



Protection against cold in prehospital trauma care

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Abstract

Background Protection against cold is vitally important in prehospital trauma care to reduce heat loss and prevent body core cooling.

Objectives Evaluate the effect on cold stress and thermoregulation in volunteer subjects by utilising additional insulation on a spineboard (I). Determine thermal insulation properties of blankets and rescue bags in different wind conditions (II). Establish the utility of wet clothing removal or the addition of a vapour barrier by determining the effect on heat loss within different levels of insulation in cold and warm ambient temperatures (III) and evaluating the effect on cold stress and thermoregulation in volunteer subjects (IV).

Methods Aural canal temperature, sensation of shivering and cold discomfort was evaluated in volunteer subjects, immobilised on non-insulated (n=10) or insulated (n=9) spineboards in cold outdoor conditions (I). A thermal manikin was setup inside a climatic chamber and total resultant thermal insulation for the selected ensembles was determined in low, moderate and high wind conditions (II). Dry and wet heat loss and the effect of wet clothing removal or the addition of a vapour barrier was determined with the thermal manikin dressed in either dry, wet or no clothing; with or without a vapour barrier; and with three different levels of insulation in warm and cold ambient conditions (III). The effect on metabolic rate, oesophageal temperature, skin temperature, body heat storage, heart rate, and cold discomfort by wet clothing removal or the addition of a vapour barrier was evaluated in volunteer subjects (n=8), wearing wet clothing in a cold climatic chamber during four different insulation protocols in a cross-over design (IV).

Results Additional insulation on a spine board rendered a significant reduction of estimated shivering but there was no significant difference in aural canal temperature or cold discomfort (I). In low wind conditions, thermal insulation correlated to thickness of the insulation ensemble. In greater air velocities, thermal insulation was better preserved for ensembles that were windproof and resistant to the compressive effect of the wind (II). Wet clothing removal or the use of a vapour barrier reduced total heat loss by about one fourth in the cold environment and about one third in the warm environment (III). In cold stressed wet subjects, with limited insulation applied, wet clothing removal or the addition of a vapour barrier significantly reduced metabolic rate, increased skin rewarming rate, and improved total body heat storage but there was no significant difference in heart rate or oesophageal temperature cooling rate (IV). Similar effects on heat loss and cold stress was also achieved by increasing the insulation. Cold discomfort was significantly reduced with the addition of a vapour barrier and with an increased insulation but not with wet clothing removal.

Conclusions Additional insulation on a spine board might aid in reducing cold stress in prolonged transportations in a cold environment. In extended on scene durations, the use of a windproof and compression resistant outer cover is crucial to maintain adequate thermal insulation. In a sustained cold environment in which sufficient insulation is not available, wet clothing removal or the use of a vapour barrier might be considerably important reducing heat loss and relieving cold stress.

Sammanfattning

Bakgrund En skadad person riskerar att utsättas för betydande kylstress. Tunna, blöta eller trasiga kläder i kombination med fastklämning, större skador eller blödningar riskerar att leda till stora värmeförluster. Kroppens försvar mot kyla med kärlsmmandragning och huttring kan ge en kraftigt ökad belastning på hjärta och lungor. Blodets levringsförmåga påverkas och med sjunkande kroppstemperatur tillkommer medvetandesänkning, hjärtrytmrubbningar och en påtagligt ökad risk för komplikationer och död i samband med större skador. På skadeplats och under transport till sjukhus (prehospitalt) är det därför av stor vikt att åtgärder vidtas tidigt för att minska värmeförluster och motverka allmän nedkylning. Ett flertal olika materiel och produkter används idag inom ambulanssjukvård och räddningstjänst men deras specifika isoleringsegenskaper är sällan utvärderade och effekten på kylstress och kroppens termoreglering (t.ex. kroppstemperatur, hudtemperatur och huttring) av olika materiel och tekniker för skydd mot kyla har endast studerats i ett fåtal tidigare studier.

Syfte Det övergripande syftet var att fastställa isoleringsegenskaper hos olika filter och räddningstäckan samt att utvärdera effekten på kylstress och termoreglering av olika materiel och tekniker för skydd mot kyla i prehospital miljö. Specifikt avsågs att utvärdera kylstress och effekten på termoreglering hos frivilliga forskningspersoner genom att tillföra extra isolering till en spine board (bår för immobilisering och transport av skadad patient) (studie I). Vidare avsågs att fastställa isoleringsegenskaper i olika vindförhållanden hos vanligt förekommande filter och räddningstäckan (studie II). Slutligen avsågs att utvärdera effekten av att avlägsna blöta kläder eller tillföra en fuktspärr genom att fastställa värmeförluster i kombination med olika mängd isolering i kall och varm omgivningstemperatur (studie III) samt utvärdera effekten på kylstress och termoreglering hos blöta och kylstressade frivilliga forskningspersoner (studie IV).

Metod I kall utomhusmiljö utvärderades hörselgångstemperatur samt upplevelse av kyla och huttring hos frivilliga forskningspersoner immobiliserade på vanlig spine board (n=10) eller på spine board med extra isolering (n=9) (studie I). Med en termisk docka i en klimatkammare fastställdes isoleringsegenskaper hos tolv olika filter och räddningstäckan i svag, måttlig och kraftig vind (studie II). Med samma termiska docka, klädd i blöta, torra eller inga kläder, uppmättes också blöta och torra värmeförluster och effekten av att avlägsna blöta kläder eller tillföra en fuktspärr i kombination med olika mängd isolering i kall och varm omgivningstemperatur (studie III). I en uppföljande studie utvärderades effekten av att avlägsna blöta kläder eller tillföra en fuktspärr genom att mäta syreförbrukning som ett mått på huttring, central kroppstemperatur (uppmätt i matstrupen), hudtemperatur, hjärtfrekvens samt upplevelsen av kyla hos frivilliga forskningspersoner (n=8) med blöta kläder exponerade för kyla i en klimatkammare (studie IV).

Resultat Hos forskningspersoner immobiliserade på spine board med extra isolering sågs en signifikant minskad upplevelse av huttring jämfört med de forskningspersoner som immobiliserades på vanlig spine board. Det var däremot ingen skillnad i hörselgångstemperatur eller upplevelse av kyla (studie I). I svag vind var isoleringsvärdet hos olika filter och räddningstäckan framför allt beroende av isoleringens tjocklek. I måttlig och kraftig vind bevarades isoleringsförmågan bäst hos de filter och räddningstäckan som var vindtäta och motståndskraftiga mot vindens komprimerande effekt (studie II). Avlägsnande av blöta kläder respektive tillförsel av en fuktspärr minskade de totala värmeförlusterna med ungefär en fjärdedel i kall miljö och ungefär en tredjedel i varm miljö. En motsvarande minskning av totala värmeförluster uppnåddes även genom att tillföra mer isolering. (studie III). Hos forskningspersoner med blöta kläder i kall miljö så gav avlägsnande av blöta kläder respektive tillförsel av fuktspärr i kombination med en yllefilt en signifikant lägre huttring (syreförbrukning) och ökad uppvärmningstakt för medelhudtemperatur jämfört med när enbart en yllefilt tillfördes. Det var ingen skillnad i sänkning av central kroppstemperatur eller hjärtfrekvens mellan de olika isoleringsalternativen men beräknat totalt värmeinnehåll i kroppen ökade med avlägsnande av blöta kläder eller tillförsel av en fuktspärr medans det minskade med enbart en yllefilt. En motsvarande effekt på termoreglering och total kroppsvärme uppnåddes genom att tillföra två yllefilter istället för en. Upplevelsen av kyla var signifikant lägre med två yllefilter och när en fuktspärr tillfördes jämfört med enbart en yllefilt. Även med avlägsnande av blöta kläder sågs en tendens till lägre upplevelse av kyla men skillnaden jämfört med enbart en yllefilt var inte statistiskt signifikant (studie IV).

Slutsatser Vid längre transporter i kall miljö kan tillförsel av extra isolering på en spine board vara av betydelse för att motverka kylstress. Användandet av filter och räddningstäckan som är vindtäta och motståndskraftiga mot vindens komprimerande effekt är av stor betydelse för att uppnå adekvat isoleringsförmåga vid längre omhändertagande på skadepplats. I en kall miljö där tillräcklig isolering inte är tillgänglig, bör avlägsnande av blöta kläder eller tillförsel av fuktspärr övervägas för att minska värmeförluster, avlasta behovet av huttring och motverka fortsatt sänkning av total kroppsvärme.

List of publications

This thesis is based on the following studies, which will be referred to in the text by their Roman numerals:

- I Lundgren P, Henriksson O, Widfeldt N, Vikström T. Insulated Spine Boards for Prehospital Trauma Care in a Cold Environment. *International Journal of Disaster Medicine* 2004;2:33–37.
- II Henriksson O, Lundgren P, Kuklane K, Holmér I, Björnstig U. Protection Against Cold in Prehospital Care – Thermal Insulation Properties of Blankets and Rescue Bags in Different Wind Conditions. *Prehosp Disaster Med* 2009;24(5):408–415.
- III Henriksson O, Lundgren P, Kuklane K, Holmér I, Naredi P, Björnstig U. Protection Against Cold in Prehospital Care: Evaporative Heat Loss Reduction by Wet Clothing Removal or the Addition of a Vapor Barrier – A Thermal Manikin Study. *Prehosp Disaster Med* 2012;26(6):1–6.
- IV Henriksson O, Lundgren P, Kuklane K, Holmér I, Giesbrecht G, Naredi P, Björnstig U. Protection Against Cold in Prehospital Care – The Effect on Thermoregulation by Wet Clothing Removal or Addition of a Vapour Barrier in Shivering Subjects. Manuscript.

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Abbreviations

°C	Degrees Celsius
CI	Confidence interval
IQR	Interquartile range
Pa	Pascal
SD	Standard deviation
SEM	Standard error of the mean
W	Watts

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Introduction

Prehospital trauma care

In an outdoor environment, an injured or ill person often is exposed to considerable cold stress (1). Heat loss might be aggravated because of wet, torn or insufficient clothing for the ambient conditions; immobilisation; major bleeding; administration of cold intravenous fluids; or exposure during resuscitation and primary care (2-6). In addition, thermoregulatory mechanisms might be impeded because of head or spinal injuries, circulatory shock, energy depletion, intoxication or the administration of analgesics or sedative drugs (7-11). If heat loss exceeds possible endogenous heat production peripheral and central cooling will occur and hypothermia will develop.

In Sweden (9.5 million inhabitants), death by accidental hypothermia through exposure to extreme cold as the primary diagnosis (ICD 10 X.31), is reported only in 35 – 63 cases per year (1997 – 2010) (12). Secondary hypothermia in conjunction with trauma, intoxication, sepsis or other severe endocrine or metabolic disorders is more common but is often neglected or not reported (13-15). In trauma patients, the reported incidence of hypothermia, defined as a body core temperature $\leq 35^{\circ}\text{C}$ varies from 1.6% to 43% (16-22). The severity and mechanism of injury, the presence of shock, duration of evacuation and prehospital induction of anaesthesia are demonstrated to be predictive variables of the patient arriving hypothermic to the emergency department (23-30).

Although induced hypothermia in experimental studies on haemorrhagic shock or traumatic brain injuries have indicated beneficial effect on neurological outcome, clinical studies on therapeutic hypothermia in trauma patients show contradictory results (8, 31, 32). The physiological effects of cold stress and hypothermia render increased cardiac and respiratory demands that might be detrimental to an already compromised patient. In conjunction with major trauma, especially in the presence of haemorrhagic shock, the increase in oxygen consumption from shivering thermogenesis might exceed possible oxygen delivery. The resultant anaerobic metabolism contributes to the development of acidosis and multi-organ failure (17, 30). Hypothermia, aggravating the trauma induced coagulopathy, significantly increases blood loss and fluid resuscitation requirements compared to normothermic trauma patients (33-35).

Accordingly, in several studies, admission hypothermia is demonstrated to be associated with increased mortality and posttraumatic complications (18, 26, 28, 30), but the question remains whether hypothermia simply is a marker of injury severity and shock or an independent factor associated with worse outcome. In some studies on severely injured trauma patients there were no differences in adjusted mortality between hypothermic and normothermic trauma patients (17, 22, 29, 30, 36). On the contrary, large retrospective analyses of trauma registries as well as prospective observational clinical studies have found admission hypothermia, to be an independent predictor of increased mortality with an odds ratio ranging from 1.19

(95% CI; 1.05–1.35) to 4.05 (95% CI; 2.26–7.24) (16, 19-21, 23, 37). The diverging results might be attributed to different characteristics of the study populations and to the variety of confounding factors included in the regression analysis (30).

Whether an independent predictor of mortality or an indicator of injury severity and shock, hypothermia in trauma patients constitutes a substantial circulatory problem and rewarming during resuscitation is considered imperative (9, 38, 39).

In addition to immediate care for life threatening conditions, actions to reduce heat loss and prevent body core cooling is, therefore, an important and integrated part of prehospital trauma care (18, 27, 40-42). Initial measures should be taken to protect the patient from ambient weather conditions and ground chill within adequate insulation ensembles (passive warming). In addition, depending on the patient's condition and injuries, body core temperature, available resources, and expected duration of evacuation; the application of external heat (active warming) is, in most guidelines, recommended to be an aid in protection from further cooling during transportation to definitive care (14, 43-49).

In the prehospital services of today many insulation materials and products are used for passive warming and protection of patients against cold, but only a few studies have been conducted to evaluate and compare such materials and products (50-56). This thesis sets out to determine insulation properties of blankets and rescue bags and evaluate the effects on cold stress and thermoregulation provided by different materials and techniques used for protection against cold in prehospital trauma care.

Cold stress and hypothermia

Heat loss

Heat is lost from the human body to the environment by conduction, convection, radiation, evaporation, and respiration (57). The amount and proportion of heat loss is dependent on ambient air temperature, radiant temperature, humidity, air velocity, clothing or other insulation applied, and metabolic heat production from physical activity (58).

In a cold outdoor environment, heat loss occurs primarily because of *convection* by warming the surrounding air layer (57). It is dependent on the temperature gradient between skin or clothing surface and the surrounding air, and greatly increases by wind or movement. Convection also occurs in water where currents and waves, or swimming and treading water significantly increase the rate of warm to cold water exchange around the body (59).

To a smaller extent, heat is also lost as *radiation* by infrared electro-magnetic waves, from the skin or clothing surface to surrounding colder objects and to the atmosphere (57). Radiation is dependent on the temperature gradient between the skin or clothing surface and the mean surrounding radiant temperature. In a cold outdoor environment the clothing surface temperature is often close to the ambient

radiant temperature and thus heat loss through radiation is minimal. From bare skin, however, radiative heat loss can be significant, especially in wind-still conditions with clear sky.

If the body is in direct contact with a cold surface, heat will be lost through *conduction* (57). It is mainly dependent on the surface area and temperature gradient between the skin or clothing surface and the cold object and on the conductivity, i.e., the heat transfer capability of the material (60). Conduction also occurs to the medium surrounding the body, such as air and water. Air, however, is a poor conductor and virtually no heat is lost through conduction to dry air. In water, the conductivity is about 25 times greater than air, rendering a substantial increase in conductive heat loss (59). Metals are even greater conductors with 700 times (stainless steel) or 10,000 times (aluminium) the conductivity compared to air (60).

If the skin or clothing is wet, heat loss through *evaporation* can be considerable (57). Evaporation is dependent on the water vapour pressure gradient, defined by relative humidity and temperature, between skin or clothing surfaces and the surrounding air. Evaporation is affected by the moisture permeability and ventilation openings in surrounding clothing or insulation ensembles and by condensation in the textile layers.

The body also constantly loses heat through *respiration* by evaporation and convection in the airways (57). It is dependent on the temperature and water vapour pressure gradients between the airway and the inhaled air and on the minute ventilation. Accordingly, the administration of high flow non-humidified oxygen increases heat loss through the airways (15).

Thermoregulation

The human body is dependent on maintaining a core temperature at about 37°C for optimal performance of vital organs (61). A deviation of more than a few degrees will have serious consequences threatening the physiological and cellular mechanisms of the body. This demands a dynamic equilibrium between heat production and heat loss in response to ambient conditions and physical activity (62).

The thermal state of the body is sensed by temperature receptors in the skin, the spinal cord, the medulla oblongata, the hypothalamus, and other parts of the brain as well as in deep abdominal and thoracic tissues. The afferent temperature information is integrated in the preoptic nucleus of the anterior hypothalamus, considered the main thermoregulatory centre of the body (61, 63, 64).

In response to peripheral or central cooling, or both, the thermoregulatory system elicits a sympathetically mediated efferent response involving peripheral vasoconstriction to reduce blood flow in skin and extremities, thus reducing heat loss and involuntary muscle contractions (shivering) to increase endogenous heat production (61, 63, 64). The thermoregulatory system also affects behavioural responses, such as putting on clothing or increasing the level of physical activity (62).

With an intact thermoregulatory system, body core temperature can often be maintained at near normal levels, even in a profoundly cold environment. However, the total heat content of the body will be reduced as skin and extremities are cooled in the effort of preserving body core temperature (61, 63, 64). The increased temperature gradient between core and superficial tissues will contribute to a continuing decline in body core temperature, even after the person is relieved from the cold stress. The magnitude and rate of this body core temperature reduction, also known as the afterdrop phenomena, is dependent on temperature gradients in the tissues, peripheral circulation, and endogenous heat production (3, 11).

For optimal heat production and heat conservation an adequate energy supply, a patent nervous system, and functional effector organs are critical. In a severely injured or ill person, thermoregulatory mechanisms often are affected (15, 65). Central and peripheral nervous system lesions might impair the thermoregulatory ability. The influence of alcohol, opioids, sedatives, or anaesthetic drugs promotes vasodilation and inhibits shivering thermogenesis. Hypoxia, endotoxin shock, and severe malnutrition might lower the thermoregulatory threshold and increase body core cooling. In conjunction with major trauma there are reports of decreased skin and body core temperatures without compensatory shivering and in circulatory compromised patients, the possibility for endogenous heat production will be limited (8, 9).

Physiological effects

When exposed to a cold environment the thermoregulatory system stimulates an initial secretion of catecholamines eliciting a general stress response in the body (65). Shivering, which commences as an increased muscle tone progresses through mild and intermittent involuntary muscle fibrillations to more intense and continual contractions as cold stress increases. The endogenous heat production from shivering can increase oxygen consumption up to five times compared to an at rest basal metabolism and is accompanied by an increase of minute ventilation and cardiac output (66). The thermoregulatory vasoconstriction raises mean arterial pressure and increases the cardiac work-load even further (65). Peripheral vasoconstriction will also render an increase in central blood volume with a subsequent increase in renal filtration pressure and urine output. Cooling of the extremities might be pronounced and the risk of local cold injuries is increased. Manual performance is affected with impaired finger dexterity, coordination disturbances, and muscle fatigue (67, 68).

If heat loss exceeds possible endogenous heat production, body core cooling will follow. As body core temperature declines, shivering, which peaks at about 35°C will be impaired and eventually cease below 32°C (65). This might be a result of energy depletion but is also a temperature dependent effect on nerve conduction and muscle enzyme activity. Accordingly, metabolic rate and oxygen consumption is

reduced with a general reduction in cellular metabolism and enzyme activity of about 5-10% for each degree drop in core temperature.

The initial arousal following cold exposure is soon replaced with mental depression that might be presented as impaired judgement or memory, apathy or aggression, slurred speech, and eventually a decrease in consciousness as the temperature declines below 32°C (65).

As shivering and general metabolism declines, the respiratory rate and tidal volume decreases (15). An atropine resistant bradycardia develops, cardiac output is reduced, and mean arterial pressure lowered (65). Below 32°C there is an increased risk of cardiac arrhythmias as the conduction of action potentials in the cold heart is altered. Widening of the QRS complex, a J-wave (Osborne), and QT prolongation are common electrocardiographic manifestations (69). Atrial fibrillation might develop and below 28°C there is an increasing risk of ventricular fibrillation provoked by hypovolemia, hypoxia, acid-base disturbances or physical manipulation (65, 70). With a continuing fall in body core temperature bradycardia will eventually progress into asystole. The initial respiratory alkalosis will soon be superseded by a progressing lactic acidosis as ventilatory depression and vasoconstriction limits tissue perfusion and oxygenation (65). Concomitantly there is often a progression of hyperkalaemia which might be further aggravated by immobilisation and the development of rhabdomyolysis.

The enzymatic systems of blood coagulation and fibrinolysis are depressed (71-73). In conjunction with platelet alterations and sequestration in the spleen and liver, a general coagulopathy develops, which might be clinically significant already below 36°C (74-76). Increased hematocrit and the formation of microvascular thrombosis might provoke a disseminated intravascular coagulation syndrome that further aggravates the situation (65).

In a prolonged cold exposure, the cold induced diuresis, aggravated by impairment of distal tubular reabsorption of sodium and water and reduced sensitivity to antidiuretic hormone will lead to a substantial loss of fluids (77). Accompanied by capillary leak and peripheral oedema, a severe hypovolemia might develop. In the lungs the capillary leak and increased bronchoreactivity might provoke lung oedema or the development of acute respiratory distress syndrome (15). A general immune system depression increases the susceptibility to infections and with prolonged and severe hypothermia, ileus, gastric ulcers, and hemorrhagic pancreatitis might develop (65).

Clinical stages of hypothermia

In the literature there are numerous different definitions for describing the severity of hypothermia, most of which rely on body core temperature (15). Often a body core temperature of 32-35°C is defined as mild, 28-32°C as moderate and below 28°C as severe hypothermia. However, these temperature ranges are rather arbitrary and academic (78). Cold stress might be severe already before body core temperature is

affected and the development and implications of physiological disturbances following body core cooling will depend on the rate of cooling, the presence of accompanying illnesses or injuries, the physiological status of the patient and pre-existing co-morbidities (65). The implications of hypothermia in conjunction with major trauma have resulted in a revised definition with a body core temperature below 36°C considered as hypothermia, and below 32°C as severe hypothermia (9).

The Swiss Society of Mountain Medicine staging system (48) has the advantage of not being based solely on the measurement of core temperature and is thus useful for prehospital staging of hypothermia, which would be particularly important in multiple casualty scenarios (79). Based on the degree of consciousness, the presence or absence of shivering, cardiac activity, and core temperature; five stages of hypothermia are defined (Table 1).

Table 1. Clinical stages of hypothermia (Swiss Society of Mountain Medicine)

<i>Stage</i>	<i>Clinical signs</i>	<i>Body core temperature</i>
I	Clear consciousness with shivering	(35 – 32°C)
II	Impaired consciousness without shivering	(32 – 28°C)
III	Unconscious	(28 – 24°C)
IV	Apparent death (no vital signs)	(24 – 15°C)
V	Death due to irreversible hypothermia	(<15°C)

Differentiating a stage IV from a stage V victim; that is a victim who is apparently dead, but potentially salvageable, as opposed to a victim in whom all attempts at resuscitation would be futile, remains a clinical challenge (2) as severe hypothermic patients have been successfully resuscitated even after prolonged cardiac arrest (80).

Protection against cold

Because of the detrimental physiological effects of accidental hypothermia, protection of the patient against cold is an essential and integrated part of prehospital trauma care. Heat loss might occur both at the scene of incident (24) and during transportation (25, 81, 82) and once hypothermia is established, significant efforts are needed for rewarming (33, 83-85). Early application of adequate insulation ensembles (passive warming) already at the scene of injury event is, therefore, vitally important to limit heat loss, contain endogenous heat production and prevent body core cooling (18, 41, 42).

The insulation efficacy of a blanket or rescue bag can be established by determination of its thermal insulation properties or by assessment of the effect on cold stress and thermoregulation in volunteer subjects or patients. The basic principles for these measurements are presented in the following sections.

Determination of insulation properties

The heat retention capacity of an insulation ensemble, determining its effect on body heat exchange, depends on its thermal and evaporative resistance (57).

Thermal resistance (R_t), measured in $\text{m}^2\text{C}/\text{W}$, is defined as the resistance to dry heat loss by convection, radiation, and conduction, and depends mostly on the ability to retain air (57, 86). Insulation thus increases with number of layers and thickness of the insulation ensemble; the fibre type being less important. Wind will significantly reduce the thermal resistance due to loss of the still outer air layer surrounding the ensemble, the compressing effect on the textile layers, and the air permeability of the fabric (87). Wetting of textiles will reduce its ability to retain air; thereby reducing thermal resistance (88).

Evaporative resistance (R_e), measured in $\text{kPa m}^2/\text{W}$, is defined as the resistance to wet heat loss by evaporation of moisture through the material (57, 86). Depending on the water vapour pressure gradient between skin surface and the surrounding air, on the moisture permeability of the material, and dew point location in the textile layers; the water vapour will either evaporate through the ensemble to the environment (real evaporation), or condense back to water within outer parts of the ensemble (heat pipe effect) (89). The dew point is defined as the temperature at which the air is saturated with water vapour and condensation will occur (58).

Thermal and evaporative resistance of textiles can be measured with a heated hot plate (90). However, as heat flow through an insulation ensemble surrounding the body is three dimensional passing through combinations of layers of textiles and retained air, a full size thermal manikin is required for the determination of total insulation capacity (57). A thermal manikin is a human-shaped dummy, heated to a set surface (skin) temperature, e.g., 34°C , and where a constant surface temperature is maintained by regulating power input (91). Typically, the manikin is divided into anatomical body parts that form independent zones, enabling area weighted heat flux recordings. The manikin is placed (standing, sitting or supine) in a climatic chamber with a defined ambient air temperature and dressed in or covered with the insulation ensemble (clothing, sleeping bag, etc.) that is to be evaluated. If requested, wind can be applied or the manikin can be modified for the evaluation of wet conditions.

Total thermal insulation (I_t), measured in $\text{m}^2\text{C}/\text{W}$, of the surrounding insulation ensemble is calculated from measurements of manikin surface temperature, ambient air temperature, and power consumption (heat loss) during steady state conditions (86), and results are often converted to clo units ($1 \text{ clo} = 0.155 \text{ m}^2\text{C}/\text{W}$). In wind conditions or if the manikin is moving, total thermal insulation is denoted *total resultant thermal insulation* (I_{tr}). Results from manikin measurements have shown

good reproducibility and in certain conditions also good agreement with human wear trials, and the values obtained can be used in physiological models for prediction of required insulation in different ambient conditions (92-95).

Assessment of cold stress

The combined effect of ambient conditions, clothing, and physical activity influence the human thermal environment (58). The amount of thermal strain in a cold environment can be assessed by measurements of skin temperature, body core temperature, and metabolic heat production (96-98). In addition, thermal sensation or comfort can be evaluated as a measure of the psychological aspects of cold stress (99, 100).

Skin temperature (T_{sk}) varies over the body surface, especially in cold ambient conditions with peripheral vasoconstriction and local effects of clothing or insulation applied. For an estimate of mean skin temperature in a cold environment, area weighted calculations of at least eight different measurement sites are recommended (forehead, scapula, upper chest, upper arm, forearm, hand, thigh, and calf).(96) For safety reasons, sometimes finger and toe temperature measurements are required.

Body core temperature (T_c) may be approximated by measurements at different points of the body; e.g., oesophagus, rectum, axillae, mouth, tympanic, aural canal, urinary bladder, or by catheterisation of the pulmonary artery (98, 101). Each site has its own characteristics, limitations, and method of interpretation (96). Oesophageal and aural canal temperatures were measured for assessment of body core temperature for the purposes of this thesis. The proximity of the oesophagus to the descending aorta and the left auricle provides an accurate and highly sensitive measurement of arterial blood temperature and thus body core temperature (102, 103). A flexible temperature probe is inserted through the nasopharyngeal airway down to a retro-cardiac position in the lower third part of the oesophagus. A correct position is important to avoid variations from tracheal air flow and the insertion depth can be determined from the person's body height (104). The aural canal provides a more accessible site for body core temperature measurements. A transducer is placed in the inner part of the aural canal. If properly sealed from the ambient environment, aural canal temperature is proven to correlate well with oesophageal temperature, reflecting the temperature of the tympanic membrane being supplied with blood from the internal carotid artery (105, 106).

Metabolic heat production and thus shivering thermogenesis can be determined by measurement of oxygen consumption (97, 107). The fraction of oxygen and carbon dioxide in expired air is analysed breath by breath or from expired air collected over a period of time enabling the calculation of total energy produced, i.e., the *metabolic rate* (M) in W/m^2 . With few exceptions, most energy produced is released as heat and thus metabolic rate equals metabolic heat production.

Total body heat storage (ΔS) in W/m^2 can be calculated from the change in mean body temperature, body weight, body surface area, and specific heat of the body (108, 109). Mean body temperature (T_b) is calculated from measurements of mean skin and body core temperatures. Although temperature gradient through body tissues vary with ambient conditions and metabolic heat production, in a cold environment a core to skin ratio of 2:1 is typically applied (110).

Thermal sensation is affected by an integration of central and peripheral thermal stimuli and endogenous heat production but is also influenced by previous experiences of cold exposure, motivation and expectations (99). In addition to objective measures of skin and core temperatures and oxygen consumption, various types of verbal, visual, or numerical ratings scales, typically ranging from neutral to extreme, can be used as a valuable tool for evaluation of cold stress (100).

Previous studies

Thermal manikin measurements are commonly used for assessment of protective clothing in cold environments and an international standard has been developed for the determination of thermal insulation capacity of sleeping bags and corresponding temperature limits (111). However, thermal insulation values for different blankets and rescue bags used in prehospital care are rarely determined by the manufacturers and only a few studies have evaluated the thermal properties of such materials and products or their effect on human thermoregulation.

Using a thermal manikin, Rugh et al. (55) demonstrated that even though the manikin was wrapped in different “hypothermia blankets”, in $15^{\circ}C$ and 3 m/s wind conditions the application of an additional wool blanket between the manikin and the mesh stretcher rendered a 30% to 53% reduction in total heat loss. In wind still conditions, Kuklane (56) determined thermal insulation properties for different disposable rescue blankets (1.4–4.3 clo) and recently, Vangberg et al. (54) compared a standard ambulance wrapping method using three cotton blankets (3.3 clo) to a newly developed bubblewrap sleeping bag (2.5 clo).

In the perioperative setting, Sessler et al. (112) demonstrated that a single layer of different surgical drapes or blankets rendered a total cutaneous heat loss reduction of about 30% compared to no insulation in unanaesthetized human volunteers. In a follow-up study the addition of three cotton blankets compared to one cotton blanket rendered an additional reduction in total cutaneous heat loss of about 20% (113). Pre-warmed blankets were more effective in preventing heat loss than blankets that had not been warmed, but the benefit dissipated in about 10 minutes and there was no difference in the subjects’ perception of warmth.

In the prehospital setting, Light et al. (50) found no significant differences in thermal benefit of three different lightweight rescue bags when volunteer subjects were exposed for three hours in a cold outdoor environment. Grant et al. (51) performed a cross-over study with volunteer subjects insulated in three different rescue bags for one hour in a cold chamber with an ambient temperature of $-10^{\circ}C$

and a wind speed of 3 m/s. Even though there was a difference in mean skin temperature and cold discomfort, no difference in body core temperature or oxygen consumption could be detected. Not one bag provided sufficient insulation for the ambient conditions as was indicated by a continuous decline in body core temperature. Recently, Thomassen et al. (53) demonstrated that mean skin temperature in subjects wearing wet clothing was higher with the addition of a vapour barrier under an ordinary ambulance blanket at an ambient temperature of 5°C and a wind speed of 3 m/s. There was, however, no difference in shivering metabolism, body core temperature, or cold discomfort. Whether the effect on mean skin temperature was due to a reduced convective or evaporative heat loss or both could not be evaluated.

Clinical practise

Today, many insulation materials and products are used for passive warming and protection of patients against cold in the prehospital services but the selection of materials and techniques used in the field rely mainly on local tradition and experience, not on scientific evidence.

Prehospital trauma care often mandate spinal immobilisation using rigid spineboards, scoop stretchers, or vacuum mattresses (47). Although well suited for this purpose, some adverse effects from prolonged immobilisation have been indicated; e.g., patient discomfort or pain and local tissue ischemia (114). However, to this author's knowledge there has been no study evaluating the effect on conductive heat loss from immobilisation in a cold environment.

Wind will significantly increase convective heat loss. Although both national and international guidelines on prehospital care in cold environments emphasize the importance of protection against wind and moisture (14, 43-49), the thermal insulation capacities of insulation materials and products commonly used in ambulance and rescue services have not been evaluated in wind conditions.

Moisture will increase evaporative heat loss and wetting of textiles will reduce insulation capacity of blankets and rescue bags applied. Most guidelines recommend the removal of wet clothing prior to insulation and some, the use of a vapour barrier between the patient and the insulation. In the field, however, the removal of wet clothing might be impeded due to harsh environmental conditions or the patient's condition and injuries. Additionally, encapsulation in a vapour barrier might restrict necessary access and monitoring of the patient during transportation. The effects on heat loss and thermoregulation by wet clothing removal or the addition of a vapour barrier has not been established.

Aims

General aim

The general aim of the thesis was to determine insulation properties of blankets and rescue bags and evaluate the effects on cold stress and thermoregulation provided by different materials and techniques used for protection against cold in prehospital trauma care.

Specific aims

Evaluate the effect on body core temperature, sensation of shivering, and cold discomfort in cold stressed subjects by utilising additional insulation on a spineboard (I).

Determine thermal insulation properties of blankets and rescue bags commonly used in Scandinavian ambulance and rescue services when in different wind conditions (II).

Establish the utility of wet clothing removal or the addition of a vapour barrier by determining the effect on heat loss within different levels of insulation in cold and warm ambient temperatures (III) and evaluating the effect on metabolic rate, body core temperature, skin temperature, total body heat storage, heart rate and cold discomfort in cold stressed subjects (IV).

Methods

The objectives of this thesis were addressed by a combination of measurements on a thermal manikin for the determination of insulation properties and assessment of cold stress in volunteer subjects for the evaluation of effects on thermoregulation.

Determination of insulation properties

Using the thermal manikin TORE (115), two studies were performed at the Thermal Environment Laboratory, Lund University, Sweden, to determine insulation properties of blankets and rescue bags in different wind conditions (II) and to evaluate the effect on heat loss by wet clothing removal or the addition of a vapour barrier within different levels of insulation in cold and warm ambient temperatures (III).

Study design

The thermal manikin was set up inside a climatic chamber according to the European Standard for assessing requirements of sleeping bags (111) with modifications made for wind or wet conditions. Accordingly, fans were set up to provide different wind conditions (II) or the whole setup was placed on a large scale for continuous weighing and the determination of evaporative heat loss (III). In both studies, the manikin was dressed in light two piece thermal underwear, knee-length socks, and a balaclava and was placed in a supine position on an ordinary spine board.

For the determination of insulation properties in different wind conditions (II), twelve different blankets and rescue bags commonly used in Scandinavian ambulance and rescue services were selected; four high insulation ensembles, primarily used by mountain search and rescue teams or armed forces medical field units and eight low insulation ensembles, primarily used in urban ambulance and rescue services. All ensembles were evaluated in low (<0.5 m/s), moderate (2–3 m/s) and high (7–9 m/s) wind conditions and to achieve optimal heat flux values in all zones of the thermal manikin, the climatic chamber was set to 0°C for the high insulation ensembles and 10°C for the low insulation ensembles.

For the evaluation of wet clothing removal or the addition of a vapour barrier (III), the climatic chamber was set to -15°C for cold conditions and $+10^{\circ}\text{C}$ for warm conditions and three different levels of insulation; one, two and seven woollen blankets, were selected to provide low (2.8 ± 0.1 clo), moderate (3.8 ± 0.1 clo) or high (5.9 ± 0.2 clo) thermal insulation (I_t) in the cold condition. Five different test conditions were evaluated: (a) no underwear; (b) dry underwear; (c) dry underwear with a vapour barrier; (d) wet underwear; and (e) wet underwear with a vapour barrier. The vapour barrier was made up of two large plastic bags taped together

forming a large sack and wetting of the clothing was achieved using a standardised protocol. Trials with wet underwear were conducted in both warm and cold conditions whereas trials with dry or no underwear were conducted only in cold conditions.

Data analysis

Both studies calculated the total (resultant) thermal insulation, $I_{(r)}$ ($\text{m}^2\text{°C/W}$), (parallel method) from total heat loss, Q_{tot} (W/m^2), and the gradient between ambient air temperature (°C) and manikin surface temperature (°C) during steady state heat transfer (91). For the evaluation of wet clothing removal or the addition of a vapour barrier (III), the thermal insulation determined with dry or no clothing in the cold condition was used to calculate total heat loss, Q_{tot} , in the warm condition as for the same level of insulation. Wet heat loss, Q_{wet} , was determined as the difference between total heat loss in wet and dry conditions. Real evaporation, Q_{evap} , was determined from the mass loss rate ($\text{g/m}^2 \text{ s}$) at steady state and the enthalpy of evaporation (J/g). Heat loss from evaporation and condensation within the ensemble, $Q_{heatpipe}$, was calculated as the difference between wet heat loss and heat loss from real evaporation; $Q_{tot} = Q_{dry} + Q_{wet} = Q_{dry} + Q_{evap} + Q_{heatpipe}$ (89).

In both studies, all insulation ensembles were evaluated twice for each condition and the mean (resultant) thermal insulation was converted to clo units (1 clo = $0.155 \text{ m}^2 \text{ °C/W}$). Tests were repeated if the coefficient of variation (standard deviation/ average thermal insulation) exceeded 5% (III) or 10% (II) (92). In wind conditions, tests were also repeated if average air velocity was $<2.0 \text{ m/s}$ or $>3.0 \text{ m/s}$ in moderate wind conditions and $<7.0 \text{ m/s}$ or $>9.0 \text{ m/s}$ in high wind conditions, or if the turbulence (standard deviation/ average air velocity) exceeded 25%. For accepted trials the coefficient of variation was $3.1 \pm 2.5\%$ (II) and $1.8 \pm 1.0\%$ (III). Thus, the measurements provided a high degree of precision, and in accordance to standard procedures, an additional inference analysis between the insulation ensembles was considered redundant.

Methodological considerations

The studies were designed according to the European standard for assessment of sleeping bags (111) with modifications made to provide different wind or wet conditions. In both studies, the thermal manikin was positioned on a spine board instead of on the prescribed sleeping mattress. Although variations in mattress insulation are demonstrated to have a 5–15% effect on the results in standard test conditions (116), it is expected that the effect on thermal insulation is less in wind conditions (II) where heat loss predominantly occurs from convection. In the evaluation of wet conditions (III), the primary outcome variable was heat loss, not resultant thermal insulation; thus the use of a spine board provided better resemblance to actual prehospital rescue scenarios.

For the evaluation of thermal insulation properties in different wind conditions (II), a wide range of materials and products commonly used in Scandinavian ambulance and rescue services were selected. The low insulation ensembles can be applied in multiple layers depending on ambient temperature and available resources, but for comparative reasons, a single layer of these materials was evaluated. Evaluating the use of additional layers or combinations of materials might have provided further knowledge.

For the evaluation of wet clothing removal or the addition of a vapour barrier (III), different levels of insulation, ranging from limited (one woollen blanket) in the cold condition to redundant (seven woollen blankets) in the warm condition were selected. Thus the results cover a wide range of possible combinations of insulation levels in regard to ambient temperature. However, evaluation of various clothing and moisture levels might have provided further knowledge. No wind was applied, specifically to evaluate the effect of evaporative heat loss reduction. Future studies might also involve wind for the evaluation of a possible additional effect of the vapour barrier as a wind proof layer.

With regards to the deviations from standard test procedures, no calculation of temperature limits for the range of utility (e.g., comfort or extreme) was performed (111). Instead, the model for required insulation was applied for an estimation of corresponding ambient temperature limits for thermoneutrality (II) (93). This should, however, only be seen as an indicator as the model does not take into account the effects of altered thermoregulation and physiological responses in injured or ill patients. The physiological models are also not developed for wet conditions. Therefore, the effect of wet clothing removal or the addition of a vapour barrier was further evaluated in a follow-up study for assessment of cold stress and the effect on thermoregulation in volunteer subjects (IV).

Assessment of cold stress

Two studies were performed to assess cold stress and evaluate the effect on thermoregulation in volunteer subjects. The evaluation of additional insulation on a spine board (I) was performed in an outdoor environment at the air force base of Jämtland Wing F4, Östersund, Sweden in collaboration with the Swedish Mountain Rescue organization. The evaluation of wet clothing removal or the addition of a vapour barrier (IV) was performed in a climatic chamber at the Thermal Environment Laboratory, Lund University, Sweden. Both studies were designed and conducted according to regulations and guidelines for good clinical practise as stated by the World Medical Association and the International Committee on Harmonisation (117, 118). Ethical approval was provided by the Regional Ethics Review Board in Linköping (I) and Umeå (IV).

Study design

The effect of an insulated spine board (I) was assessed by measurements of aural canal temperature, sensation of shivering, and cold discomfort. Nineteen volunteer subjects wearing light clothing were randomly allocated either to be placed on a standard spine board (n=10) or on a spine board with additional insulation (n=9). The study was conducted using a balanced parallel design over four consecutive days. Each day two or three subjects from each group participated. After 10 minutes of indoor baseline data recordings subjects went outdoors and lay down on the assigned spine boards. Body core temperature was continuously monitored using an insulated aural canal temperature sensor applied in the external meatus [*falsely described as a tympanic sensor in paper I*] with recordings at five-minute intervals. The subjects' estimation of whole-body cold discomfort and shivering were sampled at five-minute intervals using 10 degree numerical rating scales [*falsely described as visual analogue scales in paper I*]. The trial ended when either of the following termination criteria were met; a reduction in body core temperature $>1.5^{\circ}\text{C}$ or an unbearable cold discomfort.

The effect of wet clothing removal or the addition of a vapour barrier (IV) was assessed by measurements of metabolic rate, oesophageal temperature, skin temperature, heart rate, and cold discomfort. Eight healthy subjects (n=8) volunteered for participation in a cross-over comparison of four different insulation interventions; (a) one woollen blanket; (b) vapour barrier + one woollen blanket; (c) wet clothing removal + one woollen blanket; and (d) two woollen blankets. After 15 minutes of baseline data collection at room temperature, subjects dressed in the same wet underwear as previously evaluated with a thermal manikin (III), but with additional dry insulation on hands and feet to protect from local cold injuries. Subjects entered the climatic chamber set to -20°C and lay down on an insulated spine board. An initial 20 minutes of cold exposure was followed by 30 minutes of the assigned insulation intervention. Oesophageal temperature, skin temperature, heart rate, oxygen consumption, and respiratory exchange ratio were continuously monitored and cold discomfort ratings were sampled at five-minute intervals.

Data analysis

In the evaluation of insulated spine boards (I), primary outcome measure was not defined and no pre-study sample size calculation was performed. However, the results reveal that the non-significant differences are small; thus increasing the power would not have yielded any clinically relevant findings. Three subjects from the non-insulated group ended the trial after 55 minutes of cold exposure, because of either reaching the temperature limit (n=1) or because of unbearable cold discomfort (n=2). The analysis was, therefore, determined to include the first 55 minutes of data. A two-tailed statistical significance was defined as $p < 0.05$. Aural canal temperature data presented normal distribution and the difference in mean

temperature change from start cooling [*not the absolute temperature as stated in paper I*] between the two groups was compared at each five-minute interval using Student's t-test [*falsely denoted as a paired t-test in paper I*]. This was later found to be an incorrect approach. As all of the time points are included in the analysis, a repeated measure analysis of variance (ANOVA) should have been conducted prior to group-wise comparisons; the different time points considered as the levels of one factor and the grouping variable as the second factor in the analysis. Additionally, a post-hoc correction for multiple comparisons would have been appropriate. A repeated analysis is, therefore, presented in the results of this thesis. For ordinal data from subjective judgement of cold discomfort and shivering, Friedman's test, being a non-parametric equivalent of ANOVA for repeated measures could have been used for an analysis of change over time in each group. However, as the groups are unrelated it cannot be used for comparisons between the groups if all of the time points are included. The Wilcoxon rank sum test was properly used for the analysis [*falsely denoted as a Mann-Whitney U-test in paper I*]. In any case, a post-hoc correction for multiple comparisons would have been appropriate. An alternative statistical approach would have been to calculate a summary measure, e.g., change from baseline to end cold exposure or the average value for a pre-determined time interval. Such an approach would have limited the possibility of having significant findings resulting from chance by multiple comparisons. Also, the ratings of cold discomfort or estimated shivering could have been grouped in different categories; e.g., mild, moderate, or severe enabling the analysis of proportions using Chi-square or Fisher's exact test.

In the evaluation of wet clothing removal or the addition of a vapour barrier (IV), primary outcome measure was metabolic rate calculated from oxygen consumption and respiratory exchange ratio (partial method). A pre-study sample size calculation indicated that seven subjects were needed. However, the calculation was based on a difference in metabolic rate of 50 W/m². With the ambient conditions in this study, this proved to be an unrealistic difference equalling almost total metabolic rate at baseline. A more realistic difference might have been about 10 – 20% reduction in metabolic rate, rendering a minimum sample size of about 5 – 15 subjects with a within patient standard deviation of 10%. Nevertheless, the selected sample size rendered adequate power for the clinically relevant differences found. Data were analysed during steady state conditions at baseline (-10–0 minutes), cooling (10–20 minutes) and intervention (30–50 minutes) with a two-tailed statistical significance defined as $p < 0.05$. Total body heat storage was calculated from the change in mean skin and body core temperature, body mass, and specific heat of the body during cooling (10–20 minutes) and intervention (30–50 minutes) (109). Continuous data were initially compared using a repeated measures analysis of variance and ordinal data were compared using Friedman's test. Where a significant main effect was revealed, Student's t-test for pair-wise comparisons with Fisher's least significant difference for multiple comparisons or the non-parametric equivalent Wilcoxon signed rank test was performed identifying differences between the conditions.

Methodological considerations

The evaluation of insulated spine boards (I) was performed in an outdoor environment on four separate occasions, thus the ambient conditions were not identical. Air temperature ranged from -4°C to -16°C with wind speeds between 0 m/s and 3 m/s, measured with a combined temperature and wind gauge (Silva ADC Wind, Silva Sweden AB). As wind has a considerable impact on heat loss, it would have been convenient to report the wind chill effect. A renewed analysis reveals that the resultant wind chill temperature ranged from -9°C to -18°C (93). To resemble a more realistic prehospital rescue scenario and limit the effect of additional convective heat loss, the subjects could have been protected from the wind by using a windproof rescue blanket. However, at each occasion, both insulated and non-insulated spine boards were evaluated in a balanced design limiting the impact of random errors from ambient condition bias. The variance of aural canal temperature data is fairly small with a standard deviation of less than 0.5°C , whereas the median cold discomfort and estimated shivering ratings present interquartile ranges of 0.5 to 5 on the 10 degree scales. Conducting the study in a controlled environment would have increased the internal validity and choosing a cross-over design instead of parallel groups, probably would have limited the spread, providing more precise comparisons.

Body core temperature was measured using an aural canal sensor, validated for use in a cold and windy environment (105). Although properly sealed from the ambient environment according to the manufacturer's instructions, it cannot be excluded that part of the reduction in aural canal temperature readings during cold exposure could have been influenced by wind and ambient air temperature or by cold cutaneous blood flow in the ear canal. In addition to aural canal temperature, skin temperature measurements would have provided valuable information enabling the calculation of mean body temperature and total body heat content. Although the numerical rating scales used for estimation of shivering and cold discomfort are not validated, similar scales for subjective estimation of pain and other psychological variables are both validated and widely adopted in research and clinical practice (119). For more accurate values of shivering thermogenesis, the measurement of oxygen consumption is recommended. At the time that this study was conducted, we did not have the equipment necessary for field measurements of skin temperature or oxygen consumption. The specific effect on conductive heat loss could also be further evaluated by the use of a thermal manikin.

The evaluation of wet clothing removal or the addition of a vapour barrier (IV) was performed in a climatic chamber, which provided a controlled environment and enabled a more extensive evaluation of thermoregulation and physiological effects of cold stress. A cross-over design was used to limit the variance and increase the internal validity. One and two woollen blankets, previously determined to have a total resultant thermal insulation of about 2.8 and 3.8 clo respectively (III), were selected deliberately to provide less insulation than required for thermoneutrality in

a -20°C wind still ambient condition. If additional blankets had been applied, shivering thermogenesis is likely to have returned near baseline levels and the additional effect of heat loss reduction by wet clothing removal or the use of a vapour barrier would have been limited. We chose not to apply wind specifically to evaluate the effect of evaporative heat loss reduction. Future studies might also involve wind for the evaluation of a possible additional effect of the vapour barrier as a wind proof layer. Furthermore, various clothing amounts and different quantities of water content might provide valuable findings.

Metabolic rate was selected as the primary outcome measure, as a decrease in shivering heat production and thus oxygen consumption might be of considerable clinical importance in conjunction with major trauma, relieving cardiac and respiratory stress while preserving oxygen availability for vital organs. Oesophageal temperature, being highly sensitive to changes in arterial blood temperature, was selected for evaluation of body core temperature (102, 103). Although invasive and somewhat unpleasant for the subject, the benefits of accurate temperature readings independent of ambient conditions or the thermophysiological state of the body make oesophageal temperature a preferred site for body core temperature measurements. Skin temperature was measured at eight different sites of the body surface to provide accurate calculations of mean skin temperature. Additional measurements of finger and toe temperature with on-screen continuous presentation, was performed for the safety of the subjects (96). Mean skin and body core temperatures also enabled the calculation of total body heat storage, considered an important indicator of cold stress and the thermal state of the body (61).

Results

Protection against conductive heat loss

The effect on cold stress and thermoregulation by additional insulation on a spine board was evaluated in healthy volunteer subjects (I). During 55 minutes of cold exposure, mean body core temperature decreased almost linearly from $36.8 \pm 0.3^{\circ}\text{C}$ to $36.3 \pm 0.5^{\circ}\text{C}$ (mean \pm SD) in subjects immobilised on non-insulated spineboards (n=10) and from $37.0 \pm 0.2^{\circ}\text{C}$ to $36.4 \pm 0.3^{\circ}\text{C}$ in subjects immobilised on insulated spine boards (n=9) (Figure 1). *[In paper I, change in aural canal temperature is presented with SEM as an estimate of the spread.]* There were no significant differences between the groups, analysed using Student's t-test for each five-minute interval. A repeated analysis of variance for repeated measures confirm these findings ($p = 0.609$).

The median rating of cold discomfort increased almost identically to 7 (IQR; 6.75–9) in subjects immobilised on non-insulated spineboards and to 7 (IQR; 6–8) in subjects immobilised on insulated spine boards (Figure 2). *[In paper I, the spread for the cold discomfort ratings are falsely presented as half the interquartile range.]* There were no significant differences between the two groups analysed using Wilcoxon rank sum test for each five-minute interval. As stated in the methodological considerations a post-hoc correction for multiple comparisons would have been appropriate. A repeated analysis using the Mann-Whitney U-test with Bonferroni correction confirms that there is no significant difference between the groups in cold discomfort ratings at any time point ($p = 0.309$ – 0.966).

The median rating of estimated shivering increased to 8 (IQR; 8–10) in subjects immobilised on non-insulated spineboards and to 4 (IQR; 4–7) in subjects immobilised on insulated spine boards (Figure 3). *[In paper I, the spread for the estimated shivering ratings are falsely presented as half the interquartile range.]* During the last 20 minutes of cold exposure, the median estimated shivering ratings were significantly higher in subjects immobilised on non-insulated spine boards, analysed using the Wilcoxon rank sum test for each five-minute interval. However, as stated in the methodological considerations a post-hoc correction for multiple comparisons would have been appropriate. A repeated analysis using the Mann-Whitney U-test with Bonferroni correction for all five minute intervals confirms that there is a two-tailed significant difference between the groups at 35 ($p=0.022$), 45 ($p=0.044$), and 55 minutes ($p=0.044$), whereas the differences at 40 ($p=0.121$) and 50 minutes ($p=0.066$) are not statistically significant. Using the last 20 minutes as a summary measure instead of analysing each time point separately, the Mann-Whitney U-test confirms that there is a significant difference between the two groups ($p = 0.007$) with a median estimated shivering of 8 (IQR; 6–8) in subjects immobilised on non-insulated spineboards and 4 (IQR; 4–6) in subjects immobilised on insulated spine boards.

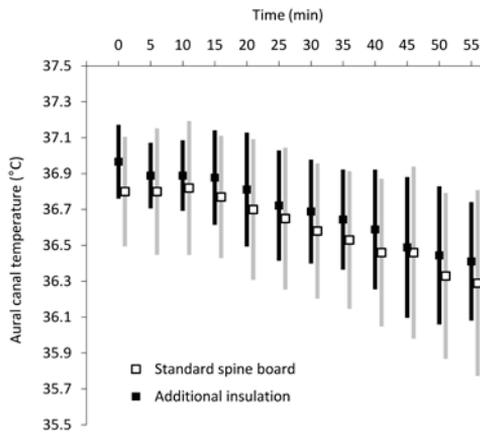


Figure 1. Aural canal temperature in subjects immobilised on a standard spine board (n=10) or on a spine board with additional insulation (n=9) (mean \pm SD).

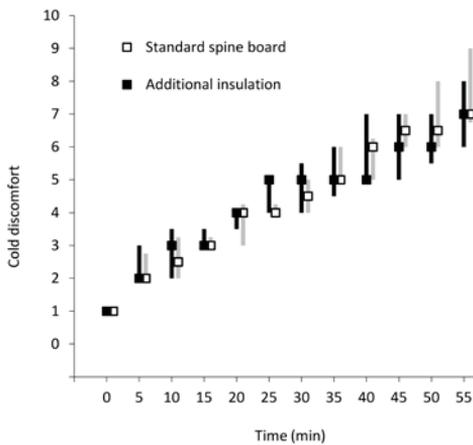


Figure 2. Cold discomfort in subjects immobilised on a standard spine board (n=10) or on a spine board with additional insulation (n=9) (median; IQR).

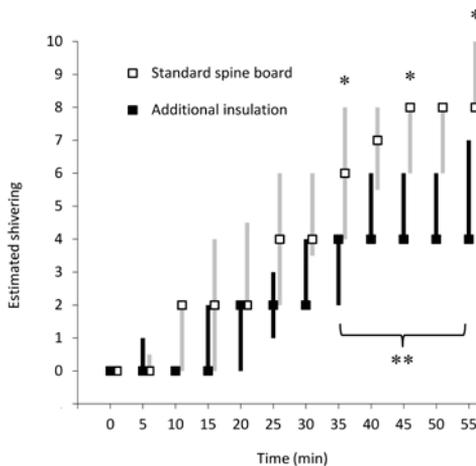


Figure 3. Estimated shivering in subjects immobilised on a standard spine board (n=10) or on a spine board with additional insulation (n=9) (median; IQR). * Significant difference between groups at 35, 45, and 55 minutes ($p<0.05$). ** Significant difference between groups when the median estimated shivering during the last 20 minutes is used as a summary measure ($p<0.01$).

Protection against convective heat loss

Thermal insulation properties of four high insulation ensembles and eight low insulation ensembles were determined using a thermal manikin in low, moderate and high wind conditions (II).

In low wind conditions (0.2 ± 0.0 m/s), the total resultant thermal insulation (I_{tr}) in the high insulation group ranged from 5.1 ± 0.2 clo (mean \pm SD) for the RC42® rescue bag to 6.0 ± 0.2 clo for the armed forces rescue blanket (Table 2). In the low insulation group, the total resultant thermal insulation (I_{tr}) ranged from from 2.0 ± 0.1 clo for the plastic blanket to 3.6 ± 0.1 clo for the RC20® rescue blanket (Table 3). Thermal insulation values were in the same order as measured thickness of the insulation ensembles, except for the reflective blankets which presented higher than expected values. [In paper II, the correlation between thickness and thermal insulation was not evaluated any further]. A correlation analysis, with the reflective blankets excluded, reveals that Spearman's rank correlation coefficient (R) for the correlation between thickness and thermal insulation is 0.999 ($p<0.001$) in the high insulation group (Figure 4) and 0.986 ($p<0.001$) in the low insulation group (Figure 5).

When wind was applied, thermal insulation values were reduced for all insulation ensembles (Figures 6, 7). In moderate wind conditions (2.7 ± 0.6 m/s), the range of reduction varied from 14% to 29% in the high insulation group (Table 2) and from 21% to 39% in the low insulation group (Table 3). In high wind conditions (8.0 ± 1.0 m/s), thermal insulation reduced even further, ranging from 20% to 63% in the high insulation group (Table 2) and from 34% to 64% in the low insulation group (Table 3).

Table 2. Total resultant thermal insulation, *Itr (clo)*, in the high insulation group.

<i>Insulation ensemble</i>	<i>Low wind (0.2 ± 0.0 m/s)</i>	<i>Moderate wind (2.7 ± 0.6 m/s)</i>	<i>High wind (8.0 ± 1.0 m/s)</i>
Armed Forces rescue blanket	6.0 ± 0.2	5.1 ± 0.1 (16%)	4.0 ± 0.1 (34%)
Five woolen blankets with plastic cover	5.8 ± 0.3	5.0 ± 0.0 (14%)	4.6 ± 0.0 (20%)
Five woolen blankets	5.6 ± 0.3	4.0 ± 0.3 (29%)	2.1 ± 0.1 (63%)
RC42® rescue bag	5.1 ± 0.2	4.0 ± 0.1 (23%)	3.5 ± 0.0 (33%)

Mean ± SD and reduction (%) of thermal insulation in relation to the low wind condition.

Table 3. Total resultant thermal insulation, *Itr (clo)*, in the low insulation group.

<i>Insulation ensemble</i>	<i>Low wind (0.2 ± 0.0 m/s)</i>	<i>Moderate wind (2.7 ± 0.6 m/s)</i>	<i>High wind (8.0 ± 1.0 m/s)</i>
RC20® rescue blanket	3.6 ± 0.1	2.7 ± 0.1 (25%)	2.2 ± 0.1 (38%)
Fly High® rescue blanket	3.6 ± 0.2	2.3 ± 0.2 (38%)	1.7 ± 0.2 (54%)
Akla reflective blanket	2.9 ± 0.1	1.9 ± 0.0 (35%)	1.2 ± 0.0 (59%)
Rescue services woolen blanket	2.7 ± 0.1	1.9 ± 0.0 (29%)	1.2 ± 0.0 (55%)
Ambulance Services Polyester blanket	2.4 ± 0.1	1.5 ± 0.0 (39%)	0.9 ± 0.0 (64%)
Bubblewrap blanket	2.4 ± 0.1	1.9 ± 0.0 (21%)	1.6 ± 0.0 (34%)
Mediwrap reflective blanket	2.4 ± 0.0	1.5 ± 0.1 (37%)	1.0 ± 0.0 (58%)
Plastic blanket	2.0 ± 0.1	1.4 ± 0.1 (28%)	1.0 ± 0.0 (50%)

Mean ± SD and reduction (%) of thermal insulation in relation to the low wind condition.

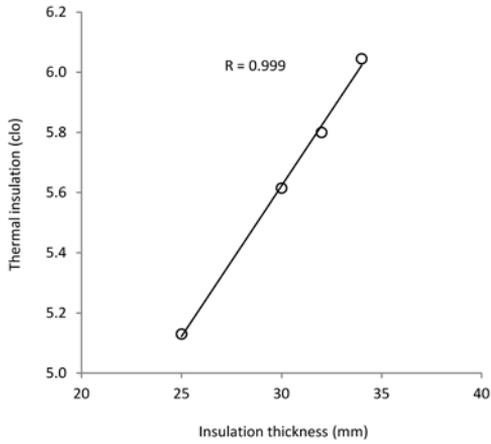


Figure 4. Correlation (Spearman's rank coefficient) between thickness and thermal insulation in the high insulation ensembles (n=4).

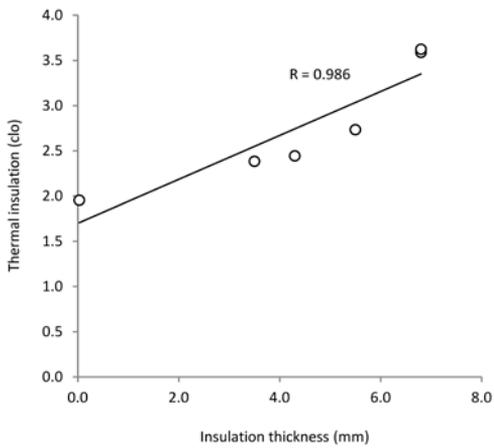


Figure 5. Correlation (Spearman's rank coefficient) between thickness and thermal insulation in the low insulation ensembles with reflective blankets excluded (n=6).

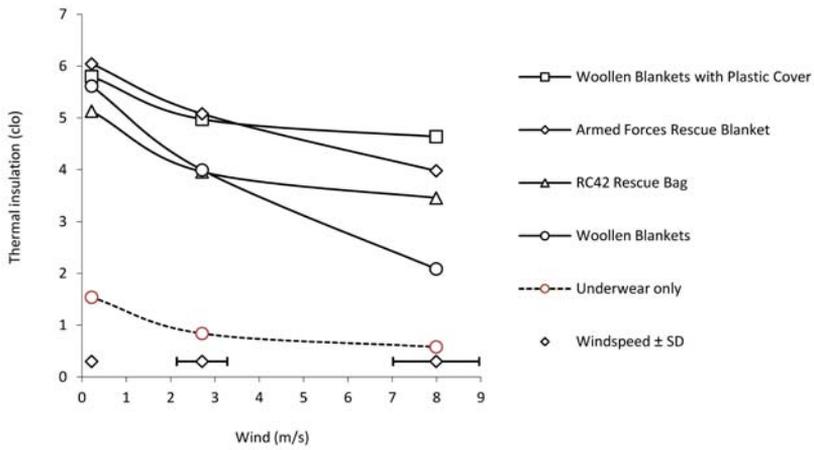


Figure 6. Total resultant thermal insulation for the high insulation ensembles in low, moderate and high wind conditions (mean).

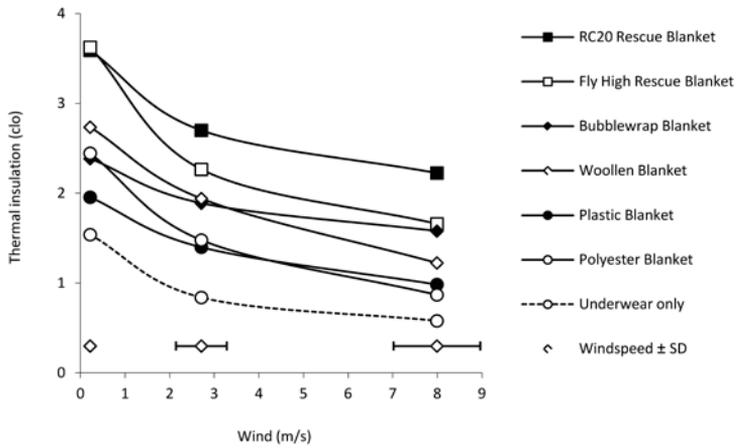


Figure 7. Total resultant thermal insulation for the low insulation ensembles in low, moderate and high wind conditions (mean). Reflective blankets are excluded for simplicity.

Protection against evaporative heat loss

Determination of heat loss

The effect on heat loss by wet clothing removal or the addition of a vapour barrier was evaluated using a thermal manikin (III). In the cold environment ($-15.4 \pm 0.4^\circ\text{C}$; mean \pm SD), wet clothing removal or the addition of a vapour barrier rendered a 19–31% total heat loss reduction (Table 4, Figure 8). The absolute heat loss reduction, however, was greater with less insulation applied. Increasing the insulation from one to two woollen blankets rendered a total heat loss reduction of 26% and increasing the insulation from two to seven woollen blankets rendered a total heat loss reduction of 40% (Table 4, Figure 8).

Table 4. Total heat loss, Q_{tot} (W/m^2), in a cold environment ($-15.4 \pm 0.4^\circ\text{C}$) with wet clothing removal or the addition of a vapour barrier within different levels of insulation.

<i>Condition</i>	<i>One woollen blanket</i>	<i>Two woollen blankets</i>	<i>Seven woollen blankets</i>
<i>Wet clothing</i>	158 \pm 3	117 \pm 0	70 \pm 1
<i>Wet clothing removal</i>	123 \pm 1 (22%)	84 \pm 1 (29%)	54 \pm 0 (23%)
<i>Wet clothing with vapour barrier</i>	110 \pm 2 (31%)	85 \pm 1 (28%)	57 \pm 1 (19%)

Mean \pm SD and reduction (%) of heat loss in relation to the wet clothing condition.

In the warm environment ($11.0 \pm 0.1^\circ\text{C}$), wet clothing removal or the addition of a vapour barrier rendered a 27–42% total heat loss reduction (Table 5, Figure 9). The absolute heat loss reduction, however, was greater with less insulation applied. Increasing the insulation from one to two woollen blankets rendered a total heat loss reduction of 27% and increasing the insulation from two to seven woollen blankets rendered a total heat loss reduction of 37% (Table 5, Figure 9).

Table 5. Total heat loss, Q_{tot} (W/m^2), in a warm environment ($11.0 \pm 0.1^\circ\text{C}$) with wet clothing removal or the addition of a vapour barrier within different levels of insulation.

<i>Condition</i>	<i>One woollen blanket</i>	<i>Two woollen blankets</i>	<i>Seven woollen blankets</i>
<i>Wet clothing</i>	77 \pm 0	57 \pm 2	36 \pm 1
<i>Wet clothing removal</i>	51 \pm 1 (34%)	35 \pm 0 (38%)	23 \pm 1 (37%)
<i>Wet clothing with vapour barrier</i>	45 \pm 1 (42%)	33 \pm 0 (42%)	26 \pm 1 (27%)

Mean \pm SD and reduction (%) of heat loss in relation to the wet clothing condition.

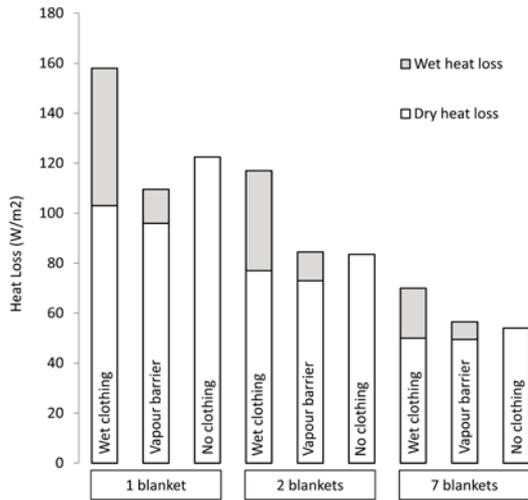


Figure 8. Total heat loss in cold conditions ($-15.4 \pm 0.4^\circ\text{C}$) with wet clothing, wet clothing and a vapour barrier, or wet clothing removed (mean).

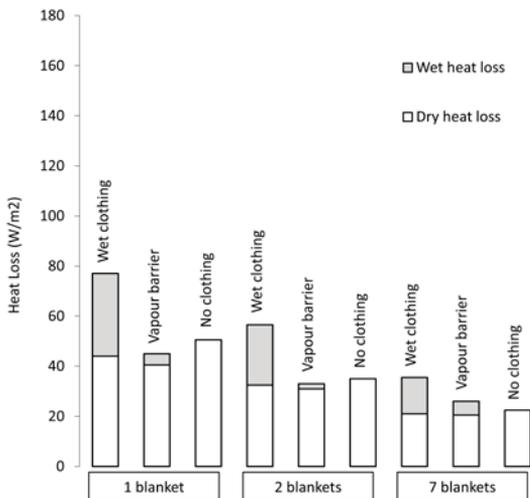


Figure 9. Total heat loss in warm conditions ($11.0 \pm 0.1^\circ\text{C}$) with wet clothing, wet clothing and a vapour barrier, or wet clothing removed (mean).

Assessment of cold stress

The effect on cold stress and thermoregulation by wet clothing removal or the addition of a vapour barrier was evaluated in a cross-over comparison of four different insulation interventions in healthy volunteer subjects ($n=8$) (IV). Data were analysed as summary measures at steady state conditions during baseline (-10–0 minutes), cooling (10–20 minutes) and insulation intervention (30–50 minutes). Air temperature in the climatic chamber was $-18.5 \pm 0.2^\circ\text{C}$ (mean \pm SD) for all trials. Mean skin temperature for all four conditions decreased from $33.4 \pm 0.3^\circ\text{C}$ to $25.2 \pm 0.9^\circ\text{C}$, while metabolic rate increased from $66 \pm 12 \text{ W/m}^2$ to $107 \pm 16 \text{ W/m}^2$, maintaining body core (oesophageal) temperature at $36.9 \pm 0.5^\circ\text{C}$ during initial cooling with no significant differences between conditions. Total body heat storage during cooling was -59 (IQR; -70 – -39) W/m^2 , heart rate remained at near baseline levels, $81 \pm 8 \text{ min}^{-1}$, and cold discomfort was increased to 6.25 (IQR; 4.5–7.75) with no significant differences between the conditions (Figure 10–15).

When insulation was applied, skin cooling was interrupted and metabolic rate was decreased in all conditions. During the last 20 minutes of steady state, metabolic rate was significantly lower with wet clothing removal ($85 \pm 11 \text{ W/m}^2$, $p=0.036$), the addition of a vapour barrier ($84 \pm 17 \text{ W/m}^2$, $p=0.022$), or when two woollen blankets were applied ($81 \pm 10 \text{ W/m}^2$, $p=0.008$) compared to with one woollen blanket alone ($98 \pm 12 \text{ W/m}^2$) (Figure 10).

Heart rate was also reduced ($67 \pm 5 \text{ min}^{-1}$) when insulation was applied but there was no significant difference between the conditions ($p=0.159$) (Figure 11).

Mean skin temperature rewarming rates were significantly higher with wet clothing removal ($2.3 \pm 1.0^\circ\text{C/hr}$, $p<0.001$), the addition of a vapour barrier ($2.8 \pm 1.4^\circ\text{C/hr}$, $p=0.002$), and when two woollen blankets were applied ($1.6 \pm 1.1^\circ\text{C/hr}$, $p=0.041$) compared to with one woollen blanket alone ($0.7 \pm 0.9^\circ\text{C/hr}$) (Figure 12).

Body core temperature was reduced after insulation was applied with no significant difference in mean body core temperature cooling rate ($-0.9 \pm 0.3^\circ\text{C/hr}$) between the conditions ($p=0.493$) (Figure 13).

Total body heat storage was increased and significantly higher with wet clothing removal (34; IQR 15–50 W/m^2 , $p=0.005$), the addition of a vapour barrier (30; IQR 10–47 W/m^2 , $p=0.003$), or when two woollen blankets were applied (12; IQR -4–24 W/m^2 , $p=0.008$) compared to with one woollen blanket alone where total body heat storage continued to be negative (-7; IQR -16–0 W/m^2) (Figure 14).

Cold discomfort was reduced in all conditions but was significantly lower with the addition of a vapour barrier (4; IQR 2–4.75, $p=0.008$) or when two woollen blankets were applied (3.5; IQR 1.5–4, $p=0.031$) compared to one woollen blanket alone (5; IQR 3.25–6) (Figure 15). There was also a tendency, although not statistically significant, for a lower cold discomfort rating with wet clothing removal (3; IQR 2–5, $p=0.094$).

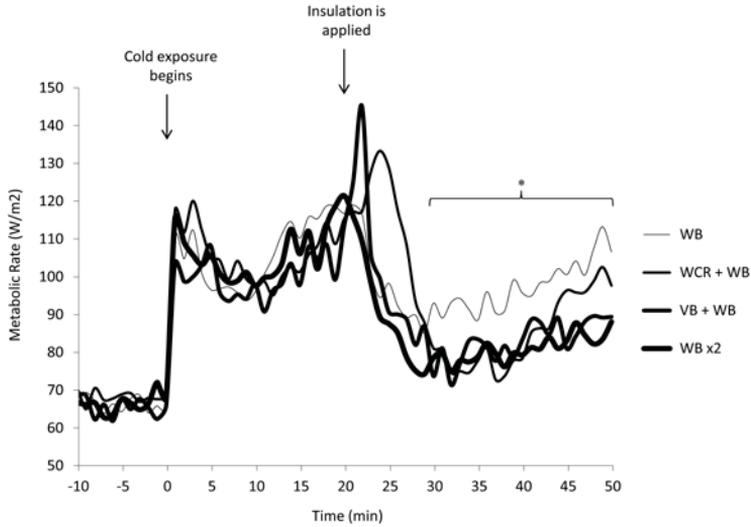


Figure 10. Metabolic rate during four insulation protocols in a cold environment (mean, n=8). WB = woollen blanket; WCR = wet clothing removal; VB = vapour barrier; WB x2 = two woollen blankets. * Significantly lower with WCR+WB, VB+WB, and WB x2 compared to WB (p<0.05).

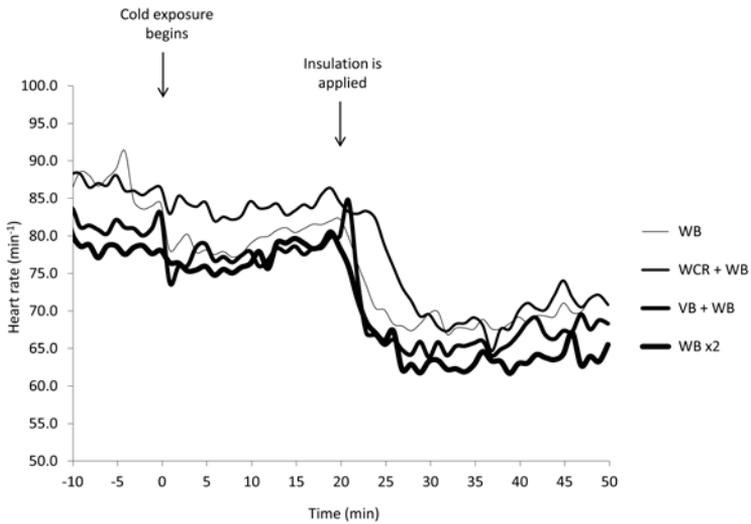


Figure 11. Heart rate during four insulation protocols in a cold environment (mean, n=8). WB = woollen blanket; WCR = wet clothing removal; VB = vapour barrier. WB x2 = two woollen blankets.

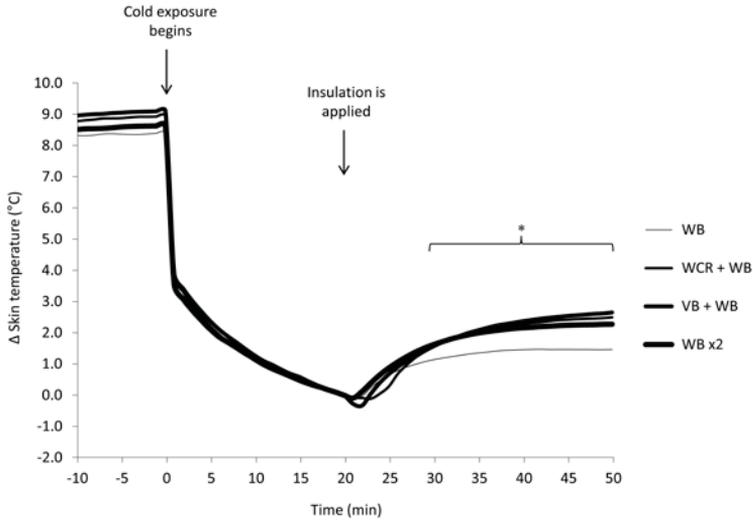


Figure 12. Mean skin temperature change from insulation is applied during four insulation protocols in a cold environment (mean, n=8). WB = woollen blanket; WCR = wet clothing removal; VB = vapour barrier; WB x2 = two woollen blankets. * Significantly higher rewarming rate (°C/hr) with WCR+WB, VB+WB, and WB x2 compared to WB ($p < 0.05$).

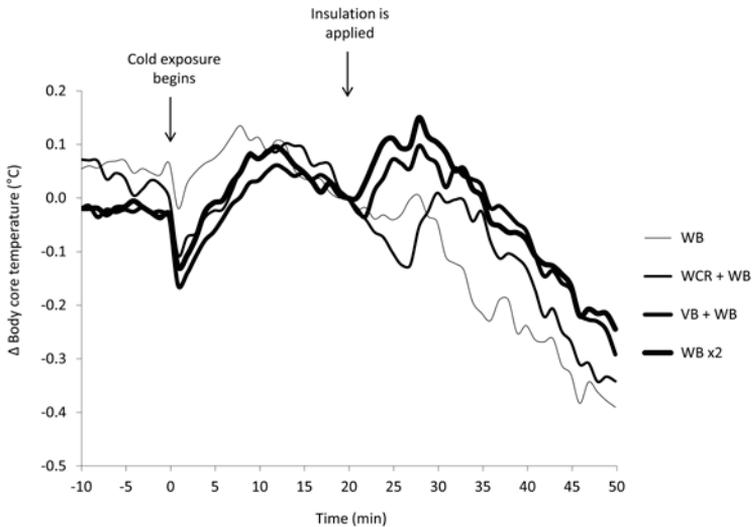


Figure 13. Body core (oesophageal) temperature change from insulation is applied during four insulation protocols in a cold environment (mean, n=8). WB = woollen blanket; WCR = wet clothing removal; VB = vapour barrier; WB x2 = two woollen blankets.

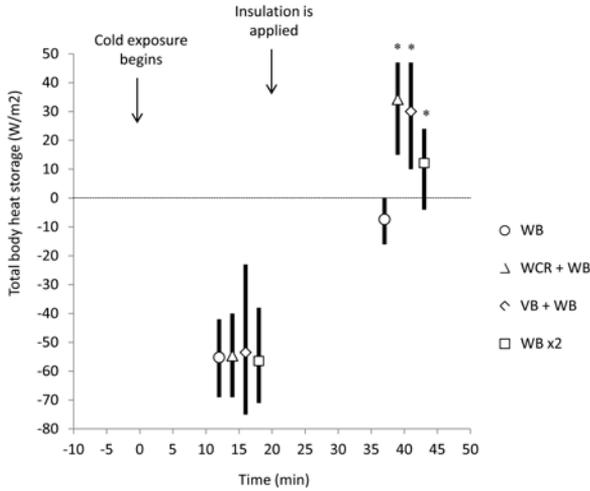


Figure 14. Total body heat storage at initial cooling (10-20 min) and with insulation applied (30-50 min) during four insulation protocols in a cold environment (median; IQR, separated in time for simplicity, n=8). WB = woollen blanket; WCR = wet clothing removal; VB = vapour barrier; WB x2 = two woollen blankets. * Significantly higher with WCR+WB, VB+WB, and WB x2 compared to WB (p<0.05).

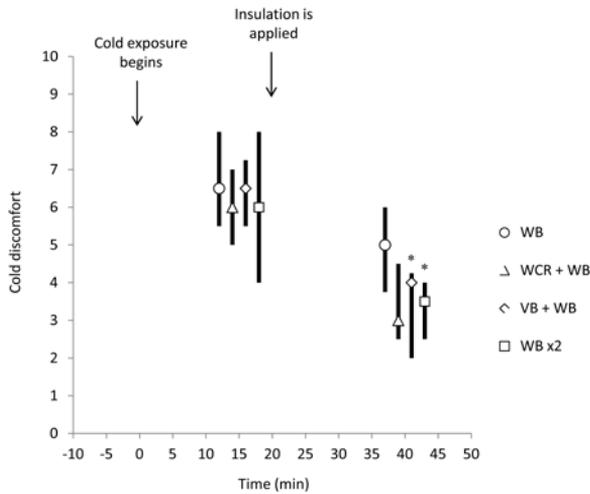


Figure 15. Cold discomfort at initial cooling (10-20 min) and with insulation applied (30-50 min) during four insulation protocols in a cold environment (median; IQR, separated in time for simplicity, n=8). WB = woollen blanket; WCR = wet clothing removal; VB = vapour barrier; WB x2 = two woollen blankets. * Significantly lower with VB+WB, and WB x2 compared to WB (p<0.05).

Discussion

Protection against cold is vitally important in prehospital trauma care. Early application of adequate insulation to reduce heat loss, contain endogenous heat production and prevent body core cooling is imperative. Major incidents and disasters are prone to occur in harsh conditions and it is thus necessary that insulation materials and techniques used in ambulance and rescue services are suitable for extended on scene durations or protracted evacuations in a cold, wet and windy environment.

Protection against conductive heat loss

Spine boards, vacuum mattresses, and scoop stretchers are commonly used in prehospital trauma care for spinal immobilisation (120). Prolonged immobilisation in a cold environment might contribute to a significant conductive heat loss. Previous studies have demonstrated that additional padding on a spineboard reduces pain and tissue pressure (121) and improves comfort (122) without compromising cervical spine immobilisation (123). In this thesis, the effect on cold stress and thermoregulation by additional insulation on a spine board was evaluated in healthy volunteer subjects (I).

In a cold outdoor environment, subjects experienced a significant reduction of estimated shivering when additional insulation was present on a spine board. Although the study was carried out in a field environment, the risk of random errors from ambient conditions was minimized using a balanced design. No blankets were applied during the cold exposure, thus it is plausible to believe that convection might have provided a large proportion of total heat loss. Nevertheless, reduction of conductive heat loss by the means of an ordinary insulation mat rendered a significant effect on shivering thermogenesis as indicated by the large difference in subjects' estimated shivering. There was, however, no difference in body core cooling probably due to the compensatory increase in endogenous heat production in subjects lying on non-insulated spine boards. Several factors influence thermal sensation and cold discomfort. In this study, the difference in estimated shivering was not accompanied by a reduction in cold discomfort.

Although the effect on conductive heat loss and thermoregulation deserves further research in a controlled environment, the results of this study indicate that additional insulation on a spine board bears the potential benefit of relieving shivering thermogenesis, thus limiting unnecessary cardiac and respiratory stress. The effect of an insulation mat might be less if heavy clothing is worn. In prehospital trauma care, however, patients are often lightly dressed or clothing is cut off during primary assessment. With protracted evacuations in a cold environment it could be well advised to apply additional insulation on spine boards as well as on other equipment used for prehospital transportation.

Protection against convective heat loss

Shelter from the wind is a key component of protection against cold in an outdoor environment (14, 43-49) Thermal insulation properties of blankets and rescue bags commonly used in Scandinavian ambulance and rescues services was determined using a thermal manikin in different wind conditions (II).

In the low wind condition, results confirmed that thermal insulation is mainly dependent on thickness of the insulation, and thus the ability to trap air. The higher than expected values for the metallised reflective blankets were most likely because of additional radiative heat loss reduction. The impact of this reflective effect is dependent on the temperature gradient between the clothing surface and the surrounding mean radiant temperature (57). According to standard test procedures, the surface temperature of the thermal manikin was regulated at a constant level providing a high temperature gradient to the surroundings. In a real life scenario the cold induced vasoconstriction will render lower skin temperatures and heat loss from radiation will be reduced. Also, with thicker clothing, the surface temperature of the clothing will near the ambient temperature causing less heat loss from radiation. The reflective effect is also dependent on maintaining a loft of air between the patient and the reflective surface. This will not be possible if additional blankets are applied. If the patient is wet, moisture will accumulate from evaporation and condensation on the metallised surface hampering the reflection (52). On the other hand, a reflective blanket, impermeable to air, might provide an important windproof cover.

In the moderate and high wind conditions thermal insulation was reduced for all ensembles but the proportions of reduction was highly divergent between the different insulation ensembles. In general, thermal insulation was better preserved for windproof compared to wind permeable textiles. As an example, the five woollen blankets in the high insulation group lost 63% of their insulation value in the high wind condition. With an additional plastic cover applied the reduction was only 20%. The reflective blankets, although wind proof, presented similar reductions as the wind permeable woollen and polyester blankets. In windy conditions, the proportion of heat loss from convection will be increased and the net effect of preventing heat loss from radiation will be diminished. Accordingly, in high wind conditions, the reflective blankets provided about the same thermal insulation as the plastic blanket. Also the form and fit of the ensemble tended to affect the results in higher wind conditions. As an example, even though the RC20® and the Fly High® rescue blankets are made of identical textiles, the latter has a loose fit around the body and the pumping effect of the wind caused greater thermal insulation reduction. Considering the different characteristics of the ensembles, it is plausible to conclude that in moderate and high wind conditions thermal insulation was better preserved for blankets and rescue bags that were windproof and resistant to the compressive effect of the wind.

Adequate insulation for maintaining thermoneutrality in a cold environment can be achieved by multiple layers of different insulation ensembles. However, in extended on-scene outdoor durations, such as during difficult extrications or in multiple casualty situations, the results of this study demonstrate that a windproof and compression resistant outer cover will significantly improve thermal insulation capacity.

Protection against evaporative heat loss

If the patient is wet from immersion, precipitation, major bleeding, or sweating because of previous physical activity; evaporative heat loss might be considerable. The effect on heat loss by wet clothing removal or the addition of a vapour barrier was evaluated using a thermal manikin (III) and the effect on cold stress and thermoregulation was evaluated in healthy volunteer subjects (IV).

Independent of the number of blankets applied, wet clothing removal or the use of a vapour barrier reduced total heat loss by about one fourth in the cold environment and about one third in the warm environment. The absolute reduction, however, was greater in the cold environment and with less insulation. A similar reduction was also achieved by increasing the insulation from one to two woollen blankets or from two to seven woollen blankets.

The vapour barrier rendered a significant decrease in evaporative heat loss, whereas the increase in thermal resistance, measured in dry conditions, was limited in all conditions. Wet clothing removal eliminated evaporative heat loss and thus total heat loss was reduced in all conditions, despite a slight reduction in thermal resistance seen in cold conditions and with less insulation applied. Increasing the insulation increased thermal resistance and thus limited both dry and wet heat losses.

These findings indicate that the clinical relevance of wet clothing removal or the use of a vapour barrier is greater in a cold environment with limited insulation available.

In cold stressed shivering subjects, wet clothing removal, or the use of a vapour barrier significantly reduced metabolic rate, increased skin rewarming rate and improved total body heat storage compared to with one woollen blanket alone. The same effect was also achieved by increasing the insulation from one to two woollen blankets. Although skin cooling was interrupted in all conditions, the lower skin rewarming rate with one woollen blanket alone probably reflects a sustained vasoconstriction because of greater heat loss in this condition. Accordingly, this difference in peripheral cold stimuli probably explains the lower metabolic rate with wet clothing removal, the addition of a vapour barrier, or when two woollen blankets were applied compared to with one woollen blanket alone. Despite the difference in metabolic rate, there was no difference in heart rate between the conditions. As all subjects in this study were young and fit, the increased metabolic and thus cardiac output demands with one woollen blanket alone was probably met by an increase in stroke volume rather than an increase in heart rate.

As a result of temperature equalisation between the warm body core and the cold peripheral parts, there was a continuing decline in body core temperature during all insulation interventions. The greater heat loss with one woollen blanket alone was counteracted by a sustained vasoconstriction and a greater endogenous heat production and thus the cooling rate was about the same as in the other conditions. However, total body heat storage, calculated from the change in mean skin and body core temperature, body mass, body surface area, and the specific heat of body tissues, was increased with wet clothing removal, the addition of a vapour barrier, and when two woollen blankets were applied, whereas it was reduced with one woollen blanket alone.

Although individual psychological factors have a great impact on cold discomfort, the differences in metabolic rate and total body heat storage between conditions probably explain why cold discomfort was significantly lower with the addition of a vapour barrier or the application of two woollen blankets compared to with one woollen blanket alone. There was also a tendency, although not statistically significant, for a lower cold discomfort with wet clothing removal compared to one woollen blanket alone.

The results of these studies should be evaluated in the lights of optimal conditions for the different insulation interventions and a rather homogenous group of young and healthy non-injured subjects. If wind had been present it might have affected the results in favour of the vapour barrier that would have served as a windproof cover. In a real life scenario, the injuries and physical condition of the patient might affect heat loss and thermoregulation capabilities as well as practical aspects of possible insulation interventions.

Depending on ambient temperature and wind conditions, different thicknesses of insulation are required to maintain thermoneutrality. If the patient can be readily transferred into a warm environment, such as a heated transportation unit, sufficient insulation is easy to achieve and the effect of wet clothing removal or the addition of a vapour barrier will be limited. However, in a sustained cold environment in which sufficient insulation is not available; e.g., in difficult extrications, mass casualty situations, or during a protracted evacuation in a non-heated transportation unit, wet clothing removal or the addition of a vapour barrier might be of considerable clinical importance reducing heat loss and possibly relieving cardiac and respiratory stress caused by shivering thermogenesis.

Conclusions

Specific conclusions

In a cold environment, additional insulation on a spine board rendered a significant reduction of estimated shivering in healthy volunteer subjects. There was, however, no significant difference in body core temperature or cold discomfort (I).

In the low wind condition, thermal insulation correlated to the thickness of the insulation. In moderate and high wind conditions, thermal insulation was better preserved for blankets and rescue bags that were windproof and resistant to the compressive effect of the wind. In high wind conditions, metallised blankets did not add any beneficial effect over similar but non-reflective plastic blankets (II).

Wet clothing removal or the use of a vapour barrier reduced total heat loss by about one fourth in the cold environment and about one third in the warm environment. The absolute reduction was greater in the cold environment and with less insulation applied. A similar reduction in heat loss was also achieved by increasing the insulation (III).

In cold stressed, shivering volunteer subjects with limited insulation applied, wet clothing removal or the use of a vapour barrier significantly reduced metabolic rate, increased skin rewarming rate, and improved total body heat storage. There was, however, no significant difference in heart rate or body core temperature cooling rate. A similar effect on thermoregulation was also achieved by increasing the insulation. Cold discomfort was reduced with the addition of a vapour barrier and with an increased insulation but the reduction with wet clothing removal was not statistically significant (IV).

Practical implications

The results of this thesis indicate that spine boards and other equipment used in prolonged transportations in a cold environment should be well insulated to prevent conductive heat loss and possibly limit cold stress. In extended on scene durations, the use of a windproof and compression resistant outer cover is crucial to maintain adequate thermal insulation capabilities. In a sustained cold environment in which sufficient insulation is not available, wet clothing removal or the use of a vapour barrier might be considerably important reducing heat loss and relieving cold stress.

Future perspectives

The results of this thesis might serve as an evidence-based reference for guidelines on protection against cold in prehospital trauma care and prove valuable for planning and acquisition of insulation materials used in different prehospital rescue services.

Future studies should be directed at determination of conductive heat loss from the use of different spinal immobilisation devices or transportation equipment. Further evaluation of the combined protection against convective and evaporative heat loss in a wet and windy environment is preferable. In addition, the application of external heat sources in conjunction with adequate passive warming deserve further research as the more severely injured or hypothermic patients might be dependent on active warming for prevention of continuous body core cooling during resuscitation and transportation.

The knowledge and experience gained throughout this thesis clearly advocate the use of thermal manikins as a first line approach for the determination of heat loss and thermal properties. Once important aspects are identified, further evaluation of specific effects on thermoregulation in volunteer subjects or in a clinical trial is recommended.

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Pictures



Prehospital care in a cold environment (Photograph: LO Pettersen, 330 Skvadron)



Protection against cold (Photograph: LO Pettersen, 330 Skvadron)



Thermal manikin TORE with the RC20® rescue blanket applied (study II)



Thermal manikin TORE with the vapour barrier applied (study III)



Volunteer subject wearing wet clothing in -18.5°C (study IV)



Wet clothing removed and woollen blanket applied (study IV)



Volunteer subjects in a cold environment (study I)



On a journey for more knowledge in prehospital trauma care

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