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# Human performance and medical treatment during cold weather operations – synthesis of a symposium

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**ABSTRACT**

In October 2022, the Human Factors and Medicine (HFM) panel of the NATO Science and Technology Organization convened a review of progress in military biomedical research for cold weather operations. This paper represents a summary of the research presentations and future directions. The importance of realistic training was an overarching theme. Many reported studies took advantage of cold weather training exercises to monitor soldiers' health and performance; these are valuable data, using winter exercises as a platform to gain further knowledge regarding human performance in the cold and represent an excellent extension of controlled laboratory studies. Topics also included prevention of Cold Weather Injuries (CWI); effects of cold weather stressors on cognitive function; field treatment of freezing cold injuries (FCI); and new consideration to injury and trauma care in the cold. Future work programmes re-emphasise development of cold weather training and establishment of consensus diagnostic criteria and treatments for FCI and non-FCI. CWI prevention should take advantage of biomathematical models that predict risk of CWI and provide guidance regarding optimal clothing and equipment and move from group averages to personalised predictions. The publication of selected presentations from the symposium in this special issue increases attention to military cold weather research.

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## Introduction

The Arctic region poses a significant threat to those who are not trained for work at sub-zero temperatures. This challenge is of specific interest for military operations, where winter warfare can be turned to advantage with proper training and preparation for individual and team performance, instead of simply a struggle for survival and a cause for failure. This challenge is recognised by member countries and close partners in the North Atlantic Treaty Organization (NATO). The primary requirement for success in the cold is training in the actual environment, followed by iterative research that will make training more effective, and new research and engineering to provide technological enhancements to preparation, protection, and performance in extreme cold. This was the discussion at a symposium sponsored by the NATO Science and Technology Organisation (STO) Human Factors and Medicine (HFM) panel on "Human Performance and Medical Treatment during Cold Weather Operations" and it is the subject of this paper and symposium articles in this special issue of the International Journal of Circumpolar Health on Arctic Military Conference in Cold Weather Medicine (presentations are listed in Table 1) [1].

Cold weather proficiency training was emphasised in the opening keynote talk by Colonel Haugom, director of the NATO Centre of Excellence for Cold Weather Operations (COE-CWO). This centre provides the armed forces of NATO countries the opportunity to participate in CWO training programmes, and thus develop and strengthen cold weather capabilities in preparation for any potential conflicts in this region. Colonel Haugom also noted the need for continued research to understand the most effective protection and enhancement strategies and most effective applications of technology in the cold. For example, he noted that the simple replacement of cotton with wool garments in the Norwegian military has been a game changer. The operational community would like to know what else we can learn and implement to

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**Table 1.** Presentations at the symposium, October 2022.

**Introduction**

- Haugom J. **Keynote**: Training for cold weather operations in the NATO Center of Excellence for Cold Weather Operations
- Potter A. Frozen Russian soldiers in Ukraine
- Stromberg E. Basis of the U.S. cold weather ration

**Preparation for operations in the cold**

- Kingma B. We are all exposed to the same environment, but some are more exposed than others
- Weller A. Aircrew glove cold protection: defining thermal requirements accounting for loss of manual dexterity
- Teien H. Training videos to prevent cold weather injury
- Xu X. Development of interactive guidance for warfighters in cold using thermal models
- Norheim A. **Position paper**: Classification of freezing cold injuries
- Van de Laar D. **Demonstration**: immersive cold weather experience

**Brain and cognitive function in the cold**

- Kallinen K. Cognitive performance among Finnish paratroopers during and after 20-day winter military field training
- Dunn T. Low hand temperature predicts individual differences in cognitive adaptability during cold water immersion
- Zheng W. Altered neural network oscillations and impaired cognitive performance during military cold water immersion

**Cold immersion and diving issues**

- Sullivan-Kwantes W. Extremity cooling during Op NU 2019
- Saunders S. Scoping study of the thermal strain experienced by UK military dive support boat personnel
- Wheelock C. Prediction of the decrease in core temperature during cold-water immersion in thermally protected men and women
- Lundell R. The human diving responses to arctic diving – assessment of ANS activity with heart rate
- Jones D. Prevalence of hypothermia and critical hand temperatures during military cold water immersion training
- Wittnam D. **Keynote**: Training for cold weather operations at the US Marine Corps Mountain Warfare Training Center

**Metabolic balance and stress of field training in the cold**

- Ojanen T. Physiological changes during a 20-day winter military training course and its subsequent 10-day recovery
- Pihlainen K. Effects of paratroopers' initial body composition on changes in physical performance and recovery during a 20-day winter military field training
- Vaara J. Can physiological and psychological factors predict dropout from intense 1-day winter military survival training?
- Margolis L. Fueling performance for cold-weather military operations

**Freezing cold injuries and their treatment**

- Steinberg T. Freezing cold injuries in the Norwegian Armed Forces between 2004 and 2021
- Lowe J. Iloprost at the point of injury? A literature review.
- Norheim A. Botulinum toxin A in the treatment of frostbite sequelae – a randomised, double-blind, placebo controlled pilot study
- Lechner R. Control of major bleeding by application of tourniquets over clothing in cold weather warfare
- Kölegård R. Acral skin vasoreactivity and thermosensitivity to hand cooling following short-term, whole-body cold acclimation
- Poole A. **Keynote**: Clinical experience with iloprost in the treatment of freezing cold injury
- Rund T. U.S. perspective on medical issues and training for Arctic operations

**Medical training and treatment planning for medicine in austere cold environments**

- Lowe J. Optimising "reachback" capabilities to maintain operational effectiveness – lessons from military practice
- Howes RJ. Developing a bespoke extreme cold weather medical course for UK forces operating in the Arctic
- Ferraby D & Hayhurst D. MSKI in UK service personnel and the impact of in-theatre rehabilitation during cold weather warfare training

make a difference to survival and performance. Seemingly, pedestrian strategies can be game changers, but research findings supporting such useful improvements need to be effectively explained for the results to benefit the users.

This was not the first NATO symposium on extreme environments, but the organising committee's goal for this symposium was to more effectively disseminate current knowledge, accelerate the research agenda, and expand a conclusion from previous meetings that *cold weather training is more important than technology*. In an extreme environment like the Arctic, human behaviour is critical to mission success and a bad decision can lead to disaster within minutes. Several previous technical meetings and reviews of thermal research were organised by the HFM panel to address these human challenges. Protecting the soldier in extreme hot and cold conditions was reviewed in 1993 and 2001 [2,3]. More recent HFM workshops and symposia focussed on soldier protection specifically in extreme cold environments (2005, 2009, 2014) [4–6]. This latest symposium (HFM 349) brought together scientists and military personnel that have conducted controlled and uncontrolled field studies during Cold Weather Operations in the Arctic and High North. This especially involved countries that border Arctic regions (Canada, United States), including all of the Nordic countries (Denmark, Finland, Norway, Sweden), and other countries with unique cold environment research investments (including Germany, Great Britain, Netherlands, and Slovenia). Other interested country representatives, including from the Baltic nations, attended.

This paper represents a synthesis of the symposium papers, presentations, and discussion. This was derived from a more detailed technical evaluation performed by the lead author (IBM). This review displays the collaborative work between scientists and soldiers during training exercises, providing the most convincing evidence of the effect of such training on the physical and psychological capacity of soldiers.

## Organization of the symposium

The meeting was organised around six thematic sessions and several keynote and special presentations (the agenda is summarised in Table 1). These sessions form the outline of the rest of this technical review. Every presenter provided a mini-manuscript in NATO format before the meeting; many of these were further developed into manuscripts (19 papers) for a special issue of the International Journal of Circumpolar Health, of which this paper is the twentieth and final manuscript; citations are also provided for some of the other presentations that have been substantially reported elsewhere.

Two keynote sessions on training for cold weather military operations were presented by Colonel Jo Haugom (Norway), the director of the NATO Centre of Excellence Cold Weather Operations, and by Colonel Daniel Wittnam (USA), the director of the Marine Corps Mountain Warfare Training Center. The third keynote session was presented by Alex Poole, MD (Canada) from the Whitehorse General Hospital on the topic of new promising drug treatments for freezing cold injury. Additionally, a position paper on classification of cold weather injuries was presented by Arne Johan Norheim, MD (The Arctic University of Norway, Tromso, Norway) and a special demonstration was provided by Danique van de Laar (Department of Education & Training Design, Land Warfare Centre, Royal Netherlands Army) on immersive cold weather experience for pre-exposure training.

Specifically, the relevant issues to be discussed were advertised as:

- best practices for medical treatment in the cold
- new concepts for prevention and treatment of cold injury, including freezing cold injury and hypothermia.
- cold water immersion and diving, search and rescue, and land operations
- biomedical bases of human performance enhancement strategies from laboratory to field trials including advanced mental and physical strategies, drug and nutrition technologies, and multi-functional materials/textiles
- physiological monitoring technologies relevant to the safer and more effective training of warfighters for cold weather operations.

The meeting was conducted in collaboration with the NATO Center of Excellence Cold Weather Operations (located in Norway) and, in parallel with an existing NATO research task group (HFM RTG 310) on "Human Performance and Medical Treatment and Support during Cold Weather Operations".

## Analysis and summary of thematic sessions

### *Preparation for operations in the cold and cold weather injury (CWI)prevention*

Optimal performance of the warfighter in cold weather conditions depends on three key factors (Figure 1): environmental conditions (i.e. temperature, relative humidity, wind speed, solar and heat radiation); personal readiness (e.g. fitness, acclimatisation, and health status); and clothing matched to the anticipated activity.

The clothing factor is perhaps the most important in extreme cold. A warfighter conducting physically demanding activity (e.g. hiking with a load that initiates sweating) will not require clothing with as much insulation as would be appropriate for a warfighter conducting a physically less demanding task (e.g. guard duty). The former would also benefit from a textile that would be permeable, thus allowing the water vapour resulting from the evaporated sweat to be transferred to the outer environment, and not accumulating in the clothing layers. This would result in a decrease in the


**Figure 1.** Factors that contribute to warfighters' performance.

insulative characteristics of the clothing and increase the risk of cold injury. Thus, during high levels of physical activity, warfighters would benefit from clothing systems that address the issue of sweat management. Key outcomes of concern are prevention of CWI, especially for hands and feet, and preservation of manual dexterity for many relevant types of military performance (e.g. firing a weapon, pulling a parachute ripcord, performing medical procedures for a casualty).

The importance of all the factors was demonstrated by Potter et al. [7] in a biomathematical model used to determine the thermal status of Russian soldiers trapped in an armoured vehicle convoy near Kyiv in Ukraine, when ambient temperatures decreased to subzero temperatures. Predictions of significant frostbite injury, particularly to exposed skin regions and the toes and feet, were later confirmed by news reports. This demonstrated the value of scientifically based decision aids for risk mitigation, mission planning, and even tactical awareness.

According to Xu et al. [8], situational awareness and proper selection of clothing for the anticipated cold exposure are the best cold weather injury mitigation strategies. Their cold weather ensemble decision aid (CoWEDA) provides guidance regarding the selection of clothing ensembles based on anticipated physical activities and environmental conditions. Xu et al. [8] tested multinational cold weather ensemble systems with a sweating thermal manikin to obtain the thermal and evaporative resistances of a total of 64 individual garments and 34 ensemble configurations. CoWEDA was evaluated by using the six-cylinder thermoregulatory model, which predicted skin and core temperatures during cold exposures ranging from 0°C to −40°C. These predictions were compared with measured values. The CoWEDA model provides good estimates of frostbite risk and estimates of time to onset of hypothermia. Further development of this model can improve individual precision of clothing and activity effects on CWI risks and manual dexterity. The recent European Defence Agency (EDA) project "Cold Weather Operations" was inspired by the approach of Xu et al. and tested the implications to national clothing variations to joint operation capabilities in a semi-controlled field experiment.

There is a renewed focus on warfighter characteristics such as body build and body composition to improve personalised predictions. Kingma et al. [9] evaluated the effect of the clothing insulation determined by ISO 1109 on the hand temperatures of three body builds and hand sizes while conducting three levels of activity [9]. This modelling suggests that individuals with smaller hands will most likely have lower skin temperatures for the same level of cold exposure and activity as individuals with larger hands and individuals with smaller hands might therefore be prone to the loss of dexterity, and at a higher risk of cold injury. In general terms, this implicates hand morphology as another factor in the individual variability in the responses to cold.

Manual dexterity is a top priority human performance concern in cold weather operations. The teleology of the cold-induced vasodilatation response, first reported by Lewis [10] remains unresolved. Following the expected vasoconstriction of peripheral vessels in the digits as a result of immersion in cold water, the vessels dilate, allowing increased perfusion of the previously constricted digits. As a consequence, the digit temperature increases transiently, only to constrict again. This constriction-dilatation response may be repeated. Unfortunately, the response is not necessarily observed in all digits and in all individuals. Some individuals have a strong response, whereby skin temperature can increase by 5° to 10°C, others may have a minimal response with skin temperature increasing negligibly. The response, if it were strong and observed in all digits might certainly be considered as contributing to the prevention of cold injury, but this is more of an exception than the rule. Research continues to try and resolve the mechanism of this response, and to assess whether it could be trained. The latter has been addressed by Keramidas and Kölegård [11]. They investigated the effect of a 5-day whole-body cold-acclimation regimen on finger vasoreactivity and thermosensitivity to local cooling, as reflected in the finger skin temperature response to hand immersion. The cold-induced reduction in skin temperature increased the number of cold-induced vasodilatation responses and reduced the discomfort associated with hand immersions in cold water. The study suggests that the cold acclimation can be attributed to central neural habituation.

Active warming interventions to preserve manual dexterity in the cold were discussed as long ago as a 1956 landmark symposium on hands in cold climates [12]. Battery power requirements have been one of the technology limiters, but this is less of a barrier in a cockpit during aircrew operations. Boyd and Weller [13] analysed the thermal characteristics of gloves for aircrew using a heated thermal manikin and evaluated the effect of a range of temperatures on manual dexterity. One important outcome of this study was the recognised need to use finer indices of manual dexterity (e.g. Purdue Peg Board Test), particularly for aircrew personnel whose manual tasks perhaps require a high degree of precision to operate aircraft consoles.

More effective training, even pre-exposure, was raised as a key concern in this symposium; individuals should not have to "learn by injury". Teien et al. [14] introduced training videos to prevent cold injuries, covering basic thermal physiology, introducing concepts regarding the correct use of clothing and equipment and providing instructions on the importance of taking care of one another other especially during exposure to cold and wet conditions. These are being used by the Norwegian Armed Forces in an effort to reduce surprisingly high rates of FCI. A demonstration of a virtual reality cold weather training developed by the Netherlands Ministry of Defence in collaboration with the Dutch Royal Marines illustrated how pre-exposure training can be gamified for the modern generation of recruits. It was noted that specific terms from the game were used by the soldiers in the actual winter training, embodying the lessons in practice. Anecdotal responses to initial testing such as "can I keep this game on my mobile phone; I want to play it again" suggest opportunities for greater effectiveness in developing appropriate trained actions ("muscle memory" or implicit memory) and skills to "win" by not encountering a CWI.

## Brain and cognitive function in the cold

Although it is well established that physical and mental stress affect cognitive performance, until recently neuropsychological effects of cold have been relatively neglected in cold weather operations. In soldiers exposed to stressful environments, decrements in cognitive function usually result when the demands of the tasks exceed the soldier's capacity [15]. Tasks deemed relatively simple when conducted in non-stressful environmental conditions can become demanding in extreme cold environments [16]. The way cold affects cognitive performance remains unresolved [17], specifically, the degree to which cold exposure affects brain function, and how cognitive performance is affected by the changes in brain function. It is common to conduct experiments assessing the effect of extreme environmental conditions in controlled laboratory conditions. In contrast, the studies presented by Kallinen and Ojanen [15], Dunn and Jones [16] and Zheng et al. [17] were conducted under field conditions. Such studies are difficult to perform, but extremely relevant for supporting soldiers in cold weather operations. These represent new contributions to cold weather operations research.

Cognitive performance (reflected in reaction time and error rate, grammatical reasoning, and visual perception) was impaired during a 20-day training exercise in northern Finland. Decrements were as high as 20%. Ten days after completion of the exercise, testing demonstrated complete recovery. In this multistressor cold weather training (average temperatures −11.3°C; lowest temperature −31.8°C), soldiers travelled long distances by cross-country skis while carrying loads of up to 40 kg [15]. Such information is useful to mission planning in extreme environments, both in terms of anticipating decrements in performance and the rate of recovery following such an exhaustive mission.

The studies reported by Dunn and Jones [16] and Zheng et al. [17] were conducted during a cold water immersion exercise by Marines at the Marine Corps Mountain Warfare Training Center (MCMWTC) in California (USA). Soldiers entered a pond fully clothed with water temperature at about 1.5°C for 10 min. Upon completion of the 10-min immersion, soldiers exited the water and remained standing in their wet clothing (air temp approximately −5°C) for 10 min, after which they changed into dry clothing and passively rewarmed in a sleeping bag for 60 min. The results of the cognitive tests (simple reaction times and match-to-sample tests) exhibited two distinct groups, with one (~37% of the sample) demonstrating poorer adaptability to the cold stress and demonstrating low hand temperatures compared to the more resilient group [16].

In the same cold water immersion exercise, Zheng et al. [17] analysed brain activity (neural network functions) using electroencephalography (EEG). Their underlying assumption was that the dominant oscillatory neural activity over the motor cortex are beta (β) oscillations (13–30 Hz): the power of this activity varies with different phases of a motor task (i.e. sensorimotor integration, coordination, motor preparation, etc.). These β oscillations are organised in bursts, which appear to reflect sensorimotor processing. The investigators discovered that transient β-bursts in the motor cortex underwent dynamic changes associated with the changes in body temperature and cognitive performance. They speculate that modulation of β-burst activity by brain stimulation and neurofeedback might be a strategy to prevent impairment of cognitive performance during cold exposure.

Of note, the cold water immersion studies were conducted at an altitude of over 2000 m, thus the subjects were exposed to hypobaric hypoxia. Future studies might compare the results of these immersions with those performed at sea level, to assess any effect of hypoxia on the thermoregulatory responses.

## Cold immersion and diving issues

The current diving strategy on Diver Support Vessels servicing oil drilling platforms in the North Sea is that divers conduct daily dives to depths exceeding 100 msw for up to 6 hrs in water at temperatures around 2°C. The developed technology prevents body cooling during such dives [18]. Technologically, under normal working conditions, cold water diving does not pose a problem from a thermal balance perspective. However, as pointed out by Haugom, the High North may become a region of conflict, due to the untapped natural resources that are now accessible, as the ice cap disappears. The problem will therefore not be in conducting the dives in these regions, rather the logistics of getting the divers to sites in the High North to conduct safe dives. These issues were addressed by the studies of Sullivan-Kwantes et al. [19] and Saunders et al. [20].

Sullivan-Kwantes et al. [19] demonstrated that despite the complex logistics involved in transporting equipment and personnel to a dive site in the High North, the dives could be performed safely and efficiently. In addition to the complexity of the diving logistics, the surface sub-zero ambient conditions needed to be considered when preparing the equipment for the dive.

Saunders et al. [20] focussed on the effect of cold weather conditions on the thermal status of the crew on the diver support boat. The core temperature of the support personnel remained stable, and did not approach levels considered to represent mild hypothermia. A nonthermal factor that may influence thermal status of individuals in such conditions is also seasickness. Motion sickness attenuates vasoconstrictor tone, resulting in greater loss of body heat and has been implicated in fatalities during sea accidents [21,22]. In the scenario described by Saunders [20] vestibular stimulation in rough seas might induce similar vascular responses which may affect the thermal balance of individuals.

The prediction of core temperature responses during cold water immersion of thermally protected (i.e. wearing a neoprene suit) personnel has not received much attention. Wheelock et al. [23] used the data from cold water immersions while wearing a 7 mm neoprene wetsuit with gloves and boots, to develop an equation predicting core temperature during immersion. The best-fit model predicted core temperature on the basis of body mass index (BMI), body surface area (BSA), immersion time, water temperature, and percent body fat. On this basis two equations were developed for predicting the change in core temperature, one based on BMI, and the other on BSA.

The ability to predict the rate of cooling of core temperature is of great importance in the case of maritime accidents. Such models can be valuable tools for search and rescue personnel, who would benefit from information regarding the anticipated thermal status of victims immersed in cold water. Such tools provide the rescuers with a time frame which predicts survival during accidental cold water immersion. The work of Saunders et al. [20] underscores the importance of accounting for the clothing layers worn during cold water immersion, when attempting to predict the changes in core temperature. Other important issues increase the complexity of such predictions, including modelling partial submersion and repetitive partial submersion (e.g. stream crossings or inadvertent wet exposures). Any model predicting the change in core temperature, would need to account for the regional differences in submersion. Predictions of core temperature cooling rate, and thus survival, of personnel immersed in cold water may in future require the assessment of the immersed insulation provided by the clothing. Large variations in the thermal properties of wet fabrics have been previously reported such as high insulative properties of wet wool compared to cotton and many synthetics [24].

Immersion in cold water, particularly during diving when the face is also immersed, may elicit two responses: the cold shock response during head-out immersion and the dive response to facial immersion. The former, reflected in substantial and immediate elevations in heart rate and ventilation, is a result of the stimulation of skin cold receptors providing activation of sympathetic nervous system (SNS). The latter results in a decrease in heart rate due to the increase in parasympathetic nervous system (PNS) activity, as a consequence of the stimulation of the cold receptors in the trigeminal region. Sudden cold water immersion, combining stimulation of the skin cold receptors of the facial region and remaining parts of the body results in concomitant elicitation of both PNS and SNS activity, referred to as autonomic conflict [25], which may give rise to arrhythmias. With this in mind, Lundell et al. [26] evaluated the SNS and PNS activity of divers conducting a series of cold water dives (based on an analysis of heart rate variability). Concomitant increases in PNS and SNS activity were observed at the onset of the dive; thereafter, PNS activity increased over the course of the dive, whereas SNS activity remained reduced. These results confirm the likelihood of an autonomic conflict at the onset of the dive, which may cause irregular heart activity. The study suggests a short adaptation phase in cold diving before physical activity to minimise the effects of the trigeminal cardiac reflex, while whole face masks should be preferred when diving in very cold Arctic water temperatures.

Colonel Wittnam, in his keynote presentation, emphasised the benefits of realistic cold weather training at the MCMWTC and he described a brief cold water immersion trial followed by a period of passive rewarming. This is meant to provide soldiers with the experience of having to cross a river during extreme cold conditions, and instruction on passive rewarming to recover from hypothermia. The cognitive performance studies conducted by Dunn and Jones [16] and Zheng et al. [17] involved this cold-water immersion paradigm. In this same series of studies at the MCMWTC, Jones et al. [27] focussed on the practical scenario of soldiers having to cross a river and how such a short cold-water immersion would impact on their body temperature. The results of the study demonstrated the substantial individual variability in the responses of core temperature during cold water immersion and partial rewarming. Mission planning should account for the range of anticipated individual responses in such scenarios, and not only an estimate of average responses.

## Metabolic balance and stress in field training in the cold

Winter operations in extreme cold environments are physiologically and psychologically extremely demanding on the soldiers, and may impact their strength, aerobic capacity and result in energy deficit. These issues were addressed by several field studies conducted in Finland and Norway.

Ojanen et al. [28] monitored physiological changes in Finnish paratroopers during a 20-d training course and a 10-d recovery period. They observed a drastic decline in soldiers' physical performance even for highly physically fit soldiers. At the end of a 10-d recovery period, soldiers' physical performance, particularly explosive force production, had not been re-established to levels prior to the 20-d training exercise. During this training exercise, Pihlainen et al. [29] investigated the changes in body composition, to test the hypothesis that soldiers' relative body fat may influence the magnitude of the observed changes in physical performance and rate of recovery following the exercise. All the soldiers experienced body mass loss, but those with higher relative baseline fat mass seemed to inhibit loss of muscle mass during the 20-day field training in the arctic environment. They hypothesised that soldiers should consider overfeeding to increase body fat mass which may result in protein sparing and mitigate decrements in physical performance.

In addition to the individual variability in the physiological responses to cold stress, as noted above, there is also substantial individual variability in how soldiers perceive and experience the intense, physiologically and psychologically exhaustive training exercises described by Ojanen et al. [28] and Pihlainen et al. [29]. In these exercises, the soldiers had to work as a team, thus relying on each other to ensure successful completion of the mission. Under somewhat different scenarios, this type of stressful exercise might cause some soldiers to drop out, potentially compromising mission success for the entire team. This was the aim of the study by Vaara et al. [30] who discovered the most prominent and statistically significant predictor of dropping out was aerobic fitness level.

Cold-weather military operations, such as those described above, result in high daily energy expenditures. Based on results obtained from winter military exercises in

Norway, Margolis and Pasiakos [31] noted that soldiers failed to achieve energy balance, resulting in severe energy deficits, which caused negative physiological effects that ultimately lead to reductions in physical performance. They concluded that higher-fat energy dense food products are a viable nutrition intervention to minimise the severity of energy deficits to sustain physical performance. An important issue to consider in the development of food rations for cold weather operations is the availability of carbohydrate stores to the shivering musculature. Namely, skeletal muscle stores maintain heat production and delay the onset of hypothermia [32]. Blood glucose is another nonthermal factor that affects shivering thermogenesis. Hypoglycaemia has been demonstrated to significantly attenuate shivering heat production and increase the rate of cooling in high heat loss environments [33]. Certain food supplements could potentially enhance certain physiological and psychological functions. Castellani et al. [34], for example, demonstrated that tyrosine supplementation attenuated the cognitive and psychomotor deficits observed in cold environments. The development of optimal ratios for CWO by the US Army Combat Field Feeding Program was an important contribution to the meeting, particularly in view of the significant decrements in physical capacity due to energy deficits.

## Freezing cold injuries and their treatment

Freezing cold injury (FCI) continues to be a significant occurence, even in countries where exposure to cold extremes is not uncommon. This was shown by Steinberg et al. [35], who reported that 5% of all registered injuries in the Norwegian Armed Force are FCIs. Of these, 30% were registered as 2nd degree injury, and 20% of these injuries affected work ability of those inflicted. Around 2/3 of the soldiers with FCI had less than 6 months of military service, suggestive of a low level of preparedness. Steinberg et al. [35] also highlighted the deficiencies in cold injury data reporting, where more accurate and consistent reporting by NATO countries will permit longitudinal evaluation of the effectiveness of interventions. This is a problem which has compromised all previous military cold epidemiology reports.

Prevention of CWI requires effective metrics to assess the success of interventions. There are many barriers to CWI reporting that include stigma and even potential disciplinary actions for soldiers reporting injuries, but also the lack of clarity in classifications of CWI and definitions of severity. A subcommittee of NATO HFM RTG 310 conducted a review of existing literature with the aim of establishing a classification system for FCI, specifically for military activities [36]. Even though nomenclature in existing classification systems is not coherent, the existing classification systems for FCI classification for monitoring and management are military relevant and should be followed.

During winter exercises, the field treatment of a freezing cold injury becomes logistically complex. Normally, FCI casualties are transported immediately to the nearest hospital. In contrast, Lowe and Warner [37] have focussed on how FCIs could be treated in the field at the point of injury using iloprost, a prostacyclin analogue with vasodilatory properties. This builds on the work of Poole and others who have demonstrated the benefits of iloprost in the treatment of FCI. A scoping review by Gautier et al. [38] included 20 studies with a total of 254 patients and 1000 digits with FCI. The results of their analysis indicate a much lower amputation rate of digits in patients that had been treated with iloprost compared to those that had not received iloprost during their treatment. The main side effect concern is a drop in blood pressure because of the vasodilatory effects of the drug, but this has not emerged as problem in carefully monitored inpatients and may not be a showstopper for point of care field use.

Norheim and colleagues [39] presented evidence from a case study, whereby off-label use of Botulinum Toxin A (BTX-A) was used to treat a patient suffering from long-term sequelae of frostbite to his hands after a military exercise. Frostbite sequelae may include cold hypersensitivity, sensory loss, chronic pain, hyperhidrosis, growth plate disturbances and osteoarthritis, and paraesthesia. The authors proposed the design of a more controlled multi-centre study of the potential use of BTX-A in the treatment of frostbite sequelae [39].

Casualties and injuries occurring in extreme cold conditions in remote, inhospitable and difficult to access regions are a challenge to medical personnel. In such instances, survival skills are essential, as described in de Groot's personal account of the 1993 military aircraft disaster near Alert, Canada [40]. The resupply plane crashed and initial survivors (mostly seriously injured) began to die over the next 30 hours exposed to −22°C blizzard conditions before rescue teams arrived. As a medical officer on the aircraft, de Groot's first-hand account of the problems of administering medical care in extreme cold weather conditions covers the majority of the issues discussed in this symposium. One aspect of this is the need for specialised medical equipment for extreme cold environments. This was emphasised by Rund [41], investigating the stabilisation and evacuation of injured personnel in the Arctic. The study identified a need for an insulated bag that would provide appropriate thermal protection of the injured soldier, but it must also be designed to allow medical personnel easy and quick access to the patient. Rund [41] used four Arctic trauma patient scenarios to highlight each of four main gaps in current cold weather trauma care.

Lechner et al. [42] compared three candidate tourniquet systems for use over clothing in field conditions. The study suggested that maximum pressure is dependent on the clothing characteristics and emphasised the need to test such equipment under simulated Arctic conditions in the laboratory, as well as under field conditions as sub-zero temperatures could render components of such systems inoperable.

## Medical training and treatment planning in austere cold environments

Lowe and Warner [43] provide an example of how telemedicine can be used to maintain operational effectiveness in the Antarctic. They reviewed the current telecommunication capabilities in the British Antarctic Territory, and conducted a review of cases, particularly the challenges posed in treating them. Telemedicine is a potential solution to maintaining operational effectiveness in remote cold regions, but in the absence of proper communications infrastructure, other solutions such as just-in-case training and prepositioned medical kits have been developed.

Even with telecommunications availability for quality telemedicine solutions, it is essential to also provide training for medical personnel accompanying soldiers on winter exercises in the Arctic region. Howes [44] recommended an extreme cold weather medical training programme for the Arctic region. Such a course has been developed and comprises a pre-deployment package in the UK and a tactical field exercise phase in Norway.

Cold weather warfare training includes mastering cross-country skiing skills and load carriage during skiing. Ferraby and Hayhurst [45] surveyed the musculoskeletal injuries that occurred during such training provided by the UK Defence Mountain and Cold Weather Warfare training in Norway. Of the 1179 deployed personnel on these missions to date, 11% reported musculoskeletal injury, with the majority (88%) of cases occurring during military training. Of these, 61% were ski-related injuries, and 10% were injuries sustained due to load-carriage. The injuries were treated by the Forward Rehabilitation Team, and as a consequence, on average the improvement progressed from injured with restricted duties to fully fit. Of the 136 cases, only 19 were unable to continue their Cold Weather Deployment due to their injuries and were evacuated to the UK for continued care in rehabilitation centres. Their study confirms the effectiveness of in-theatre rehabilitation, treating injured personnel during deployment.

## Conclusions and recommendations

The NATO Cold Weather Operations Centre of Excellence offers training that is essential in the preparation of personnel for deployment in Arctic regions. NATO members have excellent opportunities to take advantage of such training. Other strategies to improve the effectiveness of cold weather training even before exposure should be actively pursued and rigorously evaluated.

Cold Weather Operations conducted in Norway, Finland, Canada and USA offer a platform to capture important physiological data from the field. Such collaboration between scientists and soldiers during such training exercises should be encouraged, as they provide the most convincing evidence of the effect of such training on the physical and psychological capacity of soldiers. These data could also be used to establish a data base for further fine-tuning of biomathematical models predicting cold injury during such exposures, and providing guidance for mission planning. Biomathematical models for predicting the risk of cold injury and as aids to mission planning are being developed by many NATO members. It would be worthwhile to share knowledge in the development of such models, perhaps developing a guidance tool that can be used by all NATO members.

Treatment of any injury proceeds according to algorithms, and these provide guidance based on the severity of the injury. To this extent, the classification of cold injuries is currently being developed for field conditions, and this effort should be supported by experts from NATO countries. Similary, there should be a consensus on the manner in which cold injuries should be treated. There appear to be innovative approaches in different member states, regarding the management of freezing (FCI) and non-freezing (NFCI) cold injuries. The Human Factors and Medicine panel would be the obvious body to support international working groups on the issues raised in this meeting.

A common observation among the presentations reporting the physiological and psychological responses to the physically demanding field exercises conducted in cold weather conditions, is the substantial variability observed in these responses among the participants. Such variability could impact on mission success, and should this be considered by mission planners. These factors and their variability need to be characterised and included in predictive planning models.

Data presented in previous NATO HFM research task groups and workshops on cold weather operations have not been generally accessible to the wider research communities. However, the proceedings published in this special issue of the International Journal of

Circumpolar Health might contribute to increased attention to cold weather military biomedical research. The information from such HFM meetings should be clearly communicated, highlight research advances, their real-world applications, and the next priorities for additional research.

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## Author roles

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## References

[1] North Atlantic Treaty Organization (NATO). Science and Technology Organisation (STO). Human Factors and Medicine Panel (HFM). Human performance and medical treatment and support during cold weather operations. NATO STO HFM Meeting Proceedings 349. Washington DC, USA, 19-21 October 2022. NATO Collaboration Support Office, Neuilly-sur-Seine, Paris, France. 2023.

[2] North Atlantic Treaty Organization (NATO). Advisory Group for Aerospace Research and Development (AGARD). The support of air operations under extreme hot and cold weather conditions. AGARD Report No. 540. Proceeding of symposium, Victoria, Canada, Victoria, British Columbia, Canada. Paris, France: AGARD Neuilly-sur-Seine. 17-21 May 1993.

[3] North Atlantic Treaty Organization (NATO). Research and Technology Organisation (RTO). Human Factors and Medicine Panel (HFM). Blowing hot and cold: protecting against climatic extremes. NATO RTO Meeting Proceedings 76. Dresden, Germany 8-10 October 2001. NATO RTO, Neuilly-sur-Seine, Paris, France. 2002.

[4] North Atlantic Treaty Organization (NATO). Research and Technology Organisation (RTO). Human Factors and Medicine Panel (HFM). Prevention of Cold Injuries. NATO RTO HFM Meeting Proceedings 126. Amsterdam, Netherlands, 19-20 May 2005. NATO RTO, Neuilly-sur-Seine, Paris, France. 2005.

[5] North Atlantic Treaty Organization (NATO). Research and Technology Organisation (RTO). Human Factors and Medicine Panel (HFM). Soldiers in cold environments. NATO RTO HFM Meeting Proceedings 168. Helsinki, Finland, 20-22 April 2009. NATO RTO, Neuilly-sur-Seine, Paris, France. 2002.

[6] North Atlantic Treaty Organization (NATO). Science and Technology Organisation (STO). Human Factors and Medicine Panel (HFM). Cold extreme environmental operations: optimizing warfighter performance in extreme cold. NATO STO HFM Meeting Proceedings 255. Kjeller, Norway, 28-30 October 2014. NATO Collaboration Support Office, Neuilly-sur-Seine, Paris, France. 2014.

[7] Potter AW, Looney DP, Friedl KE. Use case for predictive physiological models: tactical insights about frozen Russian soldiers in Ukraine. Int J Circumpolar Health. 2023;82 (1):2194504. doi: 10.1080/22423982.2023.2194504

[8] Xu X, Rioux T, Friedl K, et al. Development of interactive guidance for cold exposure using a thermoregulatory model. Int J Circumpolar Health. 2023;82(1):2190485. doi: 10.1080/22423982.2023.2190485

[9] Kingma B, Sullivan-Kwantes W, Castellani J, et al. We are all exposed, but some are more exposed than others. Int J Circumpolar Health. 2023;82(1):2199492. doi: 10.1080/22423982.2023.2199492

[10] Lewis T. Observations upon the reactions of the vessels of the human skin to cold. Heart. 1930;15:177–208.

[11] Keramidas ME, Kölegård R, Gäng P, et al. Acral skin vasoreactivity and thermosensitivity to hand cooling following 5 days of intermittent whole body cold exposure. Am J Physiol. 2022;323(1):R1–R15. doi: 10.1152/ajpregu.00021.2022

[12] Fischer FR. Protection and functioning of the hands in cold climates. Proceedings of a conference held at the Quartermaster Research and Development Command, Natick, Massachusetts, 23-24 Apr 1956. National Research Council-National Academy of Sciences, Washington DC. 179 pp. 1957.

[13] Boyd JWR, Weller AS Aircrew glove cold protection: defining thermal requirements accounting for loss of manual dexterity. Proceedings of the Human Factors and Medicine Panel 349 (STO-MP-HFM-349) Human performance and medical treatment and support during

cold weather operations. Arlington, Washington D.C., October 17-19, 2022.

[14] Teien HK, Rones N, Renberg J. Training videos to prevent cold weather injuries. Int J Circumpolar Health. 2023;82(1):2195137. doi: 10.1080/22423982.2023.2195137

[15] Kallinen K, Ojanen T. Cognitive performance among Finnish paratroopers during and after 20-day winter military field training. Int J Circumpolar Health. 2023;82(1): in press. doi: 10.1080/22423982.2023.2225896.

[16] Dunn TL, Jones D Low hand temperature predicts individual differences in cognitive adaptability during cold water immersion. Proceedings of the Human Factors and Medicine Panel 349 (STO-MP-HFM-349) Human performance and medical treatment and support during cold weather operations. Arlington, Washington D.C., October 17-19, 2022.

[17] Zheng W, Weller R, McClintock R, et al. Altered neural network oscillations and impaired cognitive performance during military cold water immersion training. Proceedings of the Human Factors and Medicine Panel 349 (STO-MP-HFM-349). Human performance and medical treatment and support during cold weather operations. Arlington, Washington D.C., October 17-19, 2022.

[18] Mekjavic IB, Golden FSC, Eglin M, et al. Thermal status of saturation divers during operational dives in the North sea. Undersea Hyperbaric Med. 2001;28:149–155.

[19] Sullivan-Kwantes W, Tikuisis P. Extremity cooling during an arctic diving training exercise. Int J Circumpolar Health. 2023;82(1):2190488. doi: 10.1080/22423982.2023.2190488

[20] Saunders S, Furby W, Chillingsworth K, et al. A preliminary study of the thermal strain experienced by dive support boat personnel. Int J Circumpolar Health. 2023;82(1):2199491. doi: 10.1080/22423982.2023.2199491

[21] Mekjavic IB, Tipton MJ, Gennser M, et al. Motion sickness potentiates core cooling during immersion in humans. J Physiol. 2001;535(2):619–623. doi: 10.1111/j.1469-7793.2001.00619.x

[22] Golden FSC. Death after rescue from immersion in cold water. J Royal Navy Med Serv. 1973;59(1):5–8. doi: 10.1136/jrnms-59-5

[23] Wheelock CE, Bartman NE, Pryor RR, et al. Prediction of core temperature during prolonged cold weather immersion in thermally protected men and women. Proceedings of the Human Factors and Medicine Panel 349 (STO-MP-HFM-349) Human performance and medical treatment and support during cold weather operations. Arlington, Washington D.C., October 17-19, 2022.

[24] Hock CW, Sookne AW, Harris M. Thermal properties of Moist Fabrics. J Res National Bureau Standards. 1944;32(5):229–252. doi: 10.6028/jres.032.012

[25] Shattock MJ, Tipton MJ. 'Autonomic conflict': a different way to die during cold water immersion? J Physiol. 2012;590(14):3219–3230. doi: 10.1113/jphysiol.2012.229864

[26] Lundell RV, Ojanen T. A systematic review of HRV during diving in very cold water. Int J Circumpolar Health. 2023;82(1):2203369. doi: 10.1080/22423982.2023.2203369

[27] Jones D, Weller RS, McClintock RJ, et al. Prevalence of hypothermia and critical hand temperatures during military cold water immersion training. Int J Circumpolar Health. 2023;82(1):in review. doi: 10.1080/22423982.2023.2236777.

[28] Ojanen T, Pihlainen K, Vaara JP, et al. Physiological and physical performance changes during a 20-day winter military training course and its subsequent 10-day recovery period. Int J Circumpolar Health. 2023;82(1):2207287. doi: 10.1080/22423982.2023.2207287

[29] Pihlainen K, Ojanen T, Vaara JP, et al. Effects of paratroopers' initial body composition on changes in physical performance and recovery during 20 day winter military field training. Proceedings of the Human Factors and Medicine Panel 349 (STO-MP-HFM-349) Human performance and medical treatment and support during cold weather operations. Arlington, Washington D.C., October 17-19, 2022.

[30] Vaara JP, Eränen L, Ojanen T, et al. Can physiological and psychological factors predict dropout from intense 10-day winter military survival training? Int J Environ Res Public Health. 2020;17(23):9064. doi: 10.3390/ijerph17239064

[31] Margolis LM, Pasiakos SM. Performance nutrition for cold-weather military operations. Int J Circumpolar Health. 2023;82(1):2192392. doi: 10.1080/22423982.2023.2192392

[32] Jacobs I Fueling shivering in humans during cold water immersion. Proceedings of the AGARD-540 meeting. Support of Air Operations under Extreme Hot and Cold Weather Conditions. Aerospace Medical Symposium Panel, Victoria, Canada. 1993.

[33] Passias TC, Meneilly GS, Mekjavic IB. Effect of hypoglycemia on thermoregulatory responses. J Appl Physiol. 1996;80(3):1021–1032. doi: 10.1152/jappl.1996.80.3.1021

[34] Castellani JW, Mahoney C, O'Brien C Tyrosine supplementation attenuates cognitive and psychomotor performance deficits in cold environments. Proceedings of the Human Factors and Medicine Panel 168 (RTO-MP-HFM-168). Soldiers in Cold Environment, Helsinki, Finland; 2009. p. 38-1 to 38–15.

[35] Steinberg T, Kristoffersen A, Bjerkan G, et al. Freezing cold injuries among soldiers in the Norwegian Armed Forces – a cross sectional study. Int J Circumpolar Health. 2023;82(1): in final revision. doi: 10.1080/22423982.2023.2227344.

[36] Norheim AJ, Sullivan-Kwantes W, Steinberg T, et al. The classification of freezing cold injuries-a NATO research task group position paper. Int J Circumpolar Health. 2023;82(1):2203923. doi: 10.1080/22423982.2023.2203923

[37] Lowe J, Warner M. Can iloprost be used for treatment of cold weather injury at the point of wounding in a forward operating environment? A literature review. Int J Circumpolar Health. 2023;82(1):2210340. doi: 10.1080/22423982.2023.2210340

[38] Gauthier J, Morris-Janzen D, Poole A. Iloprost for the treatment of frostbite: a scoping review. Int J Circumpolar Health. 2023;82(1):2189552. doi: 10.1080/22423982.2023.2189552

[39] Norheim AJ, Borud E, Mercer JB, et al. Botulinum Toxin a in the treatment of frostbite sequelae–results from a blinded, early-phase, comparative trial. Int J Circumpolar Health. 2023;82(1):2189556. doi: 10.1080/22423982.2023.2189556

[40] de Groot W. Surviving a C-130 accident in the Canadian high arctic. Aviat Space Environ Med. 1994;65(8):764–767.
[41] Rund TJ. Casualty evacuation in arctic and extreme cold environments: a paradigm shift for traumatic hypothermia management in tactical combat casualty care. Int J Circumpolar Health. 2023;82(1):2196047. doi: 10.1080/22423982.2023.2196047
[42] Lechner R, Beres Y, Oberst A, et al. Analysis of tourniquet pressure over military winter clothing and a short review of combat casualty care in cold weather warfare. Int J Circumpolar Health. 2023;82(1):2194141. doi: 10.1080/22423982.2023.2194141
[43] Lowe J, Warner B. Optimising "reachback" capabilities to maintain operational effectiveness – lessons from military practice. Int J Circumpolar Health. 2023;82(1): in press. doi: 10.1080/22423982.2023.2230633.
[44] Howes RJ, Evans J, Keenan ACM, et al. Operating in the cold weather environment–a medical officer's perspective. J Royal Naval Med Serv. 2011;97(2):62–65. doi: 10.1136/jrnms-97-62
[45] Ferraby DH, Hayhurst D, Strachan R, et al. Musculoskeletal injuries in UK service personnel and the impact of in-theatre rehabilitation during cold weather warfare training: exercise CETUS 2020. BMJ Mil Health 2022; e001972