerning ingestion of food, coffee, tea, alcohol and drugs to avoid any unwanted effects on thermoregulation, circulation or subjective responses. Each subject arrived to the laboratory the same time of day for all his/her tests in the series of experiments. The majority of the tests were performed with one or two week intervals. A few experiments were performed with fewer days in between.

The preparations for the test took place in a room at approx. 22 °C. After preparation of the subject and all baseline measurements had been taken the subjects were transferred to a cold chamber. In Paper II through V the subjects rested seated for one hour in a separate climatic chamber to equalise the thermal state of the subjects before entering a wind tunnel. In those studies the subjects were exposed to wind in a large wind tunnel, whereas in Paper VI only the faces of the subjects were exposed to wind produced by a small wind tunnel. The type of climate chamber used in the main exposure and the type of activity performed are summarised in table 6. Only one subject was studied at a time to avoid heat radiation effects.

Table 6. Description of type of exposure and activity in the studies

Paper	Wind	Type of wind tunnel	Activity at –10 °C
I	No	no wind tunnel	treadmill walking
II	Yes	whole-body	standing
III	Yes	whole-body	treadmill walking
IV	Yes	whole-body	treadmill walking
V	Yes	whole-body	treadmill walking
VI	Yes	head wind tunnel	sitting

Measurements and measuring equipment

The effects of cold stress have been studied by measurement of a number of physiological variables: core temperature, mean skin temperature and local skin temperature, blood pressure, heart rate and oxygen consumption and measurement of physical heat balance.

Partitional calorimetry (Paper I)

To determine heat transfer from the body partitional calorimetry was used. This method requires measurement of ambient thermal factors, physiological measurements on the subjects and a number of calculations, described below. Metabolic rate, ambient air and radiation temperature, air velocity, air humidity, rectal and mean skin temperature and body mass change were therefore measured. The physiological measuring equipment is described under the subtitle “Physiological measurements”.

Evaporative heat loss. To determine evaporative heat loss, the subject was weighed both nude and dressed and all garments were weighed before and after the experiment. The skin evaporation rate was determined from the repeated recordings of body mass and corrected for the rate of metabolic mass loss (99):

$$\text{metabolic mass loss} = 1.96 \cdot V_{O_2} \cdot (RQ - 0.73) \quad (\text{g} \cdot \text{min}^{-1})$$

Moisture accumulated in the clothing was subtracted from the total evaporation to calculate skin evaporation. The respiratory evaporative mass loss, m_{res} was calculated as (40):

$$m_{res} = (0.0173 \cdot M_b (P_{w,ex} - P_{w,a}) \cdot A_b \cdot (0.68 \cdot 60))^{-1} \quad (\text{g} \cdot \text{min}^{-1})$$

where M_b is the metabolic rate, $P_{w,ex}$ is the water vapour pressure in expired air, $P_{w,a}$ is the ambient water vapour pressure and A_b is the Du Bois body surface area (30). The evaporation rates were converted to energy units by using the specific latent heat of vaporisation of sweat, $2.45 \text{ kJ} \cdot \text{g}^{-1}$.

Dry heat transfer. In Paper III heat flux from the skin was measured with heat flux transducers from eight sites: forehead, chest, upper back, upper arm, back of the hand, anterior thigh, calf and foot instep. Heat flux transducers were taped to the skin with adhesive tape, without covering the sensors, near to the corresponding thermistors. Heat flux was registered every minute.

The dry heat transfer (heat loss by radiation, R , and by convection, C) in Paper I from the skin to the environment was calculated by

$$R + C (\text{W} \cdot \text{m}^{-2}) = M_b - W - H_{res} - E_{sk}$$

Where M_b is the metabolic heat production rate, W is the mechanical power, H_{res} is the convective and evaporative heat loss by respiration and E_{sk} is the evaporative heat loss from the skin. Respiratory heat loss rate by respiration and convection, H_{res} , is expressed as a function of metabolic rate (40):

$$H_{res} (\text{W} \cdot \text{m}^{-2}) = 0.0173 \cdot M_b (P_{w,ex} - P_{w,a}) + 0.0014 \cdot M (t_{ex} - t_a)$$

where t_a is the ambient air temperature and t_{ex} is the temperature of the expired air. t_{ex} was calculated as a function of inspired air (182):

$$t_{ex} \text{ (}^\circ\text{C)} = 29 - 0.2 \cdot t_a$$

Clothing insulation. The resultant basic insulation (I_{cl}), the insulation of the clothing without the insulation of the boundary air layer, was calculated as

$$I_{cl} = \frac{t_{sk} - t_a}{R + C} - \frac{I_a}{f_{cl}} \quad (\text{m}^2 \cdot ^\circ\text{C} \cdot \text{W}^{-1})$$

where I_a is the insulation of the air layer at the surface of the naked body ($\text{m}^2 \cdot ^\circ\text{C} \cdot \text{W}^{-1}$) and f_{cl} is the clothing surface area enlargement factor (n.d.).

Table 7. Physiological measurements of all studies

Paper	I	II	III	IV	V	VI
Oxygen consumption	x	x	x	x	x	
Rectal temperature	x	x*	x	x	x	
Skin temperatures (other than head)	x	x*	x	x	x	
Face/head skin temperatures	x	x	x	x	x	x
Blood pressure		x	x	x	x	x
Respiratory function		x			x	
Heart rate	x	x	x	x	x	x
Body mass change	x					

*Presented in Mäkinen et al. (135)

Physiological measurements

The physiological measurements of all studies are summarised in table 7. Rectal temperature (I-V), skin temperatures at 4-18 locations, blood pressure (II-VI), respiratory function (II-VI), oxygen consumption (I-V), heart rate, body mass change (I), evaporation (I) and subjective sensations were measured.

Metabolic rate and oxygen consumption. The oxygen consumption (V_{O_2}) was measured by analysis of expired air samples collected with Douglas-Bag technique in Paper I and with an open-circuit system in Paper II-V.

Samples were analysed for CO_2 and O_2 contents by gas analysers for determination of V_{O_2} and the respiratory quotient (RQ). Volume and gas calibration of the spirometers and gas analysers, respectively, was done prior to every measurement. A valve mouthpiece was used to avoid warming up the face. Measurements were performed for a 5-min period at the end of each condition and additionally after 25 minutes of walking (Paper III-V). With the online system the mean value of two last measured minutes was used as representative value for the period.

Metabolic rate (M_b) was calculated as (89)

$$M_b (W) = (0.23 \cdot RQ + 0.77) \cdot 5.873 \cdot V_{O_2} \cdot 60$$

The mechanical power (W) of uphill walking on the treadmill was calculated as

$$W (W) = \text{body mass} \cdot 9.8 \cdot \text{walking speed} \cdot \text{SIN (Inclination} \cdot 3.14/180)$$

Metabolic heat production rate per body surface area was then calculated as

$$M_h (W \cdot m^{-2}) = (M - W) \cdot A_b^{-1}$$

Rectal temperature (Paper I-V). The core temperature, as represented by the rectal temperature (t_{re}), was measured with a thermistor, which was inserted into the rectum, 10 cm beyond the anal sphincter. The sensor cable was held in place by a small globe fastened on the cable.

Skin temperatures. Thermistors were taped on the skin at different locations (Table 8) (Paper I: Fenwal Mil-T-23648, Fenwal Electronics, USA, Paper II-V: YSI 409b for all locations except the face, where YSI 427 was used, Yellow Springs Instruments Co., USA). In Paper VI thermocouples were used. The cheek temperature was measured in all studies. All temperature measurements, except for the head in Paper II-VI, were done every minute. The face skin temperatures were collected every 20 seconds in Paper II-V and at 3 s intervals in Paper VI.

The mean skin temperature (t_{sk}) in Paper I was calculated as the average of 14 local skin temperatures (modified from Olesen et al. (144): neck (weighted by 1.5 to represent the scalp), cheek (weighted by 0.5 to represent the face), chest, abdomen, scapular area, lumbar back, upper arm, lower arm, hand, anterior thigh, posterior thigh, shin, calf and foot. The mean skin temperature in the other studies was calculated as the area weighted average of all local skin temperatures except for the chin and nose according to Hardy and Du Bois (61).

Mean body temperature, t_b , was calculated by weighting the mean skin temperature and rectal temperature:

$$t_b (\text{°C}) = 0.65 \cdot t_{sk} + 0.35 \cdot t_{re}$$

Table 8. Locations of the skin temperature sensors in the studies

Paper	Skin temperature measurement sites
I	Cheek, neck, chest, abdomen, scapular area, lumbar back, upper arm, lower arm, dorsal side of hand, anterior thigh, posterior thigh, tibial area, calf and dorsal side of foot
II	Cheek, forehead, nose
III, IV, V	Cheek, forehead, nose, neck, chest, abdomen, scapular area, lumbar back, upper arm, lower arm, dorsal side of hand, finger tip, anterior thigh, posterior thigh, tibial area, calf, dorsal side of foot and big toe
VI	Cheek, forehead, nose, chin, earlobe

Body heat content, Q , was calculated as (43):

$$Q \text{ (Wh)} = 3.48 \cdot t_b \cdot \text{body mass}$$

3.48 is the specific heat of the body in $\text{Wh}\cdot\text{kg}^{-1}$. The change of the body heat content S was calculated from Q by using the last value of the preconditioning as zero-level.

Heart rate. Heart rate (HR) was registered telemetrically. A chest electrode belt with a signal transmitter was placed on the subject and the receiver was placed near the subject in a heated space. In all studies HR was registered every minute, except for VI where the HR was collected every 15 s.

Respiratory function/spirometry (Paper II and V). Forced expiratory volume in 1 s (FEV_1) and forced vital capacity (FVC) were measured with the subject in a standing position before, during and after the exposures. Spirometry was done at the end of each condition.

Blood pressure. The systolic (SBP) and diastolic (DBP) blood pressure was measured with a blood pressure (BP) monitoring system having automatically inflating arm cuff (Paper II-V). Blood pressure was measured on the sitting subject after a rest period before exposure, three to five times during exposure on the standing (Paper II-V) or sitting subject (Paper VI) and after exposure measured on the subject sitting. During the exposure in Paper II-V the measurements were done on the subjects in the standing position, while they were sitting during the measurements in Paper VI.

Table 9. Subjective ratings investigated in all the papers

Paper	I	II	III	IV	V	VI
Thermal sensation of:						
body	x	x				
face	x	x	x	x		x
hands	x		x			
arms, thigh, feet			x			
Pain		x		x	x	x
Shivering	x	x	x			
Acceptance	x					

Subjective ratings

In table 9 the type of subjective ratings given in the respective study is summarised. The subjects rated their thermal sensations of the body (TS), hands, face, arms, thighs, feet according to the standard (88). Shivering and thermal acceptance was also rated at regular intervals. Perception of shivering was recorded on a yes/no basis in Paper III. The subjects reported their pain sensation of the face on a four-point scale in Paper II, IV and V and extended to a five-point scale in Paper VI (Table 10). In Paper VI, pain of the face parts where temperature was rated every second minute, in the other studies at 10 to 20 minute intervals. All rating scales used are shown in table 10.

Table 10. The rating scales used in the experiments. The pain scale c) was extended by one point in Paper VI.

a) Thermal sensation

"How are you feeling now in your":

body, hands, feet, face, thighs, arms"?

-4	Very cold
-3	Cold
-2	Cool
-1	Slightly cool
0	Neutral
+1	Slightly warm
+2	Warm
+3	Hot
+4	Very hot

b) Thermoregulatory responses

Are you shivering?

No

Yes

c) Pain sensations

0	no pain
1	slight pain
2	moderate pain
3	considerable pain (Paper VI)/ severe pain (Paper II, IV, V)
4	severe pain (Paper VI)

d) Acceptance

Would you find your current thermal state acceptable during a working day?

0	Yes, in the daily work situation
1	Yes, but only at a single occasion
2	No

Manual performance test (Paper I)

Before and after the cold exposure, subjects performed a manual test with a glove on the dominant hand. The task was to screw screws into threaded holes for 30 seconds. The task was repeated after a 10-s break.

Statistical analysis and data handling

For calculations of the heat balance and for some comparisons between conditions, temperatures and heart rates were averaged over 10 (Paper II-IV) and 20 minutes (Paper I), respectively.

The purpose of the selected time intervals for averaging was to describe the most constant phases of each experiment and to reduce the effects of small variations during the period.

Paired differences in physiological responses were tested with Student's t-test where suitable and multiple differences with ANOVA, repeated measures design. For

variables with some missing values at random, case-wise deletion was used. Post-hoc-tests were then performed according to Scheffé in Paper I. In the other studies significant differences between the conditions and between time points were identified by Tukey's HSD post-hoc test.

Differences in subjective responses were analysed by Kruskal-Wallis non-parametric analysis of variance and paired differences with Wilcoxon's non-parametric signed rank test (I, IV). Friedman's non-parametric rank test was used to reveal effects of wind and metabolic rate on the subjective ratings.

Correlations between continuous variables were analysed by calculation of the Pearson correlation coefficient. Association between non-parametric variables (or one discrete variable and one continuous variable) were analysed with Spearman sign ranked order test (Spearman R). The level of significance (α) was set to 0.05.

Results

Metabolic rate (Paper I, II and III)

The metabolic rate (M), calculated from the oxygen consumption, V_{O_2} , at the coldest conditions (lowest air temperature, highest air velocity) tended to be higher than in the milder conditions (Table 11). The average oxygen consumption V_{O_2} and metabolic heat production rate at steady-state (45 min) was similar at -6 , and -14 °C and tended to be higher at -22 °C ($p=0.22$). After a parka had been added, M increased by about $25 \text{ W}\cdot\text{m}^{-2}$ than with the initial clothing. Shivering was observed in three of those five subjects. One of the subjects shivered at all three temperatures.

Table 11. Oxygen consumption at sitting, standing and walking (Papers I-VI). Standard deviation in brackets

Activity	Ambient temperature (°C)	Air velocity ($\text{m}\cdot\text{s}^{-1}$)	Oxygen consumption ($\text{l}\cdot\text{min}^{-1}$)
PAPER I			
Walking, $2.0 \text{ km}\cdot\text{h}^{-1}$	-6	0.2	0.63 (0.05)
	-14	0.2	0.64 (0.09)
	-22	0.2	0.70 (0.13)
+more insulation	-22	0.2	0.81 (0.31)
Walking, $6.0 \text{ km}\cdot\text{h}^{-1}$	-22	0.2	1.11 (0.23)
PAPER II and V			
Sitting, Precondition TN	20	0.2	0.35 (0.08)
Sitting, Precondition CO	-5	0.2	0.39 (0.05)
Standing after TN	-10	0.2	0.38 (0.09)
Standing after TN	-10	1.0	0.34 (0.09)
Standing after TN	-10	5.0	0.59 (0.21)*
Standing after CO	-10	0.2	0.44 (0.15)
Standing after CO	-10	1.0	0.46 (0.13)
Standing after CO	-10	5.0	0.65 (0.17)*
PAPER III, IV and V			
Walking, $2.8 \text{ km}\cdot\text{h}^{-1}$, 0°	-10	0.2	0.70 (0.07)
Walking, $2.8 \text{ km}\cdot\text{h}^{-1}$, 0°	-10	1.0	0.69 (0.08)
Walking, $2.8 \text{ km}\cdot\text{h}^{-1}$, 0°	-10	5.0	0.83 (0.11)*
Walking, $2.8 \text{ km}\cdot\text{h}^{-1}$, 6°	-10	0.2	1.08 (0.12)
Walking, $2.8 \text{ km}\cdot\text{h}^{-1}$, 6°	-10	1.0	1.10 (0.12)
Walking, $2.8 \text{ km}\cdot\text{h}^{-1}$, 6°	-10	5.0	1.15 (0.14)

* significantly different from 0.2 and $1.0 \text{ m}\cdot\text{s}^{-1}$, $p<0.05$

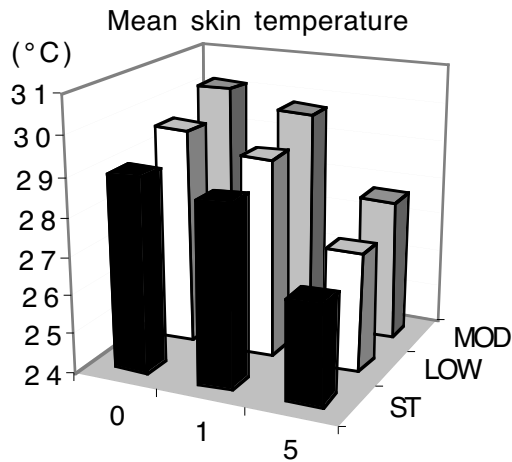


Figure 3. Average mean skin temperature at standing (ST) and walking on the level (LOW) and uphill (MOD) for 30 minutes at $-10\text{ }^{\circ}\text{C}$ and $0, 1$ and $5\text{ m}\cdot\text{s}^{-1}$ wind.

In wind M was higher than in still air, both at standing (135) and during walking. During standing M was about $38\text{ W}\cdot\text{m}^{-2}$ higher at $5\text{ m}\cdot\text{s}^{-1}$ than at lower air velocity. Shivering was reported in all subjects when standing. At the higher exercise level the difference in M was not statistically significant and was about $13\text{ W}\cdot\text{m}^{-2}$ higher at 5 than at $0-1\text{ m}\cdot\text{s}^{-1}$. In MOD no one reported shivering at any air velocity, compared to three subjects in LOW5.

Effects of activity level at cold wind exposure

Most comparisons between the three activity levels were made at 30 minutes of cold exposure, even though the walking experiments lasted for 60 minutes.

Core and skin temperatures

As expected, the rectal temperature, t_{re} , was at average 0.2 and $0.3\text{ }^{\circ}\text{C}$ higher, respectively, during walking uphill (MOD) than during walking on the level (LOW) and standing (ST). The mean skin temperature, t_{sk} was significantly higher in MOD than in ST, $p>0.001$ (Figure 3). Among the individual skin temperatures, finger and calf skin temperature was higher in MOD than in LOW. In addition calf and tibia temperature were higher in MOD than in LOW at $5\text{ m}\cdot\text{s}^{-1}$.

Face temperatures (Paper II-IV). The activity level did not affect forehead and cheek temperature significantly (Figure 4), but cooling of the nose was less in MOD (Figure 5). However, the activity had a main effect on the lowest measured cheek temperatures of the first 30 minutes ($p<0.01$). The metabolic heat production tended to counteract the reduction of cheek temperature more in MOD than in ST and LOW within 1 and $5\text{ m}\cdot\text{s}^{-1}$ (Figure 4). The difference between the outcome of the analyses (average and lowest temperature, respectively) was probably due to cold-induced vasodilatation (CIVD) in the cheek. CIVD made the temperature oscillate.

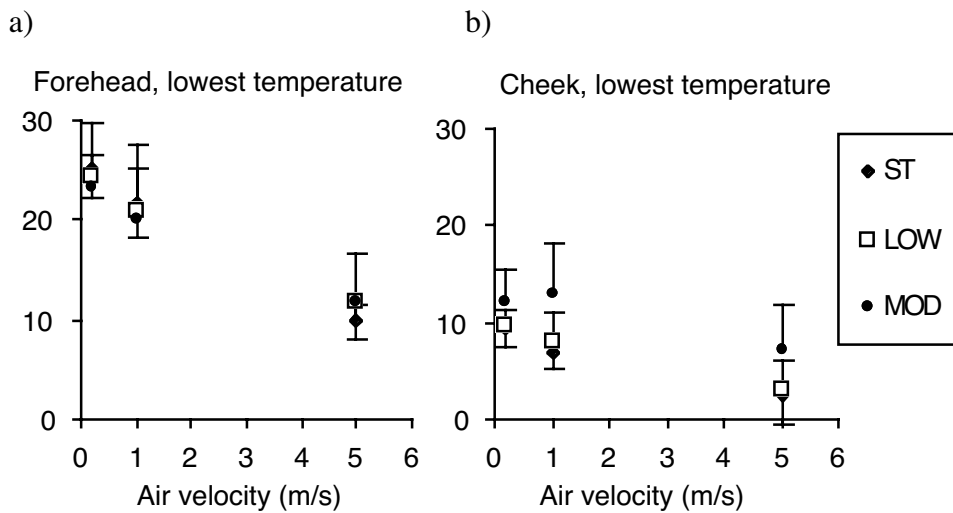


Figure 4. Lowest measured forehead a) and cheek b) temperature (°C) during standing (ST), walking on the level (LOW) and uphill (MOD) for 30 minutes.

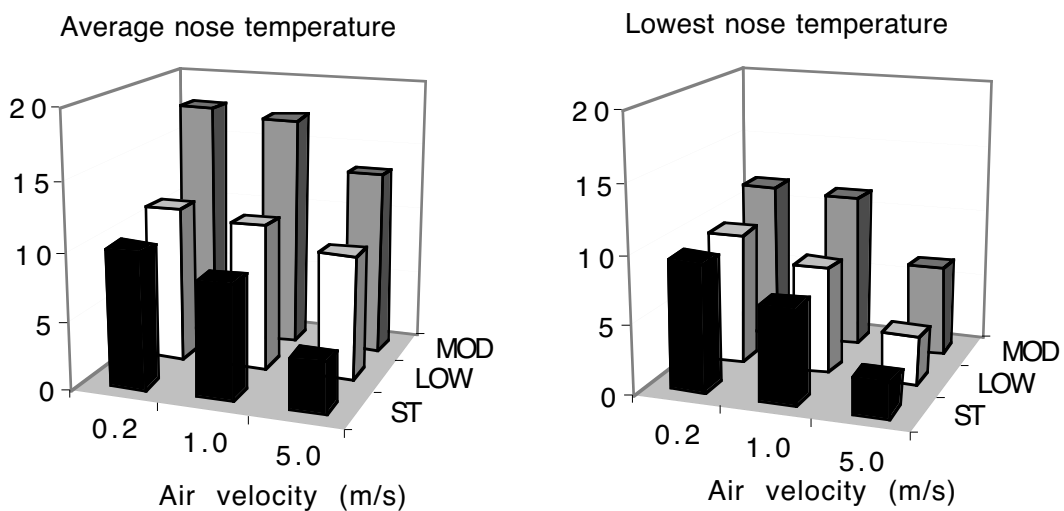


Figure 5. Average and lowest measured nose skin temperature (°C) at standing (ST) and walking on the level (LOW) and uphill (MOD) for 30 minutes (Paper IV).

The thermal sensations of the face ranged from "neutral" (0) to cold (-3) at the end of the exposure during walking. The face was reported colder in LOW5 than in MOD5 by the subjects, $p=0.03$. However, the thermal sensation of the face did not correlate with the face skin temperature, $R_s=0.02-0.26$, $p>0.3$. The pain sensations were reduced by the higher work rate (Figure 6).

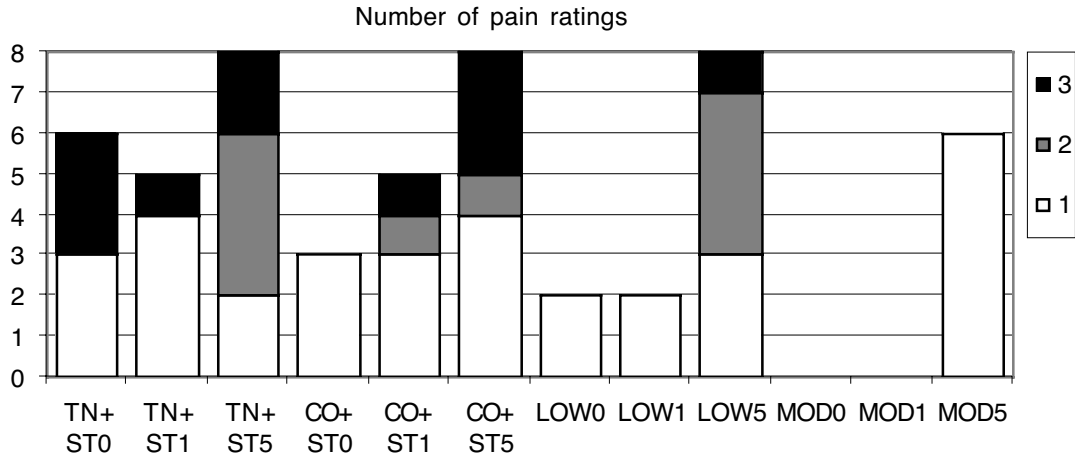


Figure 6. Number of pain sensation ratings at the different conditions studied. For explanation of condition categories see table 2. The legends denote the value of the 4-point pain scale (see Table 10), in which 0 was “no pain” (not shown), and 3 was “severe pain”.

Blood pressure and heart rate (Paper II, IV-V)

The level of physical activity influenced the *SBP* and *DBP* responses. *SBP* and *DBP* increased from preconditioning to cold exposure in *ST* and *LOW* ($p < 0.005$) (Figure 7). *DBP* increased also significantly in *MOD* ($p < 0.03$). Physical activity depressed the *DBP* response, more in *MOD* ($p = 0.0005$) compared with *LOW* ($p < 0.05$). Higher activity tended to depress the *SBP* response as well. As expected, the heart rate was significantly different between the three activities, $p < 0.001$ (Figure 8).

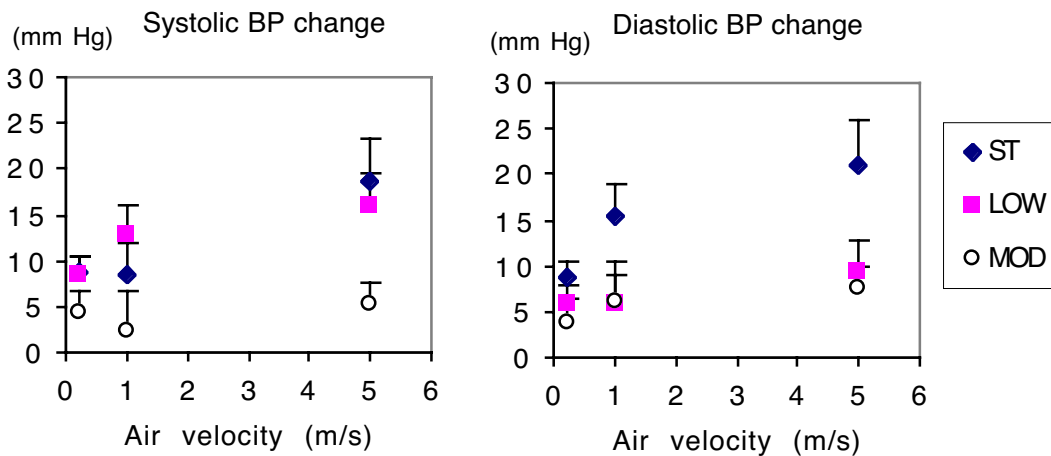


Figure 7. Systolic and diastolic blood pressure (BP) change from 10 minutes before exposure to $-10\text{ }^{\circ}\text{C}$ to 30 min of standing (*ST*), walking on the level (*LOW*) and walking uphill (*MOD*). Bars denote standard errors of the mean, $n = 8$.

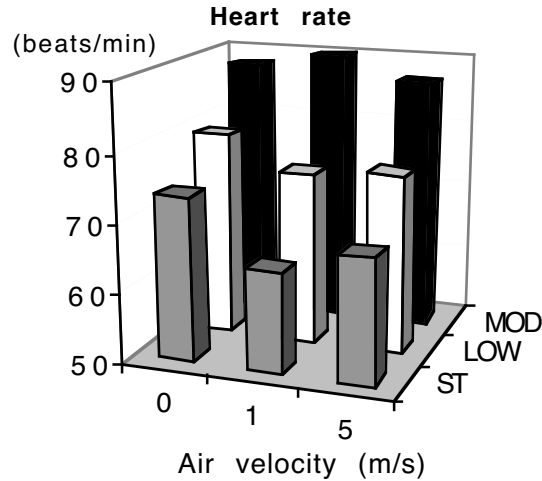


Figure 8. Heart rates at standing (ST), walking on the level (LOW) and walking uphill (MOD) for 30 minutes at $-10\text{ }^{\circ}\text{C}$ and different air velocities, $n=7$ due to one missing value.

Respiratory function

Forced ventilatory capacity (*FVC*) and forced expiratory ventilation in one second (*FEV₁*) (Figure 9) were reduced by about 3% by cold (-5 and $-10\text{ }^{\circ}\text{C}$) at standing compared to pre-experimental values, but did not change during walking at $-10\text{ }^{\circ}\text{C}$ (the results of the spirometry during walking was not reported in the papers).

Local dry heat loss (Paper III)

Mean heat flux from the skin was not affected by exercise intensity. However, the heat flux from the anterior thigh was significantly higher in MOD0 ($200\text{ W}\cdot\text{m}^{-2}$) than in LOW0 ($167\text{ W}\cdot\text{m}^{-2}$).

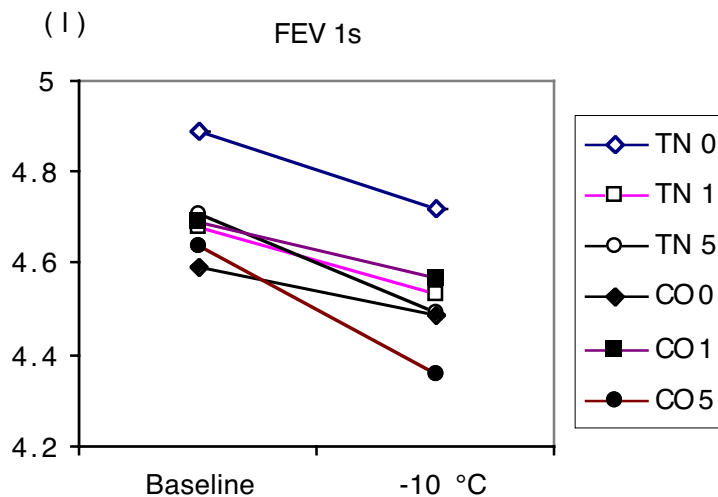


Figure 9. Forced expiratory volume (litre air in one second) in eight subjects before 60 minutes sitting at $+20\text{ }^{\circ}\text{C}$ (TN) and $-5\text{ }^{\circ}\text{C}$ (CO) and after 20 minutes of standing exposure to $-10\text{ }^{\circ}\text{C}$.

Table 12. Average face skin temperature (°C) over 80-89 minutes of standing, walking on the level and uphill (6°) for 30 minutes. SD: Standard deviation, SE: Standard error.

Activity	Standing			Walking on the level			Walking uphill		
	0.2	1.0	5.0	0.2	1.0	5.0	0.2	1.0	5.0
Air velocity, m·s ⁻¹	0.2	1.0	5.0	0.2	1.0	5.0	0.2	1.0	5.0
Forehead, n=8	25.8	22.5	10.8ab	24.9	21.6	12.8ab	24.2	20.7	12.4ab
SD	4.5	5.7	1.7	1.9	2.7	3.7	2.1	1.8	1.8
SE	1.6	2.0	0.6	0.7	1.0	1.3	0.7	0.6	0.6
Cheek, n=6	19.2	16.3	9.0ab	18.2	16.2	10.8ab	18.8	16.3	10.8ab
SD	0.7	2.0	4.1	1.5	1.0	1.4	2.0	2.0	1.5
SE	0.2	0.7	1.4	0.5	0.3	0.5	0.7	0.7	0.5
Nose, n=8	11.1	9.1*†	5.9†a(b)	10.9	9.8†	6.9a(b)	13.6	14.6a	9.5ab
SD	2.0	1.1	2.0	1.2	2.9	2.7	2.3	6.0	4.8
SE	0.7	0.4	0.7	0.4	1.0	0.9	0.8	2.1	1.7

* Different from walking on the level p<0.02

† Different from walking uphill, p<0.02

a different from 0.2 m/s, p<0.005

b different from 1.0 m/s, p<0.002, brackets denote p<0.10

Effects of air velocity

Core and skin temperatures

t_{re} was not significantly affected by wind speed at standing (135) or exercise. t_{sk} was significantly lower at 5.0 m·s⁻¹ (27.1 °C) than at 0.2 m·s⁻¹ (29.6 °C) and 1.0 m·s⁻¹ (29.3 °C) during both standing, (135) and walking, p<0.001 (Figure 3).

Face temperatures (Paper II-V). The air velocity had a significant effect on nose temperature, cheek temperature and forehead temperature, p<0.001 (Table 12). In Paper VI 11 out of 48 experiments were interrupted by the subject. A summary of the distribution of the breaks among the conditions and subjects and at experiment time is shown in table 13. Consequently, group analyses were done both on the responses after 4 minutes on eight subjects and on data from 10 min on four subjects.

Table 13. Time (min) for breaking the experiment. “+” signifies that the scheduled 10 minutes were completed.

Air velocity (m·s ⁻¹)	2		4		6		6	
	/ Subject	bare-headed	bare-headed	bare-headed	bare-headed	with hat		
1		+	5.7	+	8.4			
2		6.8	6.4	5.7	+			
3		+	7.8	+	6.2			
4		+	+	1.5	6.5			
5		+	+	+	+			
6		+	+	+	+			
7		+	6.2	4.0	+			
8		+	+	+	+			
9		+	+	+	+			
10		+	5.2	No test	No test			

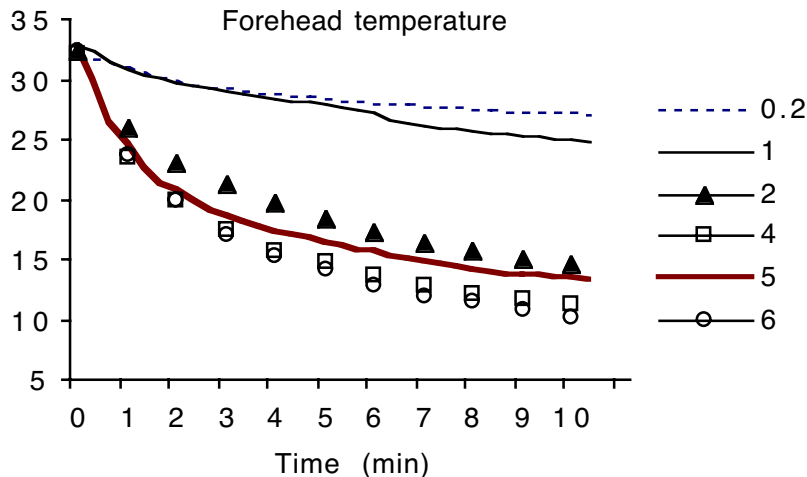


Figure 10. Average forehead temperatures ($^{\circ}\text{C}$) of subjects sitting, standing and walking exposed to $0.2\text{-}6.0\text{ m}\cdot\text{s}^{-1}$ wind. $n=8$ at $0.2, 1$ and $5\text{ m}\cdot\text{s}^{-1}$ and $n=9, 6$ and 6 at $2, 4$ and $6\text{ m}\cdot\text{s}^{-1}$, respectively, due to missing data. Thermocouples were used at $2, 4$ and $6\text{ m}\cdot\text{s}^{-1}$ (marked with symbols) and thermistors at the other air velocities (lines). Hat was used at all air velocities except 2 and $4\text{ m}\cdot\text{s}^{-1}$. The legends denote air velocity in $\text{m}\cdot\text{s}^{-1}$.

Similar to the other studies the air velocity had a significant effect on forehead ($p<0.04$), cheek ($p<0.02$), chin ($p<0.04$) and also on the ear ($p<0.01$) in Paper VI. The nose temperature was only significantly different between the three air velocities the first three minutes ($p<0.05$).

The face temperatures during the first ten minutes of all wind studies were compared. The cooling curve at $2\text{ m}\cdot\text{s}^{-1}$ followed closer to the $4\text{ m}\cdot\text{s}^{-1}$ curve than $1\text{ m}\cdot\text{s}^{-1}$ for forehead and cheek (Figure 10). The cooling curves of the nose were more congregated. The nose temperature of the study group in Paper VI levelled off more or increased in contrast to those in the other studies. All subjects reported pain sensations when standing and walking at low intensity at $5\text{ m}\cdot\text{s}^{-1}$ (Figure 6). During walking at moderate intensity, no pain sensations were reported at 0 and $1\text{ m}\cdot\text{s}^{-1}$, but at $5\text{ m}\cdot\text{s}^{-1}$ six out of eight subjects reported slight pain. The degree of pain sensation was lower in MOD5 compared to LOW5 after 59 min in the cold (median 1.0 and 2.0 , respectively, $p=0.02$). A corresponding difference in skin temperature between LOW5 and MOD5 (avg. LOW5: $4.5\text{ }^{\circ}\text{C}$ and MOD5: $8.9\text{ }^{\circ}\text{C}$, respectively) was only observed in the nose (but not forehead or cheek).

Blood pressure and heart rate

In Paper II, IV-V *SBP* and *DBP* increased from 51 to 89 min at all air velocities (all activities pooled, $p<0.03$). The air velocity had a main effect on blood pressure, $p=0.008$ (Figure 11). *SBP* and *DBP* after 29 min of exposure was higher at $5\text{ m}\cdot\text{s}^{-1}$ than at $0.2\text{ m}\cdot\text{s}^{-1}$ and $1\text{ m}\cdot\text{s}^{-1}$ ($p<0.05$). In the 60 minutes walking experiments *SBP* and *DBP* remained elevated throughout the exposure. Heart rate was unaffected by the wind speed both at standing and during walking (Figure 8).

In Paper VI the cardiovascular responses varied considerably among the individuals. Some of the subjects *SBP* increased by more than 30 mm Hg without compensatory

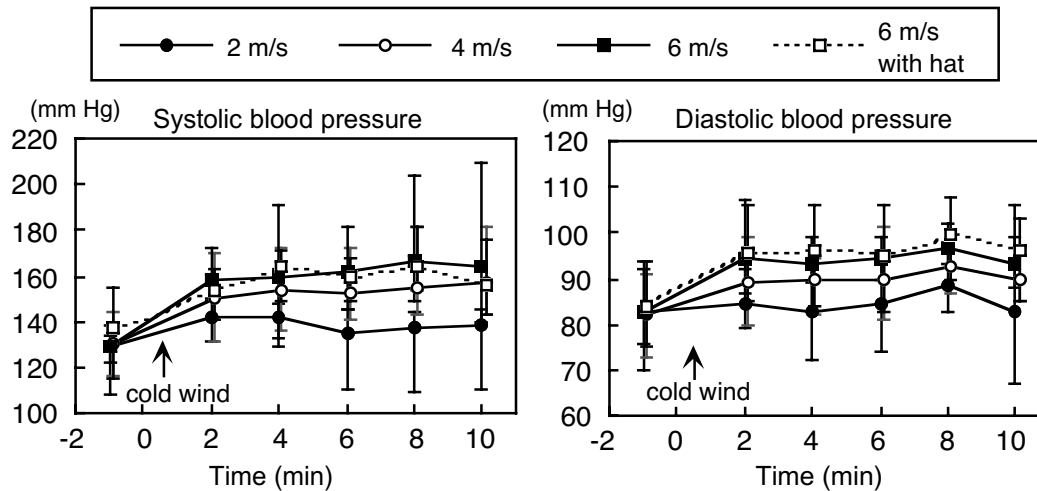


Figure 11. Average systolic and diastolic blood pressure of four subjects during exposure to wind (2, 4 and 6 m·s⁻¹). At all air velocities the subjects were bare-headed. In addition hat was worn at another exposure to 6 m·s⁻¹ (Paper VI).

bradycardia. Other subjects had a marked bradycardia response. After 4 minutes (the time that was completed in all conditions by all subjects, except one) average *SBP* and *DBP* were significantly higher at 4 and 6 m·s⁻¹ than at 2 m·s⁻¹, $p < 0.04$ (Paper VI, Figure 6). *SBP* was significantly correlated with pain, $p < 0.005$.

Respiratory function (Paper II)

FEV₁ and *FVC* were not affected by air velocity. The tidal volume (and *V_O₂*) was significantly higher (1.5 l SD 0.54 l) at 5 m·s⁻¹ than in 0.2 (0.93 l SD 0.31 l) and 1.0 m·s⁻¹ (0.85 l SD 0.25 l in ST after preconditioning at 20 °C, but not LOW and MOD (Figure 12).

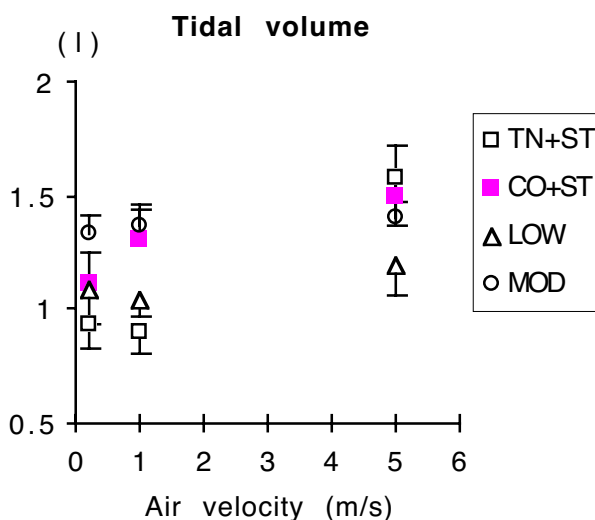


Figure 12. Average tidal volume in eight subjects after 20 minutes of exposure to 0.2, 1.0 and 5.0 m·s⁻¹ wind at standing (TN+ST and CO+ST) and walking after 60 minutes rest at +20 °C (TN, LOW and MOD) and -5 °C (CO). The bars represent the standard error of the mean.

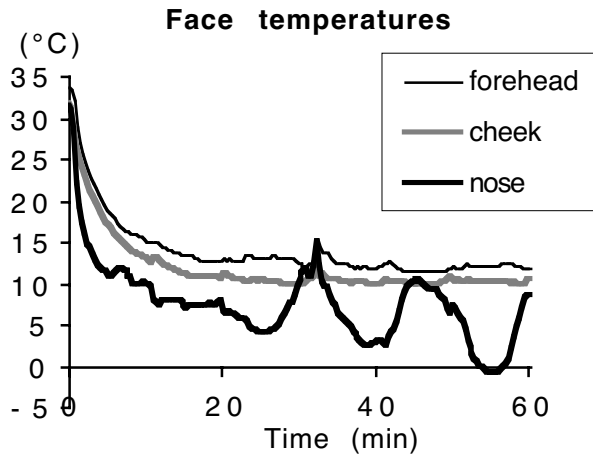


Figure 13. Face skin temperature of one subject walking at $-10\text{ }^{\circ}\text{C}$, $5\text{ m}\cdot\text{s}^{-1}$. Cold-induced vasodilatation is seen in the nose.

Effect of thermal state on blood pressure and face temperature during cold wind exposure (Paper II)

The total increase (from baseline values before the experiment to the end of exposure) of *SBP* and *DBP* was similar in both procedures (preconditioning at -5 and $20\text{ }^{\circ}\text{C}$). However, since the blood pressure increased at $-5\text{ }^{\circ}\text{C}$, but not at $20\text{ }^{\circ}\text{C}$, the following exposure to $-10\text{ }^{\circ}\text{C}$ induced a higher increase of blood pressure after $20\text{ }^{\circ}\text{C}$ preconditioning. The nose temperature of standing subjects was significantly lower after pre-cooling than after thermoneutral treatment at the end of exposure (Paper II, Figure 5). Forehead and cheek temperatures were similar at the two conditions.

Effects of rewarming by more insulation and increased physical activity (Paper I)

Both an increase of the insulation and increasing the exercise intensity of the subject resulted in abated mean body cooling rates. Mean body temperature was similar in both conditions. However, the rectal temperature continued to decrease slightly despite added insulation, while the increased metabolic heat production resulted in a $0.5\text{ }^{\circ}\text{C}$ higher rectal temperature.

Hand and foot temperatures tended to increase and thermal sensations tended to be warmer with increased exercise intensity. The arms, however, tended to cool more with increased walking speed. The added insulation raised the temperature mainly of the covered body parts, but the hands and finger temperatures levelled off or continued to cool.

Cold-induced vasodilatation, CIVD

In most of the experiments in Paper I cold induced vasodilatation occurred in the fingers at low finger temperatures. In Paper II-V CIVD was observed mainly in the nose (Figure 13 and 16) and sometimes in the cheek. CIVD started when the skin

reached a temperature below 15 °C and mostly around 10 °C. The temperature during CIVD rose higher in the nose than in the cheek.

Relation between mean skin temperature and thermal sensations

The mean skin temperature and body thermal sensations were weakly correlated (Spearman $R=0.50$). The mean skin temperatures at “neutral” body thermal sensations were generally higher than measured. They overlapped the predicted t_{sk} for comfort by Fanger (40) (Figure 14).

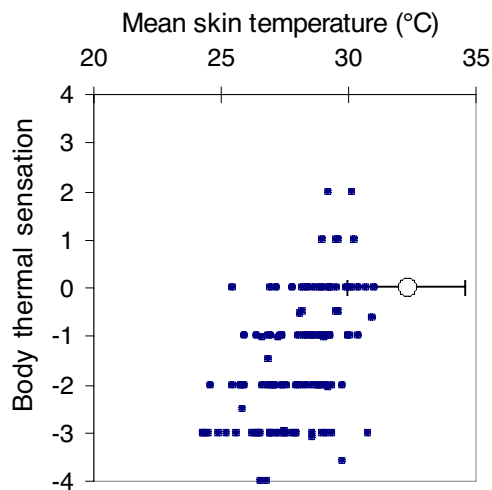


Figure 14. Relation between mean skin temperature and thermal sensation of the body of dressed subjects at standing and walking (Paper I-IV) at -6 to -22 °C ($n=126$). The corresponding average t_{sk} at the measured metabolic rates according to the comfort equation by Fanger (40) is represented by the white circle ($y=0$) and bars show range.

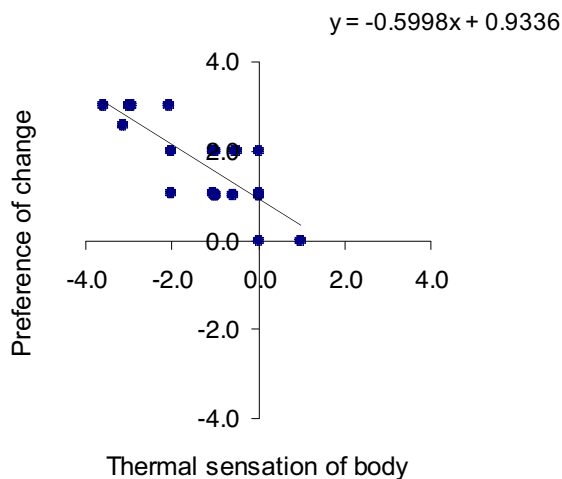


Figure 15. Relation between body thermal sensation and ambient temperature preference (Paper I)

Relation between thermal sensations and thermal preference

Thermal preference correlated rather well with the *TS* (Paper I) ($r^2=0.62$, $p<0.0001$). The intercept, 0.94, of the regression line (Figure 15) indicated that the subjects preferred a warmer ambient temperature when they had ‘neutral’ thermal sensations in the cold environment.

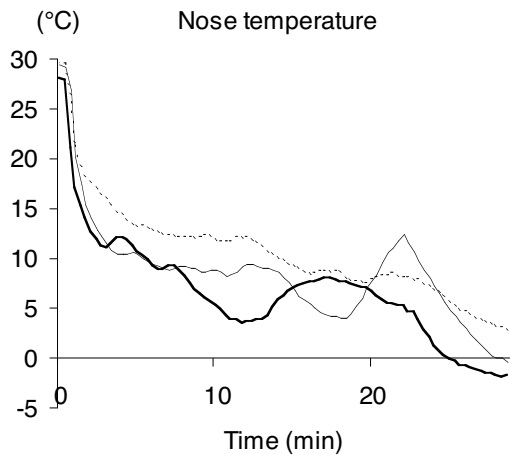


Figure 16. Nose skin temperature in three standing subjects at $-10\text{ }^{\circ}\text{C}$, $5\text{ m}\cdot\text{s}^{-1}$. Typical cold-induced vasodilatation (CIVD) is seen in two of the subjects.

Individual variation

The variation in the physiological variables was large. An example of variation in skin temperature is seen in figure 16. The vast ranges of systolic and diastolic blood pressure and heart rate responses in Paper VI are shown in table 14. The blood pressure responses could be divided into three categories: no/low, intermediate and high responses (Figure 17).

Table 14. Ranges of blood pressure and heart rate responses among a group of subjects subjected to face fanning at rest at $-10\text{ }^{\circ}\text{C}$, with (at $6\text{ m}\cdot\text{s}^{-1}$) and without hat (all air velocities).

Time (min)	Air velocity ($\text{m}\cdot\text{s}^{-1}$)	n	Systolic blood pressure change (mm Hg)		Diastolic blood pressure change (mm Hg)		Heart rate change ($\text{beats}\cdot\text{min}^{-1}$)	
			minimal	maximal	minimal	maximal	minimal	maximal
0-10	2	9	1	32	-6	23	10	-20
0-8	4	6	6	66	-3	24	3	-25
0-10	6	6	6	81	-4	30	9	-28
0-10	6 (hat)	5	3	61	9	20	4	-7

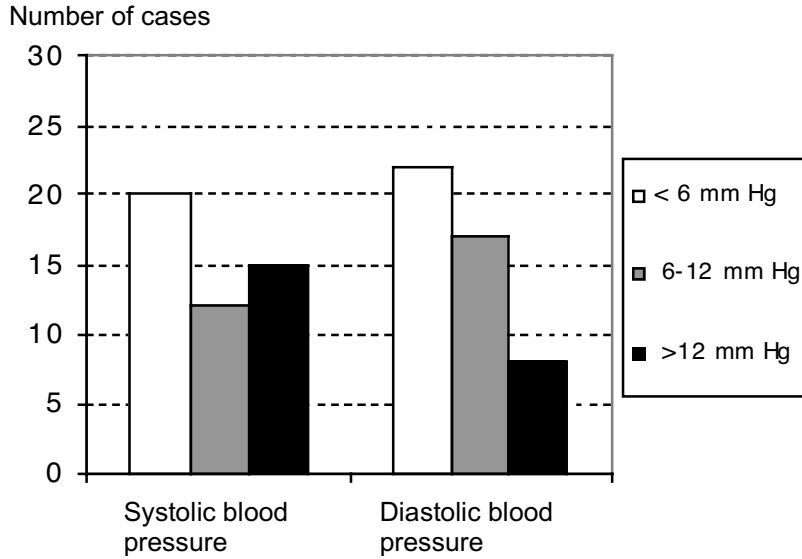


Figure 17. Systolic (SBP) and diastolic blood pressure (DBP) change in walking subjects at $-10\text{ }^{\circ}\text{C}$ and $0.2\text{-}5\text{ m}\cdot\text{s}^{-1}$ wind. The responses are grouped in categories.

Validation of IREQ/DLE (Paper I, II and III) - thermal sensation, core and skin temperatures

Heat balance was maintained in all conditions predicted to give heat balance according to IREQ. The net heat debt was less than proposed as cooling criterion ($<40\text{ Wh}\cdot\text{m}^{-2}$) in the ISO document ISO TR 11079 (90). The core temperature was maintained above $37\text{ }^{\circ}\text{C}$ in all temperatures, even though t_{sk} and t_{re} decreased slightly at the time limits of DLE at -14 and $-22\text{ }^{\circ}\text{C}$, respectively (Paper I, Table 3 and 4).

Table 15 contains a summary of the relationship between the experimental conditions (the heat production rate, the climate conditions and the available clothing insulation) and IREQ/DLE. It is supposed to show the predicted cold strain in the experimental conditions.

As mentioned in the background, corrections for the effects of wind and the pumping effect (ventilation) on the clothing insulation during walking have been proposed in the revision of IREQ as follows (Equation 1):

$$I_{t,r}/I_t = 0.54 \cdot e^{(-0.15 \cdot v_a - 0.22 \cdot v_{walk})} \cdot p^{0.075} + 0.5$$

where $(I_{t,r}/I_t)$ is the total insulation reduction, p is air permeability of the clothing ($\text{l}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$), v_a is the air speed ($\text{m}\cdot\text{s}^{-1}$) and v_{walk} is the walking speed ($\text{m}\cdot\text{s}^{-1}$). The revised IREQ (revIREQ) with the new correction of the effect of wind and body movements on the clothing insulation predicted higher cooling and gave significantly shorter DLE than the older IREQ at $5.0\text{ m}\cdot\text{s}^{-1}$ at standing and walking. At standing revIREQ and the older IREQ was similar at $0.2\text{-}1.0\text{ m}\cdot\text{s}^{-1}$. However, at walking revIREQ predicted less cooling and gave longer DLE at $0.2\text{-}1.0\text{ m}\cdot\text{s}^{-1}$.

In Paper I, DLE_{min} was about 4 h for thermal neutrality at $-6\text{ }^{\circ}\text{C}$ (Table 15), but only 40-60 minutes at lower ambient temperature. The thermal sensations, TS, were colder the lower the ambient temperature during the first hour of the exposure ($p<0.05$). TS were close to “slightly cold” at $-6\text{ }^{\circ}\text{C}$ (-0.7) after 90 minutes and at DLE in the lower t_a .

At sitting at $-5\text{ }^{\circ}\text{C}$ or standing at $-10\text{ }^{\circ}\text{C}$ (Paper II) heat balance would not be achieved according to IREQ. The rectal temperature at sitting did not decrease, but rather increased by 0.2-0.3 $^{\circ}\text{C}$. In ST after preconditioning at $20\text{ }^{\circ}\text{C}$ rectal temperatures were maintained or decreased by up to 0.6 $^{\circ}\text{C}$, but after preconditioning at $-5\text{ }^{\circ}\text{C}$ t_{re} decreased by 0.8 $^{\circ}\text{C}$ (to 36.3 $^{\circ}\text{C}$) at most. In CO+ST the thermal sensations “very cold” dominated after nearly 30 minutes, which was long before DLE (Table 15). Notably, all subjects reported pain sensations at this point. During moderate level walking at $-10\text{ }^{\circ}\text{C}$ (Paper III-IV) the available clothing insulation, I_{cl} , would give heat balance with thermoneutral sensations in 0.2 - 5.0 $\text{m}\cdot\text{s}^{-1}$. However, in LOW, where metabolic heat production was lower, I_{cl} was too low for heat balance at all air

Table 15. Presentation of the adequacy of the clothing insulation for the experimental conditions and DLE calculated with IREQ/DLE. M is the measured metabolic rate. Negative values indicate that the insulation of the clothing used was too low, 0: adequate, +: too high. I_{cl} was $0.35\text{ W}\cdot\text{m}^{-2}\cdot^{\circ}\text{C}$.

Paper number/ physical activity	Air temperature, $^{\circ}\text{C}$	Air velocity, $\text{m}\cdot\text{s}^{-1}$	M , $\text{W}\cdot\text{m}^{-2}$	DLE _{neutral}	DLE _{min}	Difference available insulation - IREQ _{neutral}	Difference available insulation - IREQ _{min}
I							
Walking, $2.0\text{ km}\cdot\text{h}^{-1}$	-6	0.2	107	2 h	4 h	-	-
	-14	0.2	108	60 min	90 min	-	-
	-22	0.2	119	40 min	50 min	-	-
II							
Standing after precondition +20 $^{\circ}$	-10	0.2	68	45 min	1 h	-	-
	-10	1.0	68	40 min	50 min	-	-
	-10	5.0	105	75 min	2 h	-	-
Standing after precondition -5 $^{\circ}\text{C}$	-10	0.2	78	1 h	75 min	-	-
	-10	1.0	84	55 min	75 min	-	-
	-10	5.0	117	2 h	4 h	-	-
III							
Sitting, precondition	-5.5	0.2	60	45 min	55 min	-	-
III							
LOW	-10	0.2	123	1.5 h	3 h	-	-
Walking $2.8\text{ km}\cdot\text{h}^{-1}$	-10	1.0	123	75 min	2 h	-	-
	-10	5.0	151	2 h	6 h	-	-
MOD	-10	0.2	164	>8 h	>8 h	+	+
Walking uphill $2.8\text{ km}\cdot\text{h}^{-1}$	-10	1.0	165	>8 h	>8 h	0	+
	-10	5.0	173	8 h	>8 h	0	0

velocities (Table 15). In LOW t_{re} increased slightly, by at average 0.1 to 0.6 °C, except for at 5.0 m·s⁻¹ where t_{re} in four subjects did not change or decreased slightly. In MOD t_{re} increased in all conditions by at average 0.2 to 0.9 °C.

The measured values were compared with the recommended criteria for thermal sensations, rectal and skin temperature (for criteria see Table 1a) for those conditions (MOD) that would give heat balance according to IREQneutral or IREQmin (Table 16). t_{sk} after 55 min was below the criterion for IREQmin, 30 °C (Table 1a), and IREQneutral in all conditions except for MOD0, where it was just met (Table 16, the small difference, 0.2 °C was of the same magnitude as the accuracy of the skin temperature measurement). Despite that, thermal sensations were neutral in MOD0 and MOD1. At 5 m·s⁻¹ the subjective sensations were around “slightly cold”.

At the predicted time limits for DLEneutral in Paper I average t_{sk} was lower than the criteria in the ISO document ISO TR 11079 (90). However, the body content was not lowered by more than 40 Wh·m⁻² (maximal heat debt proposed as physiological criterion of DLE) and the rectal temperature did not decrease at the predicted time limits.

As mentioned in the background, a new mean skin temperature criterion for high strain (IREQmin) has been suggested to replace the criterion in the revised version of the new ISO standard for evaluation of cold environments (Ingvar Holmér, personal communication). The criterion is a function of metabolic rate, in similarity with the criterion for IREQneutral: $\bar{t}_{sk} = 33.34 - 0.0354 \cdot M$ (2). The measured t_{sk} in comparison to the criteria in the old IREQ (Table 16) and revIREQ differed. The measured t_{sk} at 5.0 m·s⁻¹ was closer to the new criteria than the old criteria for IREQmin (Table 16).

Fingers, nose, cheek and chin were the coldest body parts. In Paper I the average hand temperatures were above the recommended minimal temperature, 24 °C, in ISO TR 10079 (90) at DLEneutral in all temperatures. The individual variation of peripheral temperatures was large. In three of the ten subjects the hand temperatures went below 24 °C at DLE time limits. At DLEmin the hand temperatures were as well above the recommended temperature 15 °C. The hand temperature was not below 24 °C at preconditioning (Paper II and III), but below 24 °C in 10 of the 48 walking experiments (Paper III).

Table 16. Comparison between measured variables, reported sensations and criteria in the conditions that would give heat balance according to IREQneutral or IREQmin, respectively. “difference” = measured - recommended criteria. Thermal sensations; 1=“slightly warm”, 0=“neutral”, -1=“slightly cool”, -2=“cool” (see Table10).

Paper	Ambient temperature (°C)	Air velocity (m·s ⁻¹),	Rectal temperature in balance?	t_{sk} criterion met? (difference, °C)	Thermal sensation
IREQneutral					
III (MOD)	-10	0.2	yes	no (-1.2)	0.4
III (MOD)	-10	1.0	yes	no (-1.7)	0.2
IREQmin					
III (MOD)	-10	0.2	yes	yes (-0.2)	0.4
III (MOD)	-10	1.0	yes	no (-0.7)	0.2
III (MOD)	-10	5.0	yes	no (-3.4)	-1.3

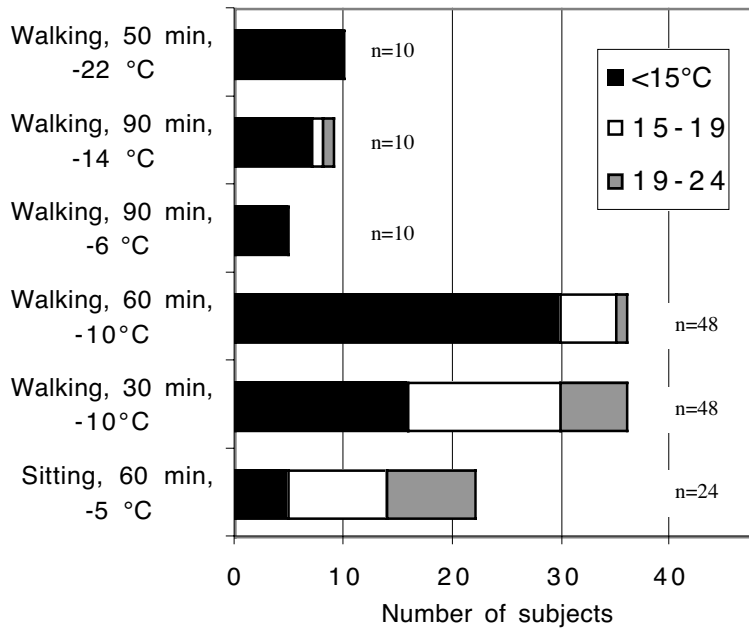


Figure 18. The number of subjects where finger temperatures below 15, 19 and 24 °C, respectively, at the end of exposure to – 5 °C and –22 °C. At –10 °C data from 0, 1 and 5 m·s⁻¹ wind were included. Values from 30 and 60 min walking (LOW+MOD) at –10 °C respectively are illustrated.

The finger temperatures were often much lower than the hand temperatures, the average finger temperature being 15-18 °C at DLE (Paper I). The finger temperature, which was not included as a limiting criterion in ISO TR 11079 (90) was below 15 °C in some subjects in Paper I, during sitting at –5 °C (Paper II) and in the majority of the walking experiments at –10 °C (Paper III). The occurrence of finger temperatures below 24 °C is illustrated in figure 18. Finger temperatures ranged between 8 and 32 °C at –6 and –14 °C and between 7 and 19 °C at –22 °C (Paper I). The low finger and hand temperatures resulted in reduced manual performance (Figure 19). Average hand temperature was about 4 °C lower at –14 °C (hand: 19.5 °C) and –22 °C (hand: 19.4 °C) than at –6 °C (hand: 23.3 °C). Pain was felt in the hands in three of the subjects and in the toes of two subjects at exposure to –22 °C. Six subjects experienced that the hands were the coldest and four that the feet were the coldest body parts.

The subjects had less acceptance the lower the ambient temperature the first hour at –6, –14 and –22 °C. Most subjects reported that they would have accepted the exposure at several occasions of a day, but not continuously. With finger temperature as an indicator of cold stress 91 % of the ratings “acceptable, only at a single occasion during a day” and “not acceptable” were reported when the finger temperature was below 15.0 °C. The corresponding mean skin temperature was 29.0 °C.

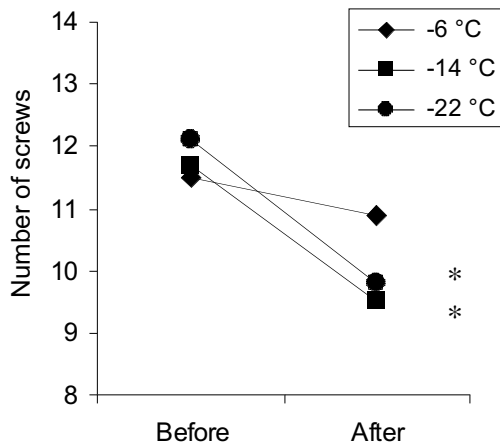


Figure 19. Average number of screws screwed in holes before and after exposure to cold before and after exposure to cold. Asterisk (*) denotes significant difference before-after.

Clothing insulation at exercise (Paper I)

The resulting insulation value measured on subjects was lower than the standard basic insulation measured on a static thermal manikin. The reduction of the standard value was approx. 25%.

Validity of the Wind Chill Index (Paper II, IV and VI)

In conditions above the risk limit of frostbite according to the Wind Chill Index the skin temperature in a number of cases reached 0 °C or close to zero. In about a fourth of the experiments of Paper VI (subjects seated) the skin temperature dropped to 0 °C before 10 minutes of exposure. The ear was the coldest site of the head in bareheaded subjects, while the nose was coldest when hat was worn. As expected, the cooling was greatest at 5 m·s⁻¹. In six subjects in Paper II (standing subjects) the nose temperature decreased below 2 °C in 5 m·s⁻¹ and in two subjects it reached 0 °C (about 15 %). Finally, in paper IV the nose cooled down to 0 °C or slightly below zero in five experiments, three in LOW5 and two in MOD5.

Effect of headgear on cold responses (Paper VI)

Wearing headgear with ear protection reduced the cooling of the ears and reduced pain sensations to cold wind and the systolic blood pressure response tended to be reduced with hat. The variation in peak *SBP* and *DBP* was much lower when hat was worn than in conditions without hat. *HR* was similar in 6 m·s⁻¹ with and without hat.

Discussion

The following discussion will primarily concern physiological and subjective criteria for cold work, effects of air velocity and metabolic rate on physiological responses and methodological issues.

Methodological considerations

Number of subjects/power of study. Considering the large variation in both temperature and cardiovascular responses a larger number of subjects would have increased the power of the studies. A problem with designing these experiments was scarcity of data on variation of responses and time. The within and between group deviation of physiological responses are not well documented in literature. Thus it was difficult to estimate the need of number of subjects. The experience of earlier experiments on temperature responses acted as guidelines for the selection of number of subjects. In the literature the individual variation has been given to little attention. After performing the present studies and finding an enormous variation in the limited and rather homogenous groups of subjects, it is astonishing to find that the individual variation is very seldom reported. This neglect results in an incomplete picture of physiological responses to the environment.

Studies have shown that there is seasonal variation in physiological variables (1, 76, 87, 104, 140). It is therefore important that each experimental series is completed in a reasonably short time to avoid time effects. This limits the number of subjects that may be used in a study. Another factor is of course the features of the subjects willing to take part in a study. In the first studies (Paper I-V) only healthy male subjects were selected. One reason for this was that the clothing ensembles used (construction worker and military clothing) were only available in larger sizes. The fit of clothing was important, since the insulation is related to fit (66, 137), and because the walking movements should not be affected in an abnormal way. The other factor was the mentioned seasonal variation. In Paper VI, which contained shorter experiments, both (healthy) women and men were asked to participate. However, only two women were interested. Unfortunately, relatively few studies on wind effects specifically have included a comparable number of women to men (3, 122). A few of these studies have found sex differences in DBP response to cold (128), in vasomotor responses to alfa and beta agonists and beta blockade stroke volume response (55), while others have failed to find differences in heart rate, mean arterial blood pressure, face temperature in response to face cooling (3, 122).

The study group was rather homogenous in age, anthropometric measures, sex and ethnic background. This may limit the generalisation of results to more heterogeneous groups of people exposed to cold wind. Despite the homogeneity, large individual differences in responses were observed. These are discussed below.

Weighing. Due to simultaneous heat balance measurements during walking experiments (not reported in the papers), the subjects had to be weighed after 30

minutes at slightly higher air temperature in a connecting chamber without wind. This increased the skin temperature temporarily.

Sensor errors. To be able to follow the cooling process thermocouples, which had short time constant, were used in paper VI. In the studies with longer duration thermistors were used to measure the skin temperature of the body, extremities and face. The accuracy of the temperature measurement (in the collecting data system) was similar in all studies, 0.2 °C.

Cold environments (large temperature gradients) are a well-known challenge for surface temperature measurements. All measurements that are done with sensors attached to the skin are actually *sensor* temperatures. However, the sensors that were used in the present studies are believed to give good estimates of the skin temperatures and may be reported as “skin” temperatures as long as one is aware that there is an error inherent in the estimate. The sensor thickness exceeded the thickness of the boundary air layer on the skin (face, nose and ear) (51). The sensors were thus exposed to the temperature of the ambient air. A slight underestimation of the skin temperature is probable in the papers II-V, due to ambient temperature influence on the sensors. However, some factors reduced the error in measurement. The sensors had a flat area in contact with the skin and a rounded top, why the relative area exposed to the environment was the smallest possible. With an insulation of tape on top of the sensor, the error became lower. The porous surgical tape used for attaching the thermistors (and the thermocouples) to the skin covered the thermistors. This means that i) the thermistor surface was insulated, which reduced the convective heat transfer from it (14), ii) the thermistors were partly “buried” in the skin, which reduced the part of the sensor exposed to the environment and iii) measurement errors due to bad skin contact were minimised. The radiation effect would also be negligible by the same reason. If the estimated error of thermistors in a paper by Danielsson (27) is used, which currently provides the closest possible estimate, the error would be about 2 °C in paper II-V. However, when thermocouples are glued to a surface, as they were reported to be in Danielsson’s paper the distance from the exposed surface of the sensor to the underlying surface would increase and actually give a larger measurement error than with the method used in the present studies. The errors of the smaller thermocouples might be less for the above reasons. However, when the forehead temperatures in the different studies were compared at 4-6 m·s⁻¹, the two sensors seemed to give compatible results (Figure 10).

Physiological responses

Metabolic heat production and oxygen consumption

The metabolic rate (and oxygen consumption) was higher at standing and walking at low intensity at -10 °C and 5 m·s⁻¹ wind (Paper II-V) compared to lower air velocity and at -22 °C after 80 minutes of slow walking (Paper I) compared to higher air temperature. The studies do not provide any evidence for the explanation of the increased metabolic rate, but most likely it was due to an increased muscle activity.

In Paper I (without wind) M was 10% higher at the lowest temperature, $-22\text{ }^{\circ}\text{C}$ than at -6 and $-14\text{ }^{\circ}\text{C}$. However, M was about 20% higher with an extra jacket than with the initial clothing. This may be explained both by the additional mass of the jacket, but also by its bulk, although the arms and not leg movements were most restricted, increasing muscle activity. At standing and during walking at low intensity (Paper I-V) the cold exposure induced shivering in some of the subjects although core temperature was above $36.5\text{ }^{\circ}\text{C}$ in all conditions. The muscle activity was not measured, but the subjects reported that they experienced shivering and the shivering was often observable. The present results are well in line with the increase of V_{O_2} by 15 % of the maximal V_{O_2} of subjects during walking in cold wind reported by Pugh et al. (154).

In wind (Paper II-V) M was higher at $5\text{ m}\cdot\text{s}^{-1}$ than in still air, both at standing (about 35% higher than control) and during walking (22% higher at low intensity than control). The higher M was probably mainly caused by shivering, which almost all subjects experienced when standing at $5\text{ m}\cdot\text{s}^{-1}$, but only four in $0\text{ m}\cdot\text{s}^{-1}$. Local cooling of the face by $1\text{-}5\text{ m}\cdot\text{s}^{-1}$ wind at $-20\text{ }^{\circ}\text{C}$ for 15 minutes increased the metabolic rate by 12% in resting subjects (172). The change was accompanied by a shift from carbohydrate substrates towards fat, but V_{O_2} was not significantly increased. In MOD5 no one reported shivering, compared to three subjects in LOW5. Shivering may increase the oxygen consumption five times the basal metabolic rate (86). Even before shivering is observable, cold-induced muscle tension may increase the oxygen consumption (180). Shivering may explain some of the difference between LOW and MOD. A small increase in myocardial oxygen demand, due to increased blood pressure may also have slightly contributed to the increase of V_{O_2} . In addition, the pressure from wind may have forced the subjects to activate their muscles more. At standing the postural muscles may have been more activated and during walking mainly the leg muscles had to work harder. Further, the higher workload of walking uphill may have masked the additional effect of the pressure of wind. It may be necessary to correct for a higher metabolic rate during work against wind when calculating IREQ.

In short, the higher V_{O_2} in wind was probably explained by shivering, higher postural muscle activity, lower muscle efficiency, higher effort to move with bulky clothing and finally to move against wind pressure and possibly an increased myocardial oxygen demand.

The increased heat production during walking provided heat for the peripheral body parts. A proportional increase of the nose skin temperature to the increase in rectal temperature was observed (Figure 20). The finger temperature change versus rectal temperature change showed a more scattered pattern (Figure 20), but above a rectal temperature increase of $0.5\text{ }^{\circ}\text{C}$, fingers were warmer than below this level (in LOW0 and LOW1). However, at a rectal temperature increase of about $0.5\text{ }^{\circ}\text{C}$, the nose skin temperature was maintained at initial level or increased in almost all subjects. The increase of temperature was particularly obvious after the increase of walking speed at $-22\text{ }^{\circ}\text{C}$ in Paper I. However, in this experimental condition the increase of hand temperature coincided with an average increase in rectal temperature only by $0.2\text{ }^{\circ}\text{C}$.

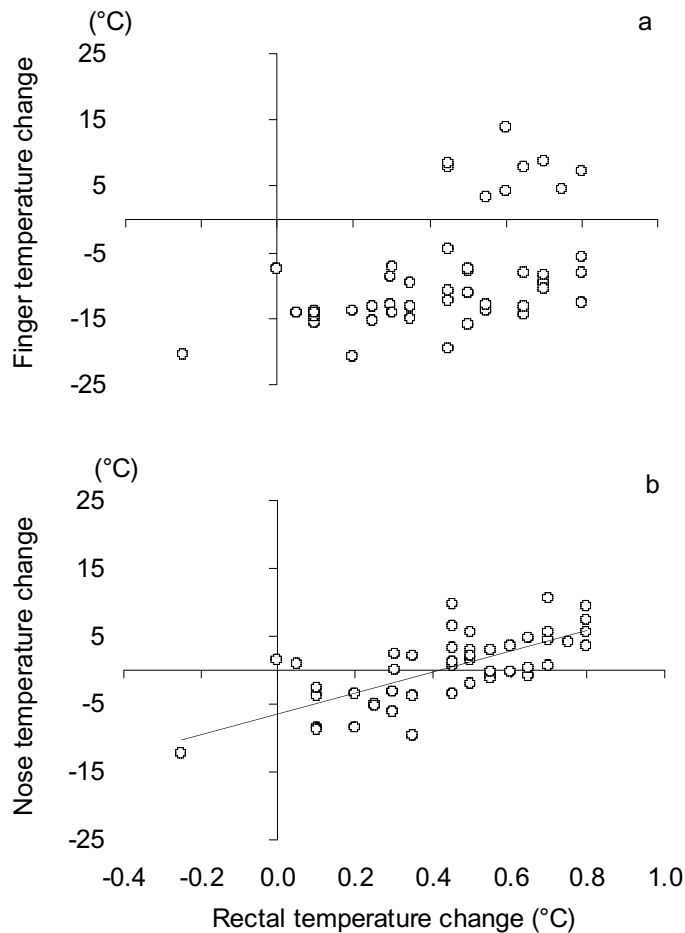


Figure 20. Change of rectal temperature and change of finger a) and nose b) temperature during walking at $-10\text{ }^{\circ}\text{C}$ without and with wind for 60 minutes, $n=48$ (Paper III, IV). Observe that data from all air velocities are represented.

The skin temperature increase most likely reflects an increase of skin blood flow, produced by reduction of sympathetic tone of the blood vessels (see (134)). It seems that the release of tone was induced by an increase of central blood temperature. The relatively lower blood flow change of the finger skin may be due to different levels of vasoconstriction initially or a difference between the maximum blood flow capacity of nose and finger skin. The similar skin temperature (and most likely blood flow) responses in nose and finger were very well in line with the results of Blair et al. (9) on whole body cooling and skin temperature responses.

Finger and foot temperatures tended to increase and thermal sensations tended to be warmer with increased exercise intensity. The arms, however, tended to cool more with increased walking speed. The added insulation raised the temperature mainly of the covered body parts, but the hands and finger temperatures levelled off or continued to cool.

Cold-induced vasodilatation, CIVD, was observed in the nose, cheek and fingers when the temperature went below $15\text{ }^{\circ}\text{C}$ and contributed to the increase of skin temperature. The core temperature is the major factor for the magnitude of increase in

temperature during CIVD in fingers and even small changes in core temperature may have a large impact on the reaction (26).

In summary, the effects of exercise on regional blood flow may prevent cold injury in the vulnerable peripheral areas, i.e. fingers, nose, ears and toes or at least prolong the exposure time.

Face temperature

The skin temperature in the face as in the rest of the body is not homogenous and differs between subjects as well. This may be due to differences in the distribution of vessels in the face and vasomotor function, differences in skin anatomy (subcutaneous fat), shape of the nose and face. The nose in the present studies was often the coldest and sometimes the cheek temperature was as low. The forehead had always the highest temperature. In other studies of cold wind exposure, the cheek temperature, which was suggested to be inversely related to the subcutaneous fat layer, was lower than other face areas (109, 167). Nose temperature showed no relationship with nose size and shape (167). Dulac et al. (33) found that cheek and forehead temperatures in cold wind ($18 \text{ m}\cdot\text{s}^{-1}$, $0 \text{ }^\circ\text{C}$) at rest and exercise at a level (50 W) similar to those in the present studies, The wind chill temperature of their conditions corresponded to $4 \text{ m}\cdot\text{s}^{-1}$ at $-10 \text{ }^\circ\text{C}$ according to WCI. The secondary effect of heat regulation on the nose and finger temperature that was observed in the current studies was not possible to be observed in their study at the beginning of exercise. However, after 12 minutes of exercise the nose temperature had increased above resting levels. Studies of very short duration may show reflexes elicited by cold wind, but not reveal sustained effects. Face skin temperature is further discussed below in relation to the Wind Chill Index.

Respiratory function

The effects of cold on respiratory function were limited to conditions where the subjects were physically inactive, although one might have expected effects of low temperature at higher lung ventilation. Similar effects on forced expiratory volume in one second (FEV_1) was found by Koskela et al. (102) with facial cooling of the skin during rest at $-17 \text{ }^\circ\text{C}$. The face stimulation triggered bronchoconstriction in patients with chronic obstructive pulmonary disease, asthmatic, and non-asthmatic subjects (101, 102). Also McDonald et al. observed bronchial narrowing in both normal subjects and patients with airway disease at rest (126). FEV_1 was reduced by 6% in normal subjects and 10% in the patients. For physically disabled individuals having respiratory problems exposure to cold wind may imply a particular risk.

In subjects breathing $-40 \text{ }^\circ\text{C}$ air during moderate exercise a substantial reduction of upper esophageal temperature was observed (93), which may affect respiratory function. However, the ventilation at the exercise levels used in the present studies was low and probably did not have effect on airway temperature.

Cardiovascular responses

Even moderate wind speeds ($1\text{-}6 \text{ m}\cdot\text{s}^{-1}$) at low air temperature caused the blood pressure to increase significantly in many subjects.

The observed blood pressure increases in response to cold and wind were probably partly a response to an increase of total peripheral resistance. The reduced skin temperatures indicated that the skin vessels were constricted. Skin vasoconstriction was caused by an increased heat loss in the cold in particular by convection in wind. Further, skin vasoconstriction was most likely strongly induced by the cold wind stimulation of the bare face (38, 68, 176). This idea is in line with the responses of a study of subjects exposed to $-15\text{ }^{\circ}\text{C}$ and $3.5\text{ m}\cdot\text{s}^{-1}$ wind (5). The blood pressure increased immediately at cold wind exposure, stabilised on a high level already after 5 minutes and stayed there although the skin temperature continued to drop until the end of exposure after 15 minutes (5). Another cause for the blood pressure increases may be the effect of catecholamines on the blood pressure. Cold stress increases the circulating catecholamine concentration and may cause a rise in both cardiac output and heart rate. However, the vagal effects of facial cold stimulation seems to dominate the sympathetic effects at low activity (112).

At standing the postural muscles performed mainly isometric work, causing low muscular blood flow. The assumed low blood volume in both the muscles would have contributed to the total peripheral resistance. However, in the study by Arjamaa et al. (5) the blood pressure increase of sitting subjects was very similar with the values at standing. During exercise vasodilatation of the muscles probably occurred to a greater extent, especially at the moderate level. Thus the blood pressure increase during walking was lower than at standing (and sitting), although not eliminated at $5\text{ m}\cdot\text{s}^{-1}$. Body movements are thus important to counteract the blood pressure response to cold.

However, in Paper VI only the face was exposed to wind and the whole body was exposed to cold for only a short time. Total peripheral resistance (TPR) was not expected to increase significantly due to increased heat loss in those conditions. Very large blood pressure responses were observed, which indicated strong cold-induced reflex vasoconstriction. Besides TPR, the increase in blood pressure may be explained by trigeminal stimulation by cold of the face, which elicited bradycardia at $6\text{ m}\cdot\text{s}^{-1}$. At $4\text{ m}\cdot\text{s}^{-1}$ bradycardia was not induced, although blood pressure increased markedly. This again indicates the role of TPR for the blood pressure responses observed. It may be that reflex vasoconstriction during isolated face fanning would have abated if the exposure had been prolonged. However, the above discussion about the mechanisms of the blood pressure increase remains speculative and requires further studies to be fully understood.

An acute blood pressure increase is normally compensated by bradycardia through baroreceptor reflexes. Bradycardia was observed during the first 6-10 minutes at sitting and standing, but the effect faded with continued exposure whereas the blood pressure remained elevated for another 20 minutes at standing. This indicates that the cardiac output was unchanged due to a stroke volume increase. This is supported in a study by McArdle et al (125) on whole-body exposure to low ambient temperature. Probably due to various experimental protocols in different studies, the results of cardiac output and stroke volume at exposure to cold are not consistent (13, 38, 98, 158, 168, 179).

Concurrently with the temperature decrease cold face stimulation probably triggered a trigeminal reflex response of the heart. Baroreceptor induced bradycardia is augmented by trigeminal stimulation (see (3)).

The pressure of wind may stimulate mechanical receptors in the face skin and thus contribute to the responses (181). A comparison of responses between wind and still air with a clamped face temperature would indicate if mechanical stimuli contribute to the response to cold stimuli.

Pain may also have contributed to the increase of blood pressure. In Paper VI the pain and SBP were associated. Stimulation of pain receptors activates somatosympathetic spinal reflexes and centrally mediated autonomic responses, producing an increase in heart rate an cardiac output, skeletal muscle vasodilatation and skin vasoconstriction (149). Pain and blood pressure was observed to be correlated in cold pressor tests (120, 149). Further, pain intensity covaries with blood pressure changes (185).

One may expect that lower face skin temperature would provide a stronger stimulus for the cold-induced reflex blood pressure response. At standing cooling rate and blood pressure responses only correlated weakly. A relationship between face skin temperature and magnitude of blood pressure response may be of non-dose-response type or it may be masked by other more important factors determining the blood pressure response.

The temperature at most studies of exercise in cold wind has been above 0 °C, why the cooling effect is mild compared to the conditions in the present wind studies.

The cardiovascular responses of the middle-aged group were similar to those of the younger subjects studied. Autonomic cardiovascular responses have been reported to be slightly attenuated in middle-aged subjects compared to young subjects and to decline rapidly in older age (96). Ageing reduces cardiac vagal activity and impaired cardiopulmonary reflexes (18, 19). The changes with age were found to be due to the receptor organ or in combination with defects in other parts of the autonomic system and not due to an isolated impairment of the peripheral autonomic nerve (96). However the groups in the present studies are not completely comparable since they followed different experimental protocols.

Cardiovascular diseases and cold

Cardiovascular problems

The high blood pressure observed at low activity may have implications for health. There are indications from epidemiological studies that cold has a sustained effect on blood pressure. Normotensive subjects (1) and hypertensive subjects (11, 65) have higher systolic pressure in winter than in summer (104, 140). On the other hand, LeBlanc reported that repeated cold exposures of outdoor workers to severe cold during a full winter season abated the sympathetic response and enhanced vagal activation (111). Unfortunately, the absolute blood pressure before and after winter was not reported.

The sympathetic nervous system plays an important role in long-term regulation of arterial pressure (see (146)). The reactivity in individuals may be divided in different groups, “high”, “mid” and “low reactors”, depending on their responses to cold or pain stimuli (149). Cardiovascular reactivity has been proposed to be a predictor and factor in subjects for later development of hypertension (see (28)) and cardiovascular disease (103, 106, 124). Increase of systolic and diastolic blood pressure and heart rate activity at exposure to stress factors would play an important role in development of arteriosclerosis (11). However, the sympathetic activation alone does not appear to be a single cause for hypertension. 25-30% of patients with primary hypertension was found to have neural hyperactivity (28).

The reduced blood pressure responses at moderate exercise in Paper III-V was in line with the results of Lassvik (107) who observed that the physiological responses in angina patients abated when they were heated before exposure.

Many studies have pointed out cold as a risk factor for cardiovascular and respiratory problems. Epidemiological studies have showed cold exposure to be associated with excess mortality (29, 58, 118). The causes for the excess mortality of winter are probably multi-factorial, involving thrombogenic (131) and reflex consequences of cold exposure. Cold stimulation of the face lowers the threshold for onset of pain in angina pectoris patients (136). The significance of cold wind exposure effects on health is supported by the findings of a strong association between mortality from certain pathological types of stroke and the current wind chill conditions (54).

Physiological and subjective criteria for cold work

IREQ

As mentioned, the IREQ/DLE method described in ISO TR 11079 (90), is being revised (Ingvar Holmér, personal communication). The corrections for the effects of wind and walking on the clothing insulation are based on results from measurements on a thermal manikin performing walking movements in a wind tunnel (139). Thus, the revised method takes into account both the effects of wind and walking on the clothing insulation. In the old IREQ only the boundary air layer is corrected for at standing. The differences in predicted cold strain between the revised and old versions of IREQ might be explained by the different corrections used. The correction factor of the reduction of the insulation in old IREQ at walking is -20% (for $M > 100 \text{ W}\cdot\text{m}^{-2}$), while the corrections in the revised IREQ at low walking speeds ($2.0\text{-}2.8 \text{ km}\cdot\text{h}^{-1}$, when the metabolic rate is $>100 \text{ W}\cdot\text{m}^{-2}$) and low air velocity ($0.2\text{-}1.0 \text{ m}\cdot\text{s}^{-1}$) are lower ($<8\%$). The correction for the reduction of the insulation for $5 \text{ m}\cdot\text{s}^{-1}$ wind in the revised IREQ exceeds that of the old IREQ at standing by 22% and during walking by 6%.

The standard document ISO TR 11079 (90) suggests certain physical and physiological criteria. These are limits for change of body heat content, mean skin temperature, hand temperature and evaporative heat loss (see “Background”, Table 1a,b). The change of body heat content is suggested to be limited to $40 \text{ Wh}\cdot\text{m}^{-2}$ (Q_{lim}), but the lowest acceptable absolute core temperature has not been suggested. Since the body measures vary widely between individuals, lean and fat individuals may end up

at different core temperatures at this limit. To some extent this is corrected for in *Qlim* by the body surface area (based on body mass and height). In Paper I where the subjects were homogenous in terms of body build, the core temperatures varied between 36.8 and 37.7 °C at *Qlim*. At standing (Paper IV) however, the rectal temperature varied between 36.3 and 37.4 °C. Within a more heterogeneous group of subjects and with longer time the rectal temperature may vary much more. Moreover, cold exposure is not always beginning with the body in heat balance. The body may be slightly cold (as in Paper II) or heated. Using a fixed change of body heat content as a criterion may lead to underestimation or overestimation respectively of the resulting cold stress.

The criteria for mean skin temperature according to IREQmin (higher strain) were not fulfilled at 5.0 m·s⁻¹ although the core temperature was at a normal level, but criteria were met at the other conditions. This indicates that the cooling effect of wind was larger than assumed in the calculations of IREQ, even in the new revised version.

The calculations of DLEmin assume a previous initial cooling to about 30 °C. From this thermal state -40 Wh·m⁻² is allowed. However, in real life the mean skin temperature changes during the exposure, while it is static in the calculations of DLE.

It was somewhat confusing that t_{sk} criteria was not met for IREQneutral (40) although the thermal sensations were 0 or warmer in MOD0 and MOD1 (except for one subject). The recommended mean skin temperatures for predicted “high strain” were reached in MOD0 and MOD1 conditions, but here thermal sensations were 0 or warmer although cool sensations were predicted. The comfort criterion for mean skin temperature describes a relationship between t_{sk} and metabolic rate, which was derived from experiments at temperatures between 10 and 30 °C, with intermittent stepping work at low activity levels (58-174 W·m⁻²) and thinner clothing ensembles. The comfort equations developed in moderate environments may not be suitable for cold and windy conditions. Increases in rectal temperature may have counteracted the effects of low skin temperature on the thermal sensations. Thermal sensations of the body are based on input from both the core and the periphery (42, 138). It should be noted that the experiments were short in comparison to an eight-hour working day and therefore both rectal temperature and skin temperature may change. Another explanation for the discrepancy between predicted and measured values may be that thermoneutral sensations do not coincide with thermal preference. Paper I showed that the subjects preferred a slightly warmer ambient temperature when they reported ‘neutral’ thermal sensations. A certain positive body heat content change is probably needed to give comfort skin temperatures in subzero environments. In the present studies the activity levels were too low to provide enough peripheral heat input. Moreover, an individual may not report thermal comfort (or thermoneutral sensation) if one or a few body parts are very cold even though the rest of the body is warm (150). Thus, criteria for t_{sk} may be suitable for moderately cold environments, while in subzero environments local temperatures dominate the overall sensation. The mean skin temperature in the papers were weighted on 15 local measurements, of which four were peripherally located (hand, foot, forehead and nose). This may result in slightly lower mean skin temperatures in cold than when fewer peripheral sites are measured

and form mean skin temperature and contribute to the reason for the discrepancy between predicted and measured values.

The relationship between thermal sensations and mean skin temperature has been studied by Afanasieva in Russia, who presented the thermal sensations as a new function of mean skin temperature and metabolic rate (2). The relationship is compliant with the Fanger criteria (40), but based on experiments at a range of low ambient temperatures. Thus, the function provides a more realistic criterion than the previous constant mean skin temperature of 30 °C. The new function:

$t_{sk} = 33.34 - 0.0354 \cdot M$ (2) is suggested to replace the criterion in the revised version of the new ISO standard for evaluation of cold environments (Ingvar Holmér, personal communication). The new t_{sk} criterion for “high strain” seemed to be closer to the measured t_{sk} values than the old IREQ constant criterion.

Extremity temperatures. Most occupational work tasks require good manual performance. Sufficiently high hand and finger temperatures are therefore important. In ISO TR 11079 (90) the lowest recommended hand temperature is 24 °C at neutral IREQ-level and 15 °C at IREQ-minimal level. Many subjects had lower hand and finger temperatures than recommended in the studied conditions. The variation was large. Similar to walking in wind, the dorsal hand and finger temperature, was below 24 °C and 15 °C, respectively, in almost half of the standing experiments, reported in a separate paper (135). In subjects standing in 5 m·s⁻¹ wind at -10 °C the average hand and finger temperatures reached 24 °C and 15 °C, respectively, already before DLE, calculated with the new wind correction (Figure 21). Quite a few of the subjects most probably had impaired hand function despite that their central temperature was maintained at acceptable levels. The results from the simple screw tests, described in paper I, confirmed that the manual performance deteriorated in the majority of the subjects when the hands were about 20 °C. This is in line with previous findings,

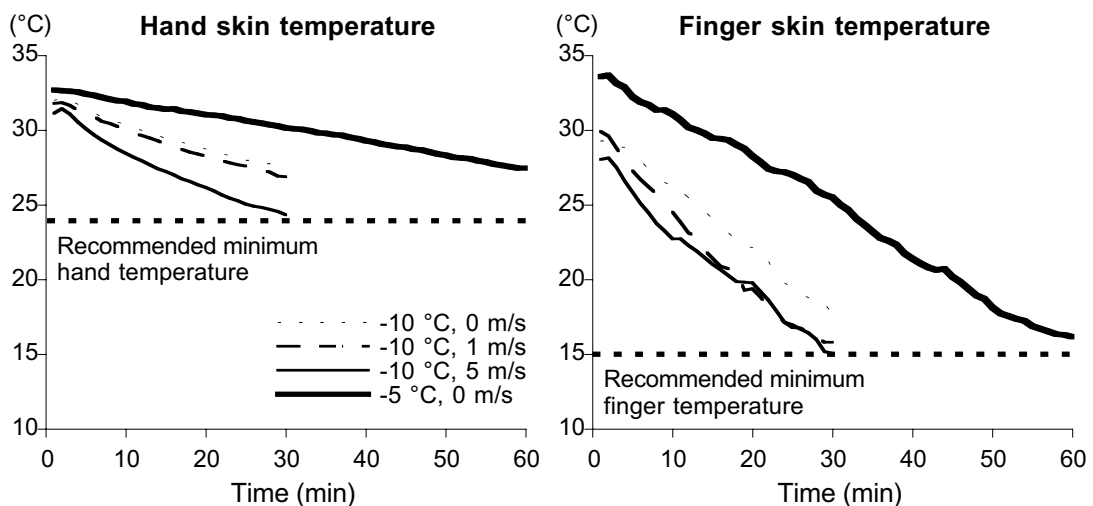


Figure 21. Average hand and finger temperature of eight sitting (-5 °C) and standing (-10 °C) subjects at cold wind exposure. $DLE_{neutral}$ was 45 min at -5 °C and 35-45 min at -10 °C. Data from Gavhed et al. (49).

which additionally states that the manual function substantially decreases at 15 °C (8, 74). The low temperatures observed in fingers and hands would not be acceptable for safely performing manual work tasks, since manual function is known to be impaired when finger temperatures are lower than 20 °C (8, 74).

A slight net heat gain is often needed to maintain high hand temperature at low ambient temperatures and low intensity work levels (116). In Paper I the increased metabolic heat production by 63 W·m⁻² after 50 min at 120 W·m⁻² tended to increase the temperature of the cooled fingers and the thermal sensations tended to be warmer. To ensure manual performance and acceptable hand and finger temperatures of the individual, the clothing insulation must be selected with respect to the type of activity and duration.

The higher metabolic heat production in Paper III was intense enough to most likely reduce peripheral vasoconstriction. Consequently, the finger skin temperature was significantly higher in MOD than in LOW at 0.2 m·s⁻¹ and 1 m·s⁻¹ wind.

Sweat evaporation. The evaporative heat loss in Paper I was calculated on the body mass loss corrected for evaporative and metabolic mass losses. At body thermal sensations ratings between -0.5 and 0.5, the measured evaporative heat losses were between 0 and 34 W·m⁻². The average was 16 W·m⁻². The corresponding value according to the comfort criterion for evaporation developed by Fanger (40) was 46 W·m⁻². Use of this comfort criterion in IREQ would result in too high sweat and evaporation rates in cold environments (46).

Heat exchange and clothing insulation. Similar with other studies (8, 56, 66, 79-81, 129, 143, 178) the initial clothing insulation in Paper I was reduced during walking, by approximately 25%.

Exercise on a treadmill does not simulate the relative air velocity produced by walking in still air in normal work situations. Hence, the reduction of total insulation in the experiments was probably less than it had been in real conditions. However, the movements of the legs and arms stirred the surface air layer partly. Air/body movements of 1.2 m·s⁻¹ reduce the largest part of the surface air layer (139). An air speed of approx. 1.5 m·s⁻¹ would correspond to the conditions with reference to convection cooling in the walking experiments of Paper I in still air. Consequently, the skin temperature was probably slightly higher in our experiments compared to walking in 'real life' in otherwise the same conditions.

WCI and frostbite

Although WCI predicted no frostbite risk in any of the experimental conditions in the present studies, temperatures of bare skin reached 0 °C or close to 0 °C. In 12% (standing) to 33% (sitting, walking) of all experiments at 4-6 m·s⁻¹ the skin temperature dropped to 0 °C. In addition the skin temperature reached 2 °C in 37% of all exposures to 5 m·s⁻¹. Thus, the cooling effect of wind at the present studies seemed to be underestimated in the zone in WCI described as "bitterly cold". This result is

Table 17. Cooling power of wind on exposed flesh expressed as a chilling temperature under almost calm conditions ($1.8 \text{ m}\cdot\text{s}^{-1}$) according to the revised Wind Chill Index (145). The wind speed is the value at 10 m above ground level.

Wind speed, $\text{m}\cdot\text{s}^{-1}$	Actual thermometer reading, $^{\circ}\text{C}$						
	5	0	-5	-10	-15	-20	-25
1.5	4	-2	-7	-13	-19	-24	-30
3	3	-3	-9	-15	-21	-27	-33
6	1	-5	-12	-18	-24	-31	-37
9	0	-7	-13	-20	-26	-33	-39
12	-1	-7	-14	-21	-27	-34	-41

Shaded area: risk of frostbite in prolonged exposure, Bold type (in shaded area): frostbite possible in 10 minutes.

perfectly in line with that of LeBlanc et al. (109). He concluded the cooling effects to be underestimated by as much as about 10°C . Further, they found that the zone “dangerously cold” was better correlated with their skin temperature results.

An underestimation by 10°C is probably exaggerated, especially in view of the short exposure time. Osczevski presented a modification of the WCI based on new data of heat loss from a thermal head model some years ago (145). The revision resulted in new equivalent temperatures, which were significantly higher than the old ones. Comparing the experimental wind conditions in the current papers with the new WCI table, $4\text{-}6 \text{ m}\cdot\text{s}^{-1}$ would still be in the “bitterly cold” zone and not exceed frostbite risk level (Table 17).

A revised Wind chill table has recently been presented in North America (10, 84). This table indicates that there is no risk for frostbite at any wind speed at -10°C (Table 17), which diverge from the results for individual subjects in the present papers. However, if only referring to the average skin temperature of all subjects no frostbite would be occurring at this ambient temperature at $6 \text{ m}\cdot\text{s}^{-1}$. A recent report from Tikuisis and Osczevski (174) supplemented the new index with a dynamic tissue cooling model which predicted the time for reaching 10°C of an exposed cheek to be about 5 minutes at -10°C and $5 \text{ m}\cdot\text{s}^{-1}$. This value is identical to the average cheek temperature at standing.

The lack of coherence may be due to physiological factors present in humans, such as skin vasomotor responses and skin morphology, but which are not simulated by the physical head model. Another important matter is that WCI predictions are based on the cheek temperature, which was not the commonest location where the skin temperature reached 0°C , but the nose. The ear was the coldest site of the head when the subjects were bareheaded, while the nose was coldest when hat was worn. Ears are the commonest frostbitten part of the head, while the nose is the commonest part of the face where frostbite occurs (113). The nose and ears have a higher area-to-mass ratio than the other parts of the head and is therefore more vulnerable to cold. Thus, the nose temperature seems to be the limiting factor for cold wind exposure of the face when hat with ear protection is worn, while the ears are at high risk when bare-headed.

Frostbite occurs at air temperatures below 0°C . In Finland the incidence increased from the ambient temperature range -6 to -10°C , more the colder the air temperature (94). The occurrence of frostbite at these ambient temperatures conforms to the data of

the present studies. Many factors increase the risk for frostbite and cold injuries (63). Predisposing factors are old age (elderly) and young age (small children), alcohol, use of some drugs and vibration exposure (fingers). In a recent study a proportional increase in frostbite incidence with age was reported (94). The reasons behind this pattern have not been studied, but an attenuated skin circulation and lower thermal sensitivity with age may be possible explanations. Many of the older subjects' nose or ears (Paper VI) reached 0 °C earlier than the younger subjects (Paper II), which would support the findings of the age relation with frostbite. However, the two studies are not entirely comparable due to slightly different air velocities and other temperature sensors.

The temperature at which the tissue actually freezes has been discussed by a number of authors. Their measurements and physical calculations indicate that skin freezes at about -0.6 °C (97), -1 to -2 °C, (115) or -4.6 °C (183, 184). The higher temperature has been confirmed by physical measurements (27). By ethical reasons the skin was not allowed to freeze during the present experiments. However, skin temperatures of 0 °C and observed decreasing temperature trends indicated that frostbite would have occurred within an hour and often much sooner even if the real freezing temperature of skin is as low as -4.6 °C. The cold-induced vasodilatation observed delayed the cooling in many experiments, sometimes very efficiently, but in many cases the average skin temperature decreased towards 0 °C despite the intermittent heating periods.

WCI contains a number of limitations, which have been pointed out (21). These are that WCI a) only applies to unprotected skin, b) does not consider respiratory heat loss, c) cannot be used in wind speeds over 20 m·s⁻¹, d) is empirical and not interpretable by thermodynamic laws and e) overestimates cooling power based on the effects on wind speed for naked surfaces and underestimates cooling for clothed surfaces. Use of a globe thermometer has been suggested to improve WCI by including the radiant heat transfer within the environment (see (175)).

In my opinion, the effect of wind on the whole body would better be handled in the IREQ index than with WCI. A development of the current calculations on the convective heat loss by wind from the surface of the body and the heat transfer between the environment and the airways would better meet some of the requirements of a cold predictive index. The WCI is better suited to only account for the effects of local cooling by wind. Many in the meteorological society are eager to provide a single index for risk evaluation, but from a scientific point of view it is probably not possible to include risk for hypothermia and risk for local cold injury in one single number without losing accuracy. It would be possible to provide a very rough index, which provides warning at certain wind chill temperatures with safety margins: However, this type of index would not be sufficient for occupational purposes, at which productivity is important. Such a rough wind chill index would probably sometimes unnecessarily limit work or even not be used due to lack of validity.

Cold-induced vasodilatation (CIVD) does not seem to reduce the risk efficiently (25). When the core temperature becomes low CIVD abates and thus contributes less to reheating of the body part.

Individual variation and modelling

The individual variation in the measured variables was large. High variability among the subjects in the freezing time of human skin was observed and reported already by Siple and Passel almost 60 years ago (166). The variation has implications for the design of similar future studies and for prediction models, among other things.

One important question is in what way prediction models should consider the individual variation. There may be various approaches. A model may be based on anthropometric measures, age, gender or other variables that determines the outcome. It may also be based on the population distribution of a certain variable. Many considerations have to be taken to decide which model is the most suitable. At the time being, referring to the state of knowledge, the distribution model is the most relevant. In the case of WCI, different risk levels may be outlined for different use. A limit for frostbite that includes the whole population should be provided as well as a limit that includes about 95 % of the population. However, a larger database than presented in this thesis is needed to state the limits on solid scientific ground. For occupational work also limits for predicted high discomfort and pain sensations would be needed.

Main findings and conclusions

The systolic and diastolic blood pressure increased in cold and increased more with higher air velocity in both young and middle-aged individuals. Wearing headgear with earflaps at wind exposure reduces severe cooling, pain sensations and the risk for frostbite. Face protection would most likely reduce the blood pressure response and reduce the risk for frostbite, especially the nose and cheeks, which reached the lowest temperatures during cold wind exposure. Protection may decrease the incidence of symptoms for patients with cardiovascular diseases during the cold season as well.

In the acute phase of cold wind exposure the blood pressure responses were compensated by a lowered heart rate, but with continued exposure blood pressures remained elevated. Thus, adaptation to a cold stimulus does not seem to occur within an hour.

During low intensity walking the core temperature (represented by the rectal temperature) was maintained at normal levels at a wide range of ambient temperatures, but at the expense of low peripheral temperatures. The IREQ/DLE predictions of the core temperature and net heat debt were satisfactory. However, DLE allowed for lower mean skin temperature and hand temperatures than proposed by the criterion in the ISO document ISO TR 11079 and also gave cold sensations at low ambient temperatures.

Manual dexterity was reduced at hand temperatures below 20 °C when finger temperatures were still lower.

After initial cooling an increase of about 0.5 °C in rectal temperature was associated with a rise of the finger and nose temperatures, mainly at low air velocity.

Exercise (and increase in rectal temperature) showed to be more effective to reheat cooled hands and fingers than additional clothing, although the improved clothing insulation was above required according to IREQ.

Physical work even at a moderate intensity level reduces some of the negative effects of cold wind on the human. Respiratory function becomes less, the blood pressure responses become smaller and the cooling rates of nose and fingers are reduced. The observations on physiological responses to cold wind exposure indicate that special attention should be taken when physically inactive individuals, hypertensive persons and patients with heart disease are to be exposed to cold wind and suggest that standing/physical inactivity in cold wind should be avoided.

The results indicate that the cooling effect of wind was larger than assumed in the calculations of IREQ, even in the revised version. The new equation for correction of wind effects on the clothing applied to IREQ improved the prediction of cold

strain, but still underestimates the required insulation for cold wind exposure. Moreover, the new criterion for mean skin temperature for "high strain" level (IREQ_{min}) was closer to the measured values than the older criterion.

The comfort criteria for cold environments tend to slightly diverge from those established for moderate temperatures. The predicted thermal sensations did not fit very well with t_{sk} criteria in cold and windy conditions. Subjects tended to prefer a warmer ambient temperature when the mean body temperature was decreasing, even though they felt thermally 'neutral'. Therefore, to be comfortable in cold conditions at low activity it seems necessary to dress slightly more than indicated by IREQ and by the thermal sensations.

The new WCI (2001) table seems to underestimate the cooling effect of moderate winds at -10 °C on the bare skin, viewed on the individual basis. For the average temperature responses of the population both the old and the new WCI are adequate.

The potential individual risk of frostbite in the nose is similar during light exercise and standing. The predicted risk for frostbite in the nose would be less at higher work rate.

For the design of future studies the thesis provides additional information about the variance in a number of variables important for further study of cold responses.

Suggestions for improvements of methods for prediction of cold stress

During field studies (45, 47, 48) in cold environments it was observed that work was seldom continued for more than four hours without a longer break in warmer conditions. Thus, calculation for recommended clothing insulation in IREQ based on four hours would be more relevant and would probably give better accuracy in the prediction.

DLE should be shorter at low ambient temperature and low intensity work to prevent the hand and finger temperatures to cool down to levels, at which manual dexterity deteriorates. Further a dynamic response in mean skin temperature is suggested to be incorporated in the calculations of DLE instead of a constant temperature to better reflect the actual change in body heat content.

Limit criteria for finger temperatures is recommended to replace the criteria for hand temperature in a revised ISO 11079 to protect from pain sensations and reduced manual performance.

Criteria for core temperatures should be provided in an ISO standard (90).

“Neutral” thermal sensations were reported at lower mean skin temperature than predicted by the criterion in IREQ_{neutral}. At the same time comfort seemed to be experienced at thermal sensations higher than thermoneutral. A modified concept

for the mean skin temperature criterion that reflects the common asymmetrical skin temperature distribution around the body in cold environments is suggested for consideration for the revised standard. Criteria for skin temperatures of the central body, the torso and the peripheral body areas would probably improve the predictions of IREQ.

The responses to air velocities 0.2 and 1 m·s⁻¹ were similar, why 1 m·s⁻¹ does not require special consideration in models for prediction of physiological responses to cold.

To improve the simplicity to use the index for the end-user, development of certain categories of required insulation with defined clothing ensembles, categories of air temperature, air velocity and walking speed/activity level is suggested. Categorisation would on one hand render less accurate predictions, but on the other hand the use of the index would probably be accepted by a larger group of people involved in activities related to cold, for example clothing manufacturers.

The very large individual variation observed must be considered in risk assessment models for cold risk assessment. Consequently, WCI risk limits for frostbite should be raised to higher wind chill temperature levels to cover the temperature responses of a greater part of the population.

It may be necessary to create more than one Wind Chill Index table or indicate more risk levels than currently in the WCI table for different target groups: a) general public, b) military and c) occupational. Different risk levels may be outlined for different use to meet the needs from the different groups.

Pain and very cold sensations, which are unacceptable at occupational work, were commonly reported at conditions below the risk level for frostbite in Wind Chill Index. For occupational work additional limits for predicted high discomfort and pain sensations would be needed. The limit should correspond to a combination of air velocity and air temperature that gives a skin temperature of bare skin at any location of about 15 °C, at which pain was frequently experienced.

Suggestions for further research

Nearly all studies on responses to cold during exercise have used leg work. The regional heat flow is most probably different during leg and upper body work. It needs to be further investigated both to understand better the physiological response, in particular cardiovascular responses to cold and to extend the database for prediction models.

Relatively few studies have been performed in cold wind, and out of them only a few with female subjects. Further, the resulting picture of female responses to cold is

scattered. Thus, research of the physiological and subjective responses of women to cold wind is needed.

The results of this thesis raised the question about the risk of development of hypertension and subsequent cardiovascular diseases due to cold wind exposure. It would be important to study the significance of repeated cold-induced blood pressure increase on human health, simulating everyday life exposure. Long-term effects of cold and wind on the blood pressure in humans would be needed to understand how the blood pressure is regulated during prolonged cold stress as well as repeated short exposures. Moreover, studies would be needed to understand the role of the catecholamines and other hormones in the responses of humans to short-term, repeated and long-term cold wind exposure and what the effects of isolated exposure of the face have got on circulating catecholamines. Future studies on the influence of age on cardiovascular responses in windy conditions are also needed to get knowledge about if this is a factor to be included in a risk model.

The wind effect on the body was underestimated. Further studies on skin temperatures and comfort at face and whole-body exposure to wind by systematic studies would be needed. Moreover, the relationship between acceptance and thermal sensations is needed to be investigated to find out at which level of discomfort workers would accept to work in the cold.

Since the studies indicated that physical activity might influence the face skin temperature higher levels of physical activity would be needed to study to correctly predict the risk of frostbite at all situations.

Recommendations for protection at work in the cold

A number of measures may be taken to safe work in cold environments. These include education, work organisation, protection against wind (and precipitation) by shields and personal protective equipment.

This thesis has dealt with the importance of reducing the risk for discomfort, deteriorated performance, cold injury and cold-related diseases of the worker. All those who are going to work in the cold should be medically examined, educated and adequately protected. Learning to prevent and recognise cold-related disorders is essential, since the possibility to reduce risks is intimately connected with knowledge.

In wind and cold, it is important to be alert of signs of cooling: 1) the skin turning pale and 2) a sharp stinging pain, which is followed by sensory loss of the affected tissue. A superficial injury that is treated immediately may be totally reversible. With further cooling the skin turns pink for a short period and then white (105). Deep cold injuries require long time to heal and may result in lifelong problems. It is common that the injured body part is very sensitive to cold and is susceptible for another cold injury (39). Thus it is important that the worker's history of cold problems is investigated during the recruitment process or before work in the cold is decided to begin.

For whole body cooling strong discomfort, fatigue, difficulty to concentrate or slurring words may be important signs for interrupting the cold exposure.

The best prevention measure may be to mitigate the exposure by creating weather shields. These reduce the air velocity and thus the risk for frostbite diminishes dramatically. For personal protection different garments or accessories are useful:

In wind it is important that the face be protected, including the nose and cheekbones. A well-insulating hat with earflaps that can be fastened under the chin is ideal to protect the ears. At occupational work a hat is to prefer before a hood (which gives very good protection even for the face (162)) due to better vision in a hat. Especially at low activity (low metabolic heat production), such as surveillance and standing manual work, hands and feet need very high insulation and a wind barrier. For high wind speeds and for cycling or driving open vehicles, snow goggles are needed to protect the eyes and the areas around the eyes.

The clothing insulation of the body may be calculated with IREQ. At low intensity work slight “overdressing” in relation to the value of IREQ may be recommended to provide the extremities with enough heat. The outermost layer of the clothing should have very low air permeability.

Sammanfattning

Gavhed D (2003) *Human responses to cold and wind*. *Arbete och Hälsa* 2003:4.

Kyla utgör en stressfaktor och har fysiologiska, subjektiva och fysikaliska effekter på människan. Nedkylning vid yrkesarbete måste förhindras för att komfort och säkerhet ska råda vid kallt arbete. Effekter av kyla studerades med avseende på de två vanligaste bedömningsmetoderna för kyla, IREQ (Insulation Required= isolationsbehov) för helkroppsavkylning och WCI (Wind Chill Index= vindkyleindex) för nedkylning av oskyddade kroppsdelar. Metoderna har inte validerats med fysiologiska studier i någon större omfattning. WCI baseras främst på teoretiska beräkningar och fysikaliska mätningar.

Påverkan av fysisk aktivitet och vindhastighet på kropps- och hudtemperatur, på kardiovaskulära, respiratoriska och subjektiva reaktioner och värmebalans undersöktes under klimatbetingelser nära beräknade risknivåer. Åtta till tio unga och medelålders försökspersoner deltog, klädda i flera lager välisolerande kläder. De satt, stod och gick på ett rullband vid $-6\text{ }^{\circ}\text{C}$ till $-22\text{ }^{\circ}\text{C}$ i 10-90 minuter i vind ($1-6\text{ m}\cdot\text{s}^{-1}$) och i vindstilla ($0.2\text{ m}\cdot\text{s}^{-1}$). I en studie kylades försökspersonerna innan de exponerades för kall vind.

Även måttliga vindhastigheter ($2-6\text{ m}\cdot\text{s}^{-1}$) i $-10\text{ }^{\circ}\text{C}$ orsakade en signifikant ökning av det systoliska and diastoliska blodtrycket, som var större vid högre vindhastighet. Förhöjningen av blodtrycket kvarstod utan att kompenseras av en sänkning av hjärtfrekvensen. Lufthastigheten påverkade också hudtemperaturerna. I en fjärdedel av vindförsöken föll ansiktstemperaturen till $0\text{ }^{\circ}\text{C}$. Smärta upplevdes ofta i vind. Kriterierna för nedkylning av kroppen i IREQ uppfylldes, men handtemperaturerna var lägre än de rekommenderade. Dessutom var fingertemperaturerna under $15\text{ }^{\circ}\text{C}$, vilket resulterade i försämrad manuell förmåga. Ökning av arbetsintensiteten var effektivare för att värma upp fingrarna efter nedkylning i $-22\text{ }^{\circ}\text{C}$ än att öka klädernas isolation. I $-10\text{ }^{\circ}\text{C}$ minskade måttligt arbete nedkylningen av fingrarna mer än arbete vid lägre intensitet, men bara då vindhastigheten var $< 1\text{ m}\cdot\text{s}^{-1}$. För att känna sig behaglig vid låg fysisk aktivitet i kyla tycks det som om något mer isolation behövs än vad som rekommenderas i IREQ, även då "termisk neutralitet" upplevs.

WCI tycks underskatta kyleffekten av $5-6\text{ m}\cdot\text{s}^{-1}$ i $-10\text{ }^{\circ}\text{C}$ på bar hud (t ex. ansikte). Resultaten gav förslag för att förbättra och vidareutveckla IREQ och WCI. Bedömningsmetoder för fysiologiska risker i kyla bör ta hänsyn till den stora variationen mellan individer som observerades i kylaförsöken. De observerade blodtrycksreaktionerna vid exponering för kall vind kan innebära att försiktighetsåtgärder bör vidtas vid exponering för kyla och vind av personer som är fysiskt inaktiva, har förhöjt blodtryck eller hjärtsjukdom.

Keywords: bradycardia, blood pressure, clothing insulation, cold, exercise, heart rate, IREQ, mean skin temperature, metabolic rate, rectal temperature, subjective ratings, wind, Wind Chill Index, work.

Summary

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Cold is stressful for the human being and has physical, subjective and physiological effects. Body cooling must be prevented to provide for the worker's comfort and safety in cold workplaces. The effects of cold were studied in view of the two predictive cold indices that are mainly used, IREQ (Insulation Required) for whole body cooling and WCI (Wind Chill Index) for bare skin cooling. The indices had scarcely been validated by physiological studies. WCI is mainly based on theoretical calculations and physical measurements. The influence of thermal state, light physical activity and wind speed on heat flows, temperature, cardiovascular and subjective responses and respiratory function were investigated at climate conditions calculated to be at the borderline of risk-no risk.

Eight to ten young and middle-aged subjects participated in the studies. The subjects were dressed in multi-layer cold-protective clothing. They sat, stood or walked on a treadmill at -6 to -22 °C for 10-90 minutes in wind ($1-6$ m·s⁻¹) and in the absence of wind. In one study the subjects were pre-cooled before the wind exposure.

Even moderate wind speeds ($2-6$ m·s⁻¹) at -10 °C caused the systolic and diastolic blood pressure to increase significantly, more at higher wind speed. They remained elevated without compensatory bradycardia. The air velocity also had effects on the skin temperatures. In about a fourth of the wind experiments the face temperature dropped to 0 °C. Pain was commonly reported at conditions below the risk level for frostbite in Wind Chill Index. The criteria of IREQ concerning body cooling were fulfilled, but hand temperatures were lower than recommended. In addition, finger temperatures were below 15 °C, which resulted in reduced manual performance. An increased exercise level was more effective to reheat fingers after cooling at -22 °C than adding insulation. At -10 °C moderate exercise reduced finger cooling more than low intensity exercise, but only at < 1 m·s⁻¹. To be comfortable at low activity in cold it seems necessary to dress slightly more than indicated by IREQ and by thermal neutrality sensations.

WCI seems to underestimate the cooling power of $5-6$ m·s⁻¹ at -10 °C of bare skin (e.g. face). The results provided suggestions for improving and developing IREQ and WCI. Prediction models for cold risk assessment should consider the large individual variation.

The observations of blood pressure responses to cold wind exposure indicate that special attention should be taken at exposure to cold wind of physically inactive individuals, hypertensive persons and patients with heart disease.

Keywords: bradycardia, blood pressure, clothing insulation, cold, exercise, heart rate, IREQ, mean skin temperature, metabolic rate, rectal temperature, subjective ratings, wind, Wind Chill Index, work.

Acknowledgements

This thesis work has affected many persons in different ways. I want to thank all those of my colleagues, friends and my family who have been concerned about my thesis work during the years. Even the brief questions now and then about how things were working out helped me to move on and their interest warmed my heart.

There are of course a number of persons who have played a more prominent part in the play of the PhD work. My family has suffered, as probably most families do when they realise that they now are confronted with a “theseoholic”, their former playmate and housekeeper. I adore my family, and I am thankful for their patience with me, and my frequent absence. I want to thank especially my husband for his loving support.

When moving my thoughts to my scientific surroundings, I first want to thank my mentor, professor Ingvar Holmér, for supervising my work, for reading and giving valuable comments on numerous versions of my manuscripts. I am also grateful to associate professor Mats Ulfendahl, who fearlessly approved to lead me through the final stage of the work and who supported and encouraged me to fulfil the process when I was in a doubtful state of mind. I also want to thank Dr Per Nylén for his involvement at this stage. Many thanks to associate professor Hannu Rintamäki and to Tero Mäkinen for their invaluable and large contribution to the studies, for valuable comments on my manuscripts and for their friendship. I also appreciate the comments of Dr Juhani Smolander on my thesis. Thanks also to the co-operative subjects who sacrificed their comfort for science.

And last, but definitely not least, I wish to express special thanks to all my fellow-workers during the years, among them Ruth Nielsen, who shared her knowledge and experience with me in the beginning of my thesis work, Birgitta Linnros, Eva Karlsson, Håkan Nilsson, Björn Sköldström, Sverker Grahn and Kalev Kuklane for skilful laboratory assistance, prompt help with solving problems and other important contributions to my thesis. I want to thank them all for making my workdays on the lab happy and filled with bracing laughs. I highly appreciate their warm involvement in my studies on cold.

With love,

Desirée Gavhed, March 2003

The main part of the studies of this thesis was financially supported by the Swedish Work Environmental Fund.

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