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Validation of standard ASTM F2732 and comparison with ISO 11079 with respect to comfort temperature ratings for cold protective clothing

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ABSTRACT

American standard ASTM F2732 estimates the lowest environmental temperature for thermal comfort for cold weather protective clothing. International standard ISO 11079 serves the same purpose but expresses cold stress in terms of required clothing insulation for a given cold climate. The objective of this study was to validate and compare the temperature ratings using human subject tests at two levels of metabolic rates (2 and 4 MET corresponding to 116.4 and 232.8 W/m^2). Nine young and healthy male subjects participated in the cold exposure at 3.4 and −30.6 °C. The results showed that both standards predict similar temperature ratings for an intrinsic clothing insulation of 1.89 clo and for 2 MET activity. The predicted temperature rating for 2 MET activity is consistent with test subjects' thermophysiological responses, perceived thermal sensation and thermal comfort. For 4 MET activity, however, the whole body responses were on the cold side, particularly the responses of the extremities. ASTM F2732 is also limited due to its omission and simplification of three climatic variables (air velocity, radiant temperature and relative humidity) and exposure time in the cold which are of practical importance.

1. Introduction

One of the most important thermal properties of cold weather protective clothing is insulation. European standard, *EN342: Protective clothing – Ensembles and garments for protection against cold*, specifies the protection offered by the clothing. It states that the insulation value shall be marked on the clothing (EN 342, 2004). In the USA, however, this is often expressed as a temperature rating on product labels and in product descriptions in catalogs (McCullough et al., 2009, ASTM F2732, 2011). In Europe, the temperature ratings on sleeping bags are also standardized (EN 13537, 2002). Compared to stating the insulation value, putting the temperature on clothing labels is an alternative and easier way for users to understand. The ultimate goal of both standards is to provide protection and thermal comfort for users.

American standard ASTM F2732 (2011) estimates the lowest environmental temperature for thermal comfort for cold weather protective clothing for two physical activity levels (2 and 4 metabolic equivalent (MET), 1 MET = 3.5 ml O_2/kg/min = 58.2 W/m^2) in cold environments based on measured clothing insulation and human heat balance model. International standard, ISO 11079 (2007): Ergonomics of the thermal environment – Determination and interpretation of cold stress when using required clothing insulation (IREQ) and local cooling effects – serves the same purpose but expresses cold stress in terms of required clothing insulation for a given cold climate condition (air and radiant temperatures, humidity, air velocity), work rate (including walking or work created air movements) and air permeability of clothing, or duration limited exposure (DLE, $D_{lim.}$) when clothing insulation is known. At very low temperatures and low activity levels, IREQ becomes high. If the clothing insulation does not provide such high insulation, indicating that a person cannot sustain this cold stress for 8 h, then a recommended maximal exposure time, i.e. DLE (in hours), is calculated. The IREQ equations are open and it is also possible to determine temperature ratings when clothing insulation is known. As both standards are based on heat balance equations, it would be of interest to compare them. The comparison was partly carried out by a recent study on the influence of different ways of wearing clothing on clothing insulation and temperature rating predictions (Li et al., 2012).

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In comparison with ISO 11079, ASTM F2732 is based on environment conditions with a number of assumptions and limitations (McCullough et al., 2009). The effects of radiant temperature and wind are not used in the heat balance model. Radiant temperature is assumed to be equal to air temperature. Wind and pumping effect are not taken into account. An average of 50% relative humidity is used in the model. The duration of cold exposure has not been taken into consideration either.

Holmér (1984) introduced IREQ for the analysis of cold stress, based on which the international standard ISO 11079 was developed in 1993, and the latest ISO version was released in 2007 (ISO 11079, 2007), and an updated web IREQ (version 4.2) was available from 2008 (Nilsson and Holmér, 2009), which provides a fully operational online program for calculation of IREQ and D_{lim}. The method used for the calculation of heat balance is the same as in the standard. Users are not only able to calculate IREQ and D_{lim} values, but are also able to view the open source code and download a copy that can be run on any personal computer with JavaScript installed. This has made the close scrutiny of the program possible in the scientific community. Recently, d'Ambrosio Alfano et al. (2013) conducted an in-depth analysis of IREQ program and found incongruities and errors in the web based program leading to a systematic overestimation of the duration limited exposure. However, they have also pointed out that the presence of the errors and inconsistencies only slightly affects the required insulation values, which indicates that the errors may be mainly related to the clothing insulation and related heat transfer through clothing when calculating DLE, as the calculation of required insulation values are based on climatic conditions and metabolic rates. Earlier versions of the standard (ISO/TR 11079:1993, ISO/CD 11079:2001) were validated by field studies (Griefahn, 2000), wearing trials and manikin measurements (Holmér et al., 2003), and human subject tests (Kuklane et al., 2007b).

Since the thermophysiological responses to cold are complex; independent validation and continuous improvements of the models are needed (Holmér, 1995). Cold environments represent a challenge to the human heat balance and protection. More studies are required to explore the interaction between thermal comfort perception and heat exchange in cold environments (Holmér, 2004). A laboratory validation of EN 13537 on sleeping bags has been recently reported (Lin et al., 2013). In contrast with the temperature ratings for sleeping bags, physical activities while wearing cold weather protective clothing play a more important role in determining the temperature ratings for thermal comfort. The first version of ASTM F2732 (2009) included only one level activity of 2 MET. The latest version has also incorporated 4 MET activity. The increase of physical activity level means a prediction of much lower temperature rating for clothing with the same insulation. Whether the increase of physical workload and metabolic rate can maintain heat balance and thermal comfort in extremely cold environments needs to be further studied and validated. Therefore, the objective of this study was to validate and compare the prediction of temperature ratings by both standards using human subjects at two levels of metabolic rates (116.4 and 232.8 W/m^2), and to provide further evidence to improve the standards.

2. Methods

2.1. Clothing

The cold protective clothing ensemble including cold weather outer garments and base ensemble 1 (ASTM F2732, 2011) was used in the study.

Base ensemble 1 consisted of the following garments:

1) Shirt: Swiss army “Gnägi” long-sleeve 100% cotton underwear shirt (~320 g) and trousers (~290 g), $R_{ct} = 0.024$ m^2 °C/W, size 52. This was the same type of underwear used in the EU project “THERMPROTECT” (Kuklane et al., 2007a,b).
2) Men's underwear briefs: Taiga Polartec, Sweden.
3) Men's socks: Ullfrotté no. 976 (400 g/m^2, $R_{et} = 0.087$ m^2 °C/W). These were the same type of socks (type 1) used in the EU project “Subzero” (Kuklane et al., 2007b).
4) Athletic shoes: sneakers (Arbesko AB) used in the EU project “Subzero”.
5) Gloves: Hestra wind stopper fleece fabric gloves used in the EU project “Subzero”, 295 g/m^2.
6) Hat: Taiga no. 25928 Rohn, Polartec, fleece hat used in the EU project “Subzero”.

Cold weather ensemble:

The cold weather outer jacket and trousers (Leijona, R_{ct}: 0.183 and 0.123 m^2 K/W, with membrane, size 52) used in the EU project “Subzero” (outer garment 1), were dressed on top of the base ensemble 1.

2.2. Insulation measurement on thermal manikin

The thermal insulation was measured on the thermal manikin Tore with 17 individually controlled (heating and measuring) zones in climatic chamber according to ISO 15831 (2004) on a standing manikin. Parallel calculation method was used for insulation calculation. Air temperature was 21.9 °C for air layer measurements, 12.4 °C for base ensemble and cold weather ensemble insulation tests. Relative humidity was 38%, air velocity 0.43 ± 0.12 m/s. The measurements on the thermal manikin in each condition were replicated 3–5 times. Average values were used for the calculation of the thermal insulation.

2.3. Human subject tests

2.3.1. Subjects and environmental conditions

Nine young and healthy male subjects participated. Their age, body height, weight, and body mass index (BMI = weight (kg)/ height (m)^2) were 24.1 ± 2.6 (mean ± SD) years, 1.81 ± 0.05 m, 74.5 ± 6.6 kg, and 22.8 ± 1.5 kg/m^2. BMI was particularly controlled in a narrow range. The subjects had previous experience of living in cold climates (e.g. in Nordic countries) for more than one year, and did not have any history of cold injury, cold related sensitivity or asthma. The subjects were not dependent on any medicine. They were asked not to drink alcohol and not to do exercises 24 h before the experiment, not to smoke, and to refrain from drinking coffee and tea 2 h before the test. Written information about the study was given to the subjects before they came to the laboratory. The first time when the subjects visited the laboratory, they were also given more detailed information about the tests and relevant equipment, sensors, etc. A written informed consent form was signed by each subject before the tests. The tests were conducted during winter season (Nov/Dec 2012). A pre-test for each participant walking on treadmill from slow walking to fast walking speed with the same clothing was performed. Oxygen uptake (VO_2) was measured continuously using MetaMax© (CORTEX Biophysik GmbH, Leipzig, Germany) to determine their individual relationships between walking speed and metabolic rate. Thereafter, their individual walking speeds to produce 116.4 W/m^2 and 232.8 W/m^2 were used in the two test conditions with each test lasting for 90 min in the climatic chamber. The average walking speeds over the nine subjects were 2.0 and 5.8 km/h respectively for the two activities.

Two air temperatures (3.4 and −30.6 °C) based on the measured insulation for the two physical activity levels were calculated