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Heat stress in chemical protective clothing: porosity and vapour resistance

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Abstract

Heat strain in chemical protective clothing is an important factor in industrial and military practice. Various improvements to the clothing to alleviate strain while maintaining protection have been attempted. More recently, selectively permeable membranes have been introduced to improve protection, but questions are raised regarding their effect on heat strain. In this paper the use of selectively permeable membranes with low vapour resistance was compared to textile based outer layers with similar ensemble vapour resistance, and for textile based outer layers the effect of increasing air permeability was investigated. When comparing ensembles with a textile versus a membrane outer layer that have similar heat and vapour resistances measured for the sum of fabric samples, a higher heat strain is observed in the membrane ensemble, as in actual wear the air permeability of the textile version improves ventilation and allows better cooling by sweat evaporation.

For garments with identical thickness and static dry heat resistance, but differing levels of air permeability, a strong correlation of microclimate ventilation due to wind and movement with air permeability was observed. This was reflected in lower values of core and skin temperatures and heart rate for garments with higher air permeability. For heart rate and core temperature the two lowest and the two highest air permeabilities formed two distinct groups, but they did not differ within these groups.

Based on protection requirements it is concluded that air permeability increases can reduce heat strain levels allowing optimisation of chemical protective clothing.

Keywords: clothing, heat strain, evaporative resistance, chemical protection, PPE

Statement of Relevance

In this study on CBRN protective clothing, heat strain is shown to be significantly higher with selectively permeable membranes compared to air permeable ensembles. Optimisation of CBRN PPE needs to balance sufficient protection with reduced heat strain. Using selectively permeable membranes may optimize protection but requires thorough consideration of the wearer's heat strain.

1 Introduction

One of the major problems associated with Chemical Warfare Protective Clothing (NBC, CW or CBRN) and their industrial chemical protective counterparts is the additional heat load created by these garments (Goldman 1985, McLellan, 1996, Rissanen and Rintamaki 1997, Havenith and Heus 2004, Brown et al. 2010). For breathable CW-overgarments, traditionally containing an activated carbon/charcoal layer in a foam or other structure with a liquid repellent/spreading textile on top (bipack), research on alleviating heat stress has been focused in two directions. The first is reducing material thickness and thus heat and vapour resistance; the second is the use of thin, selectively permeable breathable membranes (the latter refers to waterproof membranes which would stop any CW agents (gas or liquid) from penetrating, but would allow the passage of moisture vapour (Allmaras, 2007, Trentacosta and Kapur 2005). The word 'breathable' is often used for 'vapour permeable' in this context, and does not relate to permeability for breathing gases like O₂, CO₂ or N₂. Even though the thickness and the heat and vapour resistance of CW-protective clothing materials has been reduced by over 50 % over the past decades, this has not necessarily resulted in major improvements in terms of heat strain for the wearer. The cause for this lack of observable effect is that the thickness and heat/vapour resistance of the complete clothing assembly (the overgarments are usually worn over underwear and the standard combat clothing) is not only determined by the outer material layers, but is a factor of all clothing layers, including all enclosed and adjacent air layers. This total thickness, as well as the total heat and vapour resistance is hardly affected by a reduction in thickness of a single layer of the package. A different approach, which so far has received only minimal attention in a CBRN context, is the increase in air permeability of the garment materials. Such an increase could result in improved ventilation of the clothing micro-climate (especially during movement and in wind) and thus lead to reduced heat and vapour resistance (Havenith et al. 1990, Fan and Tsang 2008, Qian and Fan 2009). An obvious fear is the reduction in chemical protection, concomitant with increasing air permeability. Thus the first question to be answered is whether air permeability of common CW protective garments can be improved, while sustaining appropriate levels of chemical protection. Research on the effect of increased air permeability on CW-protection by TNO Defence, Security and Safety, has shown that for some types of CW-materials protection can be maintained at higher levels of air permeability (Kaaijk et al. 2004). This opened the floor for investigations on the relation between air permeability and clothing heat and vapour resistance for CBRN clothing.

In parallel to the trend for thinner, activated charcoal loaded, overgarments the concept of selectively permeable membranes as outer layer was introduced which should provide a higher level of liquid protection. Finally there is the combination of semipermeable

membranes (liquid repellent, but permeable for water vapour and possibly vapourised CW agents) with a charcoal layer underneath, increasing the liquid protection compared to the air permeable bipack systems. Some of these membrane based ensembles of these latter two concepts have vapour resistances similar in magnitude to the textile based systems, and hence one would expect heat stress in these garments to be similar to that in the textile versions, but with the benefit of higher protection.

Recently, researchers studied the effect of porosity of protective garments using the approach of measuring critical heat stress (WBGT) limits for such garments (Bernard et al. 2005, 2008, 2010; Caravello et al. 2008) or measuring critical metabolic rate limits (Gonzalez et al. 2006). They showed that these criteria correlated better with air permeability (convective permeability) than with vapour resistance of the fabric (diffusive permeability, e.g. measured as MVTR; Moisture Vapour Transfer Rate). They further suggested that there was an upper limit to the porosity, above which no extra benefit for heat strain was observed (Bernard et al., 2010). In their studies they used lightweight commercially available coveralls as outer layer, of which in some the air permeability was altered by puncturing them in different densities. Ueda and Havenith (2005) studied the ventilation of the garments' microclimate in commercial protective coveralls that were also punctured with a grid of fine needles in different densities, thereby creating test garments of identical material, stiffness and fit, only differing in air permeability. They observed an increase in total ventilation with increasing air permeability, both for passive and active subjects. Ventilation through openings (wrist, neck, ankles) decreased however with increasing air permeability, probably due to a reduced pressure fluctuation in the more air permeable garments. All garments used in the mentioned studies were civil designs and are much lighter and more flexible than typical military chemical protective garments.

The present study was performed with two goals. The first was to compare two CW protection concepts in terms of heat stress: the more traditional military air permeable CW garment to an air impermeable membrane based garment of higher liquid protection level, i.e. two ensembles with identical inner layers, minimally different total static vapour resistances, but mainly differing in porosities. The second was to compare a number of charcoal foam based CW protective garments of identical stiffness, design, fit etc., only differing in porosity, and look whether a relevant physiological heat strain difference between these garments is observed. For the latter set of garments, also measurements of microclimate ventilation with tracer gases were performed.

2 Methods

Experiments were performed in two locations: The comparison of the membrane to the textile garment was performed at the Norwegian Defence Research Establishment, while the other studies were performed at TNO Defence, Security and Safety in The Netherlands.

2.1 Experiment 1: Textile versus membrane

The heat stress when wearing two chemical protective garments, NORMANS C-membrane (MEM, with air impermeable membrane between two woven textiles) and NORMANS C-desert (TEX, air permeable woven textile, see Table 1 & 2 for clothing details), was compared. Five persons (age 25.4 ± 2.3 , mass 75.4 ± 10.7 kg, height 182.4 ± 8.3 cm) were tested wearing the two garments alternately in a balanced design, walking on a treadmill ($3.6 \text{ km}\cdot\text{h}^{-1}$, incline 13 %) in a climate chamber (24.7 ± 0.5 °C, 53.8 ± 4.7 % relative humidity, wind speed $< 0.2 \text{ m}\cdot\text{s}^{-1}$). Body temperatures (skin temperature at 7 sites, rectal temperature); sweat production and respiratory parameters were measured during the test-period. The protocol for the climate chamber trial was:

- 10 min: rest
- 40 min walking on treadmill ($3.6 \text{ km}/\text{hour}$; 13 % incline)
- 20 min rest.

--Table 1&2 about here--

Garments were worn in closed state (meaning that all openings were closed as tight as possible to provide maximal protection), however the gas mask was replaced by an oxygen consumption facemask. Both MEM and TEX were worn over the same underwear and over the same charcoal liner (Fig. 1).

Subjects were not allowed to drink or go to the toilet in the course of the experiment. By weighing the clothed test subjects before and after the experiment weight loss in the experimental period was determined. This weight loss is reported uncorrected for the respiratory water loss and metabolic weight changes, as this would be equal in both suits.

--Fig. 1 about here--

2.2 Experiment 2: Changing air permeability

Standard Royal Netherlands Army CW protective suits had their outer textile layer removed, leaving the charcoal impregnated foam layer, which is the main determinant of suit stiffness and fit, intact. Subsequently four textiles with differing air permeabilities were selected and

these were stitched onto these CW suits, creating 4 suits of different air permeability, but otherwise virtually identical properties, coded Low, Medium (actual NBC suit), High and Extra High. Details on the outer fabrics used are presented in Table 3. Suits were worn over underwear (cotton briefs and T-shirt) and a standard Dutch combat suit consisting of combat trousers and summer jacket, long sleeved (both cotton/polyester).

--Table 3 about here--

2.2.1 Experiment 2a: Microclimate ventilation measurement

Ventilation rate under the clothing was studied using a trace gas diffusion technique (Lotens and Havenith, 1988, Havenith et al., 1990, 2010). With this method, diluted argon is injected at the skin at numerous locations distributed over the body (except head, hands, and feet) through a distribution and sampling harness. At similar locations, gas samples of the clothing microclimate air are taken. Both injected and sampled gasses are analysed for their argon concentration using a mass spectrometer (Spectra Minilab, Crewe, UK). The dilution factor of the gas in the clothing microclimate at the skin is a measure of clothing microclimate ventilation, and can be used to calculate clothing vapour resistance (Lotens and Havenith, 1988, Havenith et al, 1990, 2010). For a validation of the method, see Havenith et al. (2010).

Ventilation that reaches the microclimate at the skin was calculated as:

$$Ventilation \ (l.min^{-1}) = Flow \frac{C_{in} - C_{out}}{C_{out} - C_{air}} \quad (1)$$

with:

Flow = circulating airflow in distribution and sample tubes ($l.min^{-1}$)

C_{in} = concentration Argon in distributed air (%)

C_{out} = concentration Argon sampling air (%)

C_{air} = concentration Argon in environment air (%)

Tests were performed on three subjects (as no physiological measurements were performed for this, individual variability was only relevant in terms of different clothing fit). Participants wore the clothing in a different (balanced where possible) order. Ventilation rates were measured while standing still, and while walking at 0.5 and at 1.4 $m \cdot s^{-1}$. These three conditions were all combined with 4 wind conditions (0, 0.5, 1.4 en 5.0 $m \cdot s^{-1}$). A minimum of three replications were performed for all conditions.

2.2.2 Experiment 2b: Heat stress test and static insulation

Six participants wore all suits in two conditions. In condition 1 the static insulation value of the clothing was determined in a neutral (20 °C, 50 %, 0.5 m·s⁻¹ wind) climate, with subjects at rest, using steady state heat balance analysis (Havenith et al. 1990). To determine whether any differences in microclimate ventilation were also recognisable as differences in heat strain, a further test was carried out with the same clothing while performing exercise in a hot environment. In this condition 2, the environment was set at 36 °C, 20 % rh, 5 m·s⁻¹ wind, representing open space, desert type conditions. Subjects performed work on a treadmill (4 km·h⁻¹).

In both conditions measurements were taken each minute for rectal temperature (T_{re}), mean skin temperature (T_{sk}) based on measurements on head, chest, back, upper and lower arm and upper and lower leg (YSI703 thermistors, surface area weighted mean). Heart rate (HR) was monitored by a Polar Electro heart rate monitor. Mass change of the clothed person was measured every 15 minutes (Sartorius YACOILA, Sartorius AG, Goettingen, Germany) for assessment of sweat evaporation rate (though only change between start and end value was used in this analysis), and twice in each test (at rest after 15 and 45 minutes; in heat after 45 and 75 minutes) the participant was connected to a metabolic cart to determine oxygen uptake and subsequently metabolic rate. Before and after the tests subjects and clothing were weighed separately to determine overall mass loss and clothing moisture accumulation. Test duration was 60 minutes for the resting test and 90 minutes for the heat stress test.

Conditions and suits were balanced over participants.

2.3 Statistics

Data were analysed using repeated measures ANOVA and post hoc tests. Differences at individual time points during the test were tested, but as the essence of the result analysis is whether a difference develops over time, the focus was on the differences at the end of the exposures.

3 Results

3.1 Experiment 1: Textile versus membrane

Heart rate (Fig. 2) in the last part of the exercise period was 14 bpm higher in MEM at the end of the test. This difference was borderline significant in the last 15 minutes ($0.03 < p < 0.07$; only one subject had a higher HR in TEX). While starting core temperatures (Fig. 3) were not significantly different, a difference in core temperature of 0.6 °C ($p < 0.01$)

developed over the course of the test, with MEM being higher than TEX. This coincides with an 0.5 °C higher skin temperature, an 8 litre.min⁻¹ higher breathing volume and a 184 g higher sweat production (see Fig. 4) (all p<0.05) for MEM. Also sweat accumulation in the clothing was higher in MEM (p<0.05, Fig. 4). The overall picture was consistently showing a higher thermal strain in MEM.

3.2 Experiment 2: Changing air permeability

3.2.1 Experiment 2a: Microclimate ventilation measurement

Results for the ventilation of the clothing in relation to movement and wind speed are presented in Fig. 5. At the 3 lower wind speeds a clear effect of walking speed is present (p<0.001), while at the highest wind speed only the change from static to walking shows a significant effect (p<0.01). The walking effect is similar for all suits (p<0.05). Wind has a strong effect on ventilation (p<0.001), with a clear interaction of wind with the air permeability of the clothing (p<0.001). The latter has only a small impact at low wind speeds (only EH separates out from the other suits), but with increasing wind the air permeability of the outer layer becomes the determining factor for the observed ventilation.

3.2.2 Experiment 2b: Heat stress test and static insulation

Static total insulation (I_{tot}) determined in the steady state test was not significantly different for the tested ensembles (p>0.05) at 0.5 m.s⁻¹ wind speed, and amounted to 0.34 m²KW⁻¹, or 2.2 clo. Based on the measurement of suit surface temperature (7 locations matching skin temperature sites), this value could be split into the intrinsic clothing insulation and the outer surface air layer insulation: 0.27 m²KW⁻¹ and 0.07 m²KW⁻¹ (effective value; translated to actual air layer insulation value using the clothing surface area factor fcl (=1.5) this is 0.10 m²KW⁻¹) respectively. The latter matches well with values presented in the literature for this wind speed (Havenith et al, 1990).

In the heat test, a clear difference among suits was observed in the physiological responses. Fig. 6, Fig. 7, and Fig. 8 show the development of core temperature, skin temperature and heart rate over the test period. The values in the last 5 minutes of the exposure were averaged and analysed. For skin temperature a difference between all consecutive suits is visible (P<0.05) consistent with their air permeability ranking, while for heart rate and rectal temperature, the two suits with lowest air permeability and the two with the highest respectively produced a similar response, though there was a clear and significant difference between these two groups (P<0.05).

Fig. 9 shows the mean participant nude weight loss for the different suits, as well as the weight loss of the clothed participants and the clothing weight gain. Finally, Fig. 10 shows the participants sweating efficiency (here defined as evaporated sweat divided by total sweat produced in the session). Sweat production increases with lowering air permeability, as does sweat accumulated in the clothing (both $P < 0.05$ for EH and H versus M and L). Sweat evaporation decreases with lowering air permeability, though this is only significant for EH and H versus M and L too. Sweat efficiency (evaporated/produced sweat) is therefore highest for highly air permeable clothing ($P < 0.05$), though again EH and H and also M and L do not differ significantly from each other.

4 Discussion

4.1 Experiment 1: Textile versus membrane

The comparison in this first test is between two ensembles with the same composition apart from the outer layer. Heat resistance is therefore very similar, and static vapour resistance too, given the low vapour resistance of these membrane types and the similar thickness of the complete ensemble of fabric and air layers of both the textile and the membrane system. The main difference is the air permeability/porosity of the outer fabric. In material tests this often does not affect heat and vapour resistance measurements as most test are set up such that wind is not present or cannot penetrate the fabrics. Despite these similarities between the ensembles, a substantial and significant difference in heat stress between ensembles was observed, which therefore must be attributed to the effect of air permeability on heat and vapour transfer through the clothing in actual use, including the pumping effect caused by walking. Looking at the sweating results in Fig. 4, it seems that evaporated sweat is similar for both and thus the same amount of cooling is achieved with the cost of increased dehydration, cardiovascular load and higher core and skin temperature in MEM. The extra increase in mean body temperature of over 0.5 °C in 40 minutes of exercise is highly significant for operational performance, whether for military or civil applications. Assuming an exposure limit of 39 °C for young healthy individuals, for the test climate used this would be reached 40 % faster in MEM based on the rate of increase in core temperature observed here. It has to be concluded therefore that it is not appropriate to use measurements on samples of the materials to be used for the evaluation of their operational performance where the porosity may differ. This finding for a comparison of a non-air permeable outer layer (MEM) to a medium porosity outer layer (TEX) sets the scene for the next part of the testing. In these next tests, variations in the porosity/air permeability of the outer layer were further investigated.

4.2 Experiment 2: Changing air permeability

4.2.1 Experiment 2a: Microclimate ventilation measurement

In the absence of wind and movement a small but significant difference in microclimate ventilation was present (significant for EH versus the other ensembles), consistent with the difference in air permeability between suits. As the suits used were identical in thickness (same underwear, same combat clothing, same foam layer), as well as stiffness (same foam layer) and only differed in the air permeability of the outermost fabric layer, this was not completely expected. Differences were expected for conditions in which air movement through the fabric would play a major role (Ueda et al. 2006). Thus even while standing still (though participants will always have some movement), with no wind, sufficient air movement through the garments must have been present to result in the observed effect for the garment with the highest air permeability. When participants start to walk however, the initial difference in ventilation between suits disappears. The pumping effect which takes place under the garment apparently is not significantly affected by the air permeability of the outer garment. Though openings at wrist, ankles and neck were closed with Velcro straps, due to design differences this may not have been as tight as it was in Experiment One. It may therefore be possible that the pumping mainly worked via leakage through openings and thus explain the lack of influence of air permeability. Low wind speeds ($0.5 \text{ m}\cdot\text{s}^{-1}$) do increase ventilation as expected (Havenith et al., 1990), but do not interact significantly with air permeability. At higher wind speeds ($>1.4 \text{ m}\cdot\text{s}^{-1}$) a significant difference in ventilation directly related to air permeability starts to show. Thus the penetration of the garments by wind is affected by outer layer air permeability, as earlier described by Burton and Edholm (1955). At higher wind speeds, the additional effect of the high versus the low walking speed/movement more or less disappears. Apparently, microclimate air layers are disturbed in such a manner that the additional pumping effect due to an increase in movement does not add further to the disturbance. Given the sizeable differences in microclimate ventilation at higher wind speeds, implying an improved removal of heat and water vapour from the skin (assuming a positive temperature and vapour pressure from the skin to environment), a considerable reduction in heat strain could thus indeed be expected when air permeability is increased while other material characteristics remain equal.

The measured ventilation rates allow an estimate of the permeation speed of the environmental air into the suit. Making a simple assumption of a suit surface of 2 m^2 , and assuming air would enter on one side of the suit (1 m^2) and leave on the other, the measured ventilations suggest that for walking in wind at $5 \text{ m}\cdot\text{s}^{-1}$ the penetration speed in the actual CW clothing (M) at a ventilation around $220 \text{ l}\cdot\text{min}^{-1}$, will be around $0.4 \text{ cm}\cdot\text{sec}^{-1}$. For the ensemble with the highest air permeability this would go up to $0.85 \text{ cm}\cdot\text{sec}^{-1}$, which is a

substantial difference that may affect the absorption effectivity of the charcoal. Finally, the ventilations reported here were measured at the skin. Havenith et al. (1995) measured ventilation in various layers and observed that only 60 to 80 % of the ventilation penetrating the charcoal layer will actually reach the skin, indicating that the air speed through the charcoal layer may be proportionally higher.

4.2.2 Experiment 2b: Insulation and heat stress test

The limited differences in static ventilation did not translate in a significant difference in clothing insulation in the static condition. Given the sensitivity of the heat balance method used, which is lower than that of thermal manikins due to inter and intra-individual variability of human test subjects (Havenith and Heus, 2004), the ventilation difference is apparently too small to produce a relevant and statistically significant effect in the static human participant tests.

However, in the heat stress test, in the presence of wind (5 m.s^{-1} , representing open space, desert type conditions), clear effects of the air permeability differences were observed. The higher the air permeability, the lower body temperature, heart rate, sweat production and moisture absorption in the clothing and the higher the sweating efficiency. The two suits with high air permeability only differed significantly from each other for some of the parameters measured however, as did the two with the lower air permeability. The expectation is, that with a more accurate (faster) determination of body core temperature (oesophageal instead of rectal) and/or a longer exposition to the heat, differences between the suits in each group would have become significant too. However, considering work by Bernard et al. (2010), this may not be the case for the highest air permeabilities. Their work suggests that above a certain permeability (porosity in their paper), no additional benefit is gained from further increases. The deflection point they observed was located around $1000 \text{ l.}(\text{min.cm}^2.\text{bar})^{-1}$, which is at the level of suit M of the present test. Hence, if the lack of difference for some parameters between E and EH is related to such a deflection point, this is located at a substantially higher value for air permeability ($> 2900 \text{ l.}(\text{min.cm}^2.\text{bar})^{-1}$) for the clothing tested here. Given that the present clothing is much thicker and stiffer than that of Bernard et al., reducing ventilation penetration to the skin, and that furthermore the deflection point determination by Bernard et al. using a logarithmic graph may have some uncertainty, such a higher value does not seem improbable.

The observed difference in the speed of increase of body temperature indicates that when the air permeability of the current CW-suit (M) would be increased by a factor 2, the tolerance time is expected to be more than one-third longer. It was thus confirmed that increasing the porosity / air permeability of CW overgarments (while meeting the required

protection) provides substantial benefits in reducing the heat strain of the wearers. Further, based on our experience in other testing, this benefit seems to be larger than that of reducing the thickness of the protective layer.

When reductions in thickness and / or resistances of CW-protective fabrics are tested, the chosen climatic conditions will strongly affect the outcome. Den Hartog et al. (1998) tested optimised CBRN clothing in a climate of 36 °C, 50 % and did not find significant differences in body temperatures, despite finding an improved evaporation (5 %) and evaporative efficiency. The difference with the present experimental clothing was that in Den Hartog's test both heat and vapour resistance had decreased. Given that skin temperature was below ambient temperature, this caused a higher DRY heat flux from the environment TOWARDS the skin, which compensated partially for the improved heat loss by evaporation FROM the skin. The latter's capacity was reduced compared to the present test however, due to the higher humidity (50 versus 20 %) chosen in their test. In the present test, static heat resistances were very similar, allowing the benefit of vapour resistance reductions to become clearer. What can be seen here is that where ambient temperatures go above skin temperature one needs to carefully consider the balance of dry and evaporative heat losses to evaluate the clothing. Looking purely at body temperature will not allow any extrapolations of the testing to predict effects at other temperature-humidity conditions.

5 Conclusions

When comparing ensembles with a textile versus a membrane outer layer that have similar static heat and vapour resistances measured for the sum of fabric samples, a higher heat strain is observed in the membrane ensemble as in actual wear the air permeability of the textile version improves ventilation and allows better cooling by sweat evaporation.

For garments with identical thickness and static dry heat resistance, but differing levels of air permeability, a strong correlation of microclimate ventilation due to wind and movement with air permeability is present. This is reflected in lower values of core and skin temperatures and heart rate for garments with higher air permeability. For heart rate and core temperature the two lowest and the two highest air permeabilities form two distinct groups, but do not differ within the group.

Based on protection requirements it is concluded that air permeability increases can improve heat strain levels allowing optimisation of protective clothing.

The effect of increasing air permeability may be stronger than improvements through the reduction of the material thickness.

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Fig. 1 The clothing layers worn in experiment 1. From left to right: 1: Underwear; 2: Charcoal layer (C-lining CD2880); 3: MEM and 4: TEX outer layer. Underwear (1) and charcoal liner (2) were worn under both the protective outer layers.

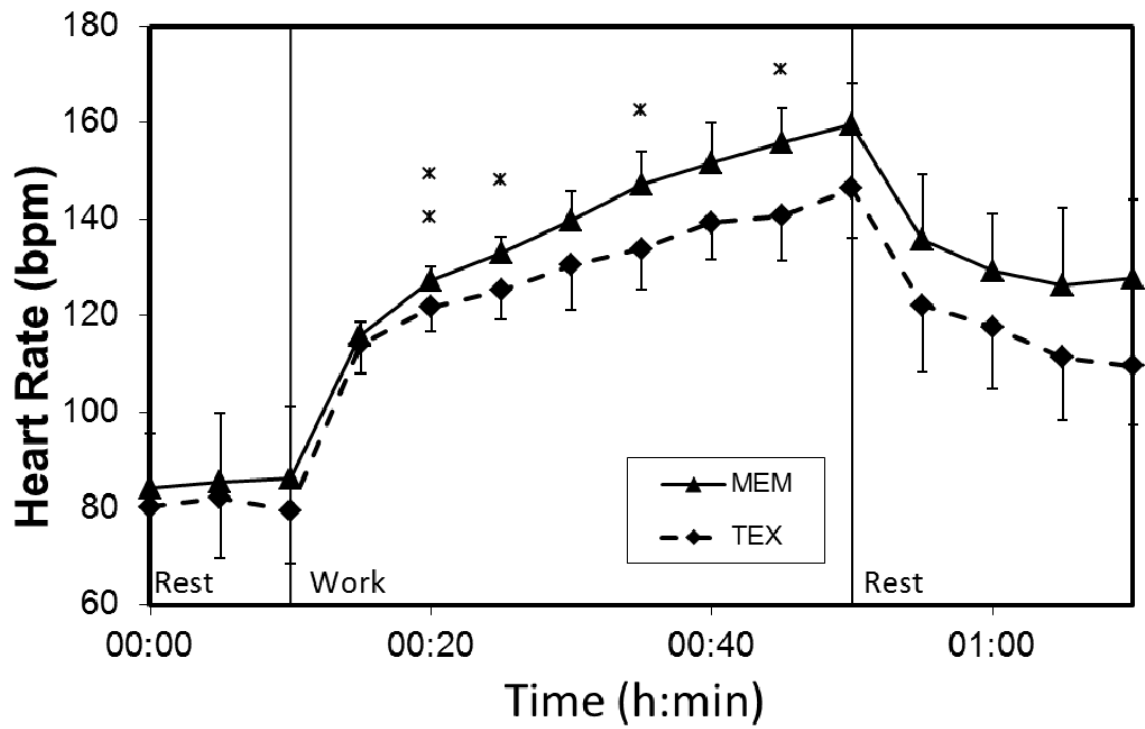


Fig. 2 Heart rate development (mean \pm SD) in experiment 1 for both MEM and TEX suits. *: $P < 0.05$; **: $P < 0.01$.

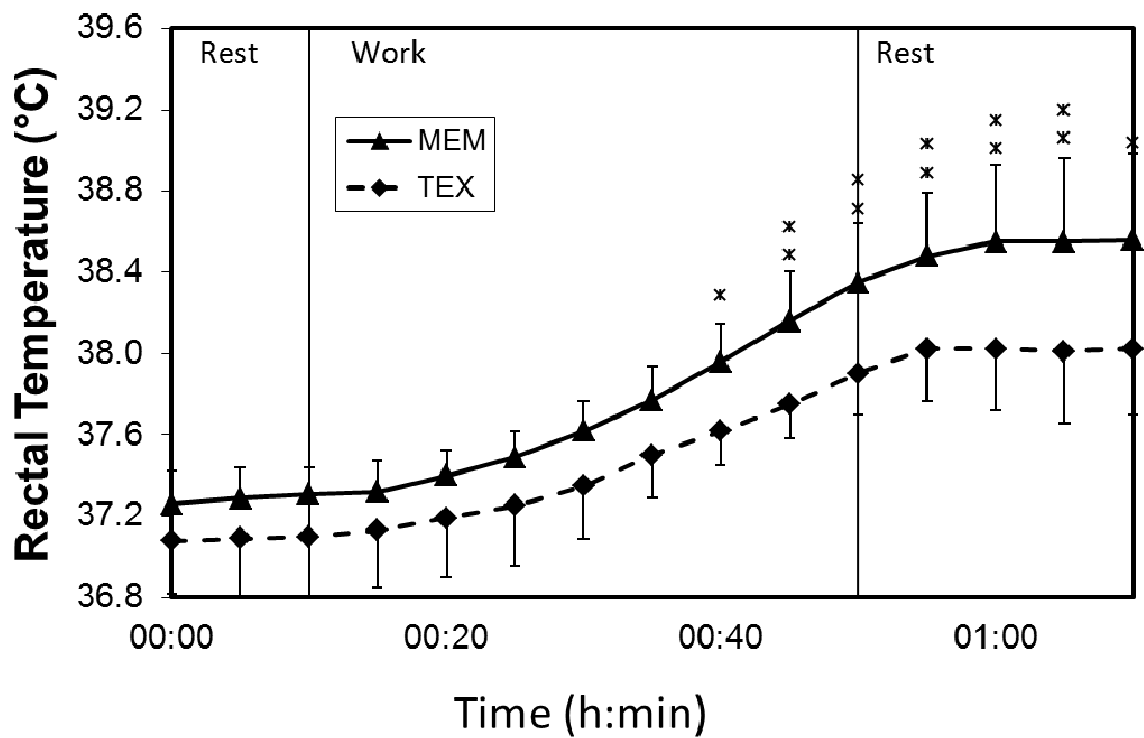


Fig. 3 Rectal temperature development (mean \pm SD) in experiment 1 for both MEM and TEX suits. *: $P < 0.05$; **: $P < 0.01$.

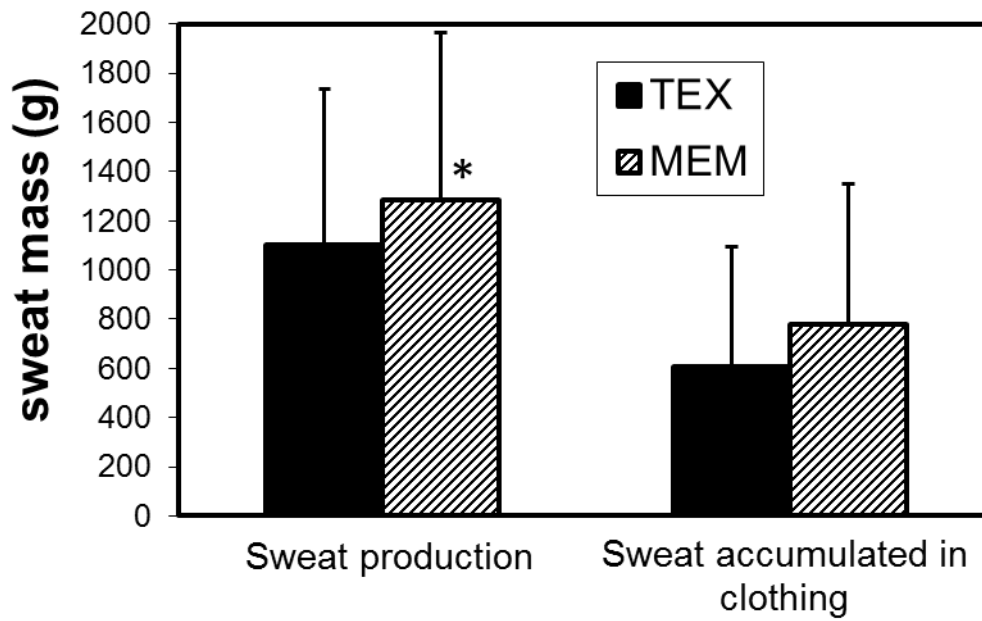


Fig. 4 sweat production and sweat accumulation in the clothing for experiment 1 (mean \pm SD). Significance indicated by: * $P < 0.05$.

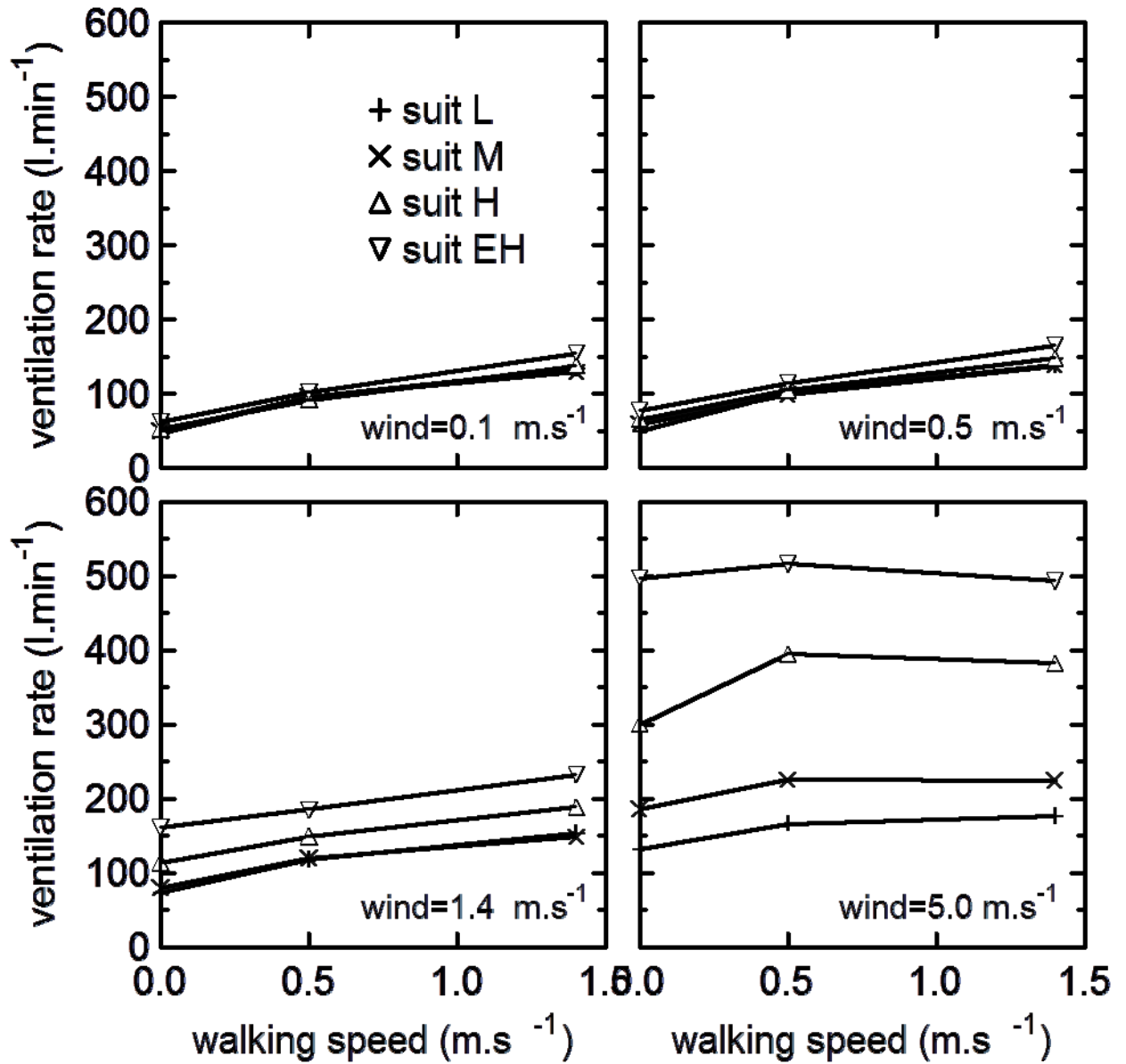


Fig. 5 Mean ventilation results in relation to walking speed and wind speed for experiment 2a for the four different air permeabilities Low, Medium, High and Extra High.

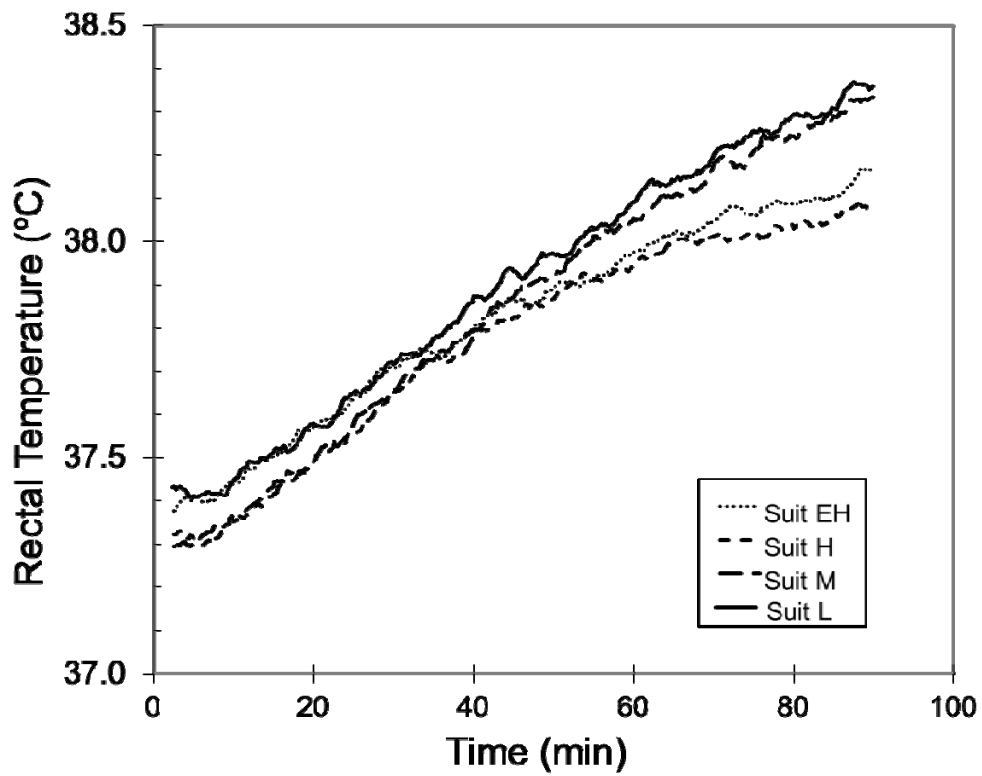


Fig. 6 Development of core temperature in experiment 2b over the measurement period averaged over participants for the four different suits with different air permeabilities: Extra High, High, Medium and Low.

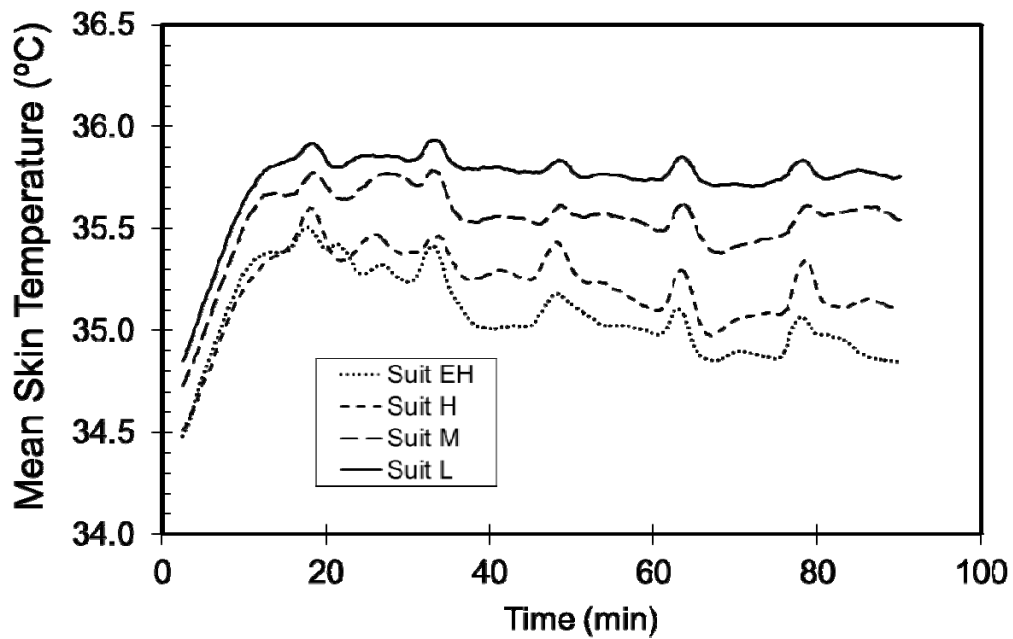


Fig. 7 Development of skin temperature in experiment 2b over the measurement period averaged over participants for the four different suits with different air permeabilities: Extra High, High, Medium and Low.

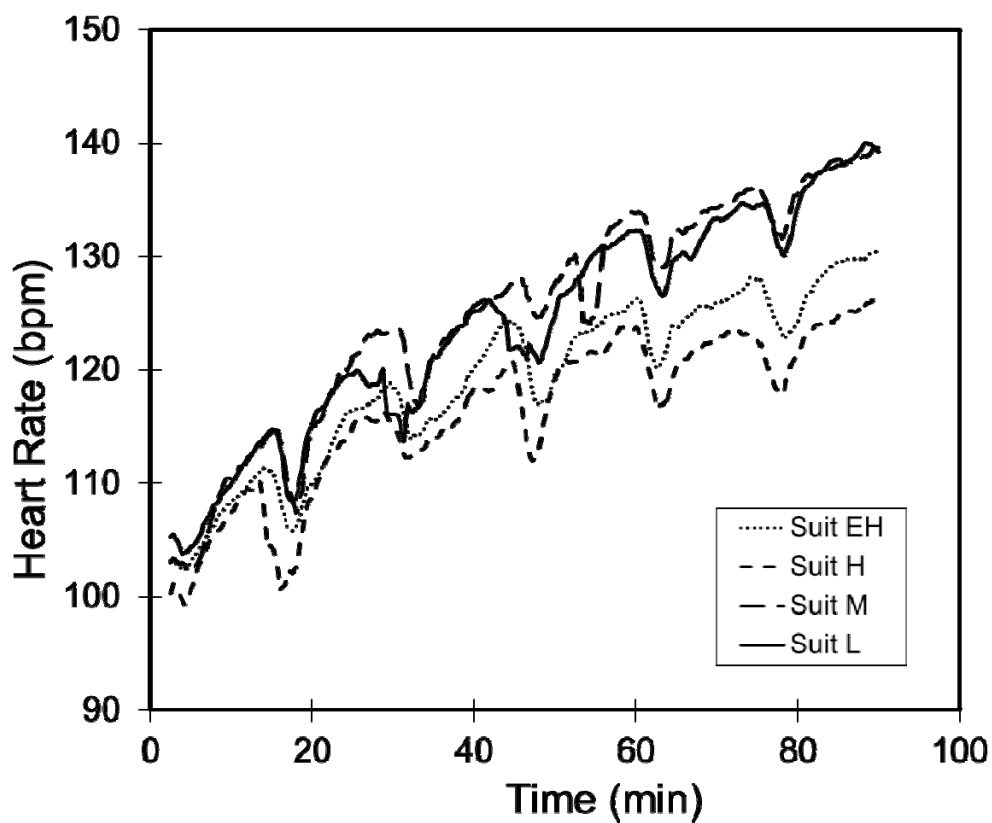


Fig. 8 Development of heart rate in experiment 2b over the measurement period averaged over participants for the four different suits with different air permeabilities: Extra High, High, Medium and Low.

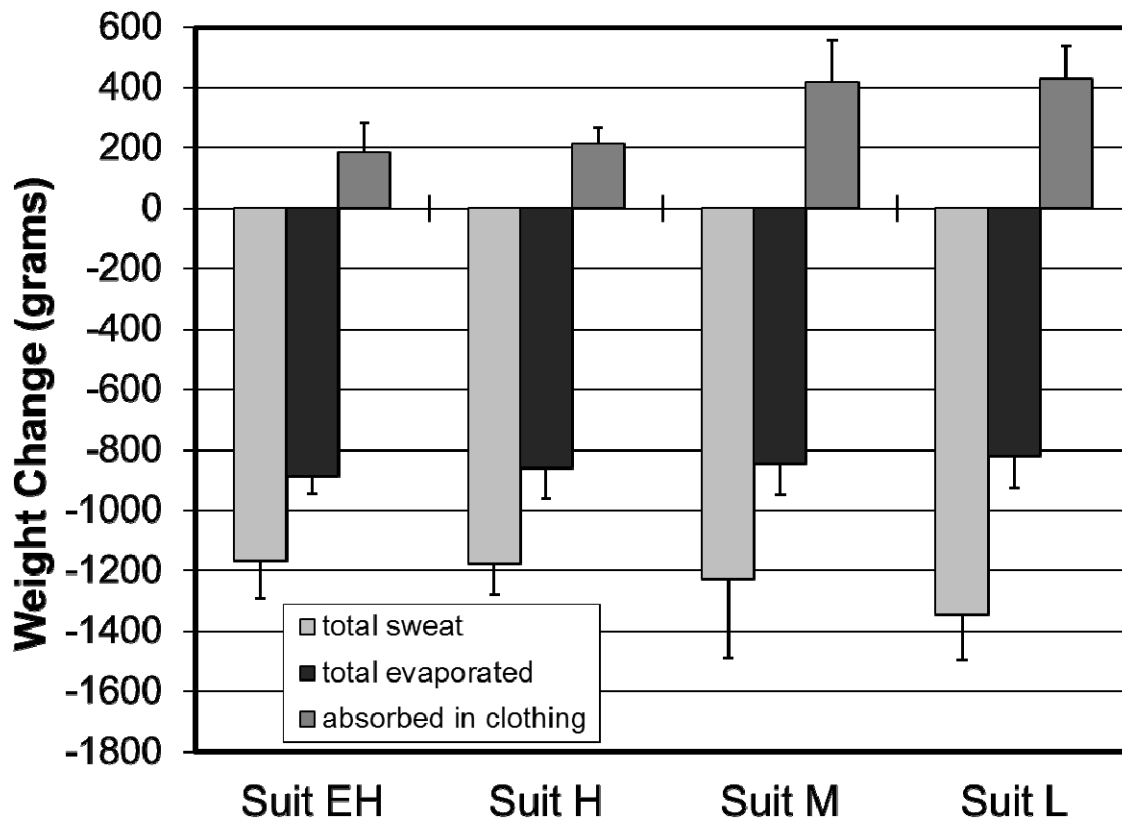


Fig. 9 Total nude weight loss (sweat production plus metabolic and respiratory losses), sweat evaporation, moisture accumulation in the clothing, and sweat efficiency (evaporated/produced sweat) averaged over participants for the four clothing types Extra High, High, Medium and Low in experiment 2b.

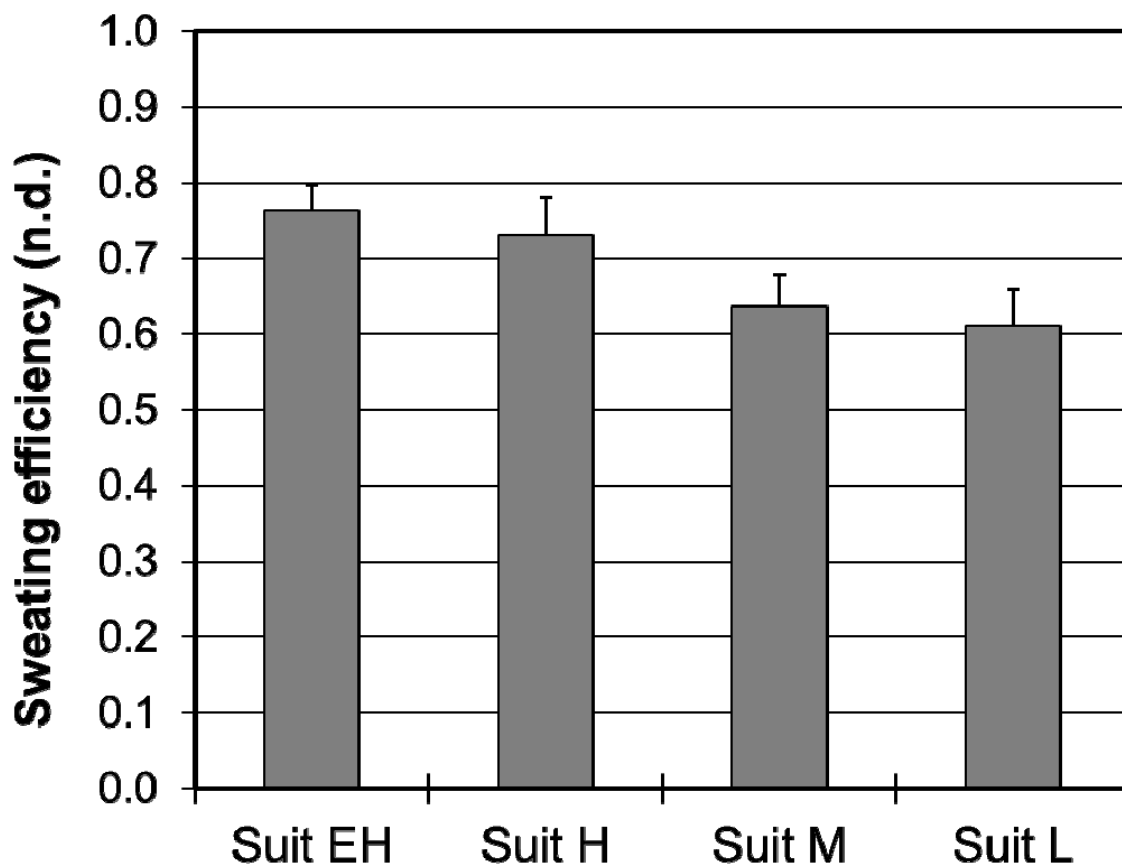


Fig. 10 sweating efficiency (evaporated/produced sweat) averaged over participants for the four clothing types with different air permeabilities: Extra High, High, Medium and Low (with standard deviation) in experiment 2b

Table 1 Details of the clothing used in experiment 1. Outer clothing in NORMANS C-membrane(MEM) and NORMANS C-desert (TEX) worn over NBC underlayers.

| Clothing | Weight [kg] | Weigh fabric [g/m2] |
|---|----------------|------------------------|
| Leg clothing | | |
| NBC trousers, C- lining (CD 2880) | 0.728 | 430 |
| TEX: Combat trousers with/suspenders (Desert 88/12 CO/Polyamide) | 0.789 | 210 |
| MEM: Combat trousers with/suspenders , membrane fabric (3 layers Proline) in between 2 textile layers | 0.794 | 190 |
| Upper part of the body | | |
| Underwear, briefs | 0.070 | - |
| Underwear, netting (Rhovyl) | 0.102 | 150 |
| NBC jacket, C- lining (CD 2880) | 0.977 | 430 |
| TEX: Combat jacket (Desert 88/12 CO/Polyamide) | 1.230 | 210 |
| MEM: Combat jacket, membrane fabric (3 layers Proline) in between 2 textile layers | 1.202 | 190 |
| Feet | | |
| Inner socks | 0.109 | - |
| C-socks (CD 2870) | 0.116 | 350 |
| Combat boots | 1.679 | - |
| Hands | | |
| C-gloves (CD 3040) | 0.112 | 300 |
| Mitten | 0.170 | 290 |

Table 2 Fabrics parameters related to the three fabrics used for the garments of experiment 1.

| Data from the different fabrics | UNIT | NBC jacket, C- lining (CD 2880) | TEX: Combat jacket (Desert 88/12 CO/Polyamide) | MEM: Combat jacket, membrane fabric (3 layers Proline, PU based membrane) |
|---|------------------------------------|---------------------------------|--|---|
| Weight | g.m^{-2} | 430 | 210 | 190 |
| Thickness | mm | 1.2 | 0.33 | 0.55 |
| Total ensemble thickness (estimate with air layers) | mm | n/a | 1.55 (23.55) | 1.75 (23.75) |
| Total ensemble heat resistance (ISO 9920, manikin) | $\text{m}^2 \cdot \text{K.W}^{-1}$ | n/a | 0.289 | 0.294 |
| Air permeability (ISO 9237) | l.min^{-1} | 25 (21 cm/s) | 10 (8 cm/s) | > 0,5 (0,4cm/s) |

Table 3, Fabric parameters related to experiment 2. Clothing air permeabilities are shown recalculated to different units to allow comparison with literature (e.g. Bernard et al. 2010)

| Type (air permeability code) | EH (extra high) | H (high) | M (medium; actual NBC suit) | L (low) |
|---|--------------------|--------------------------------|--------------------------------|----------------------------------|
| Content | 100 % Cotton | 70/30 Polyester/ Viscose | Cotton / Acryl or PolyAmide | 50/50 polyester/ polyamide |
| Thickness incl. charcoal loaded foam layer | 2.8 | 3.1 | 2.9 | 2.8 |
| Weight g.m ⁻² | 133,1 g | 255,7 g | 225,3 g | 128,8 g |
| air resistance mm H ₂ O.s.cm ⁻¹ [cm.s ⁻¹ @100 Pa] | 0,0948 [105,4] | 0,2054 [48,7] | 0,5370 [27,0] | 6,7940 [1,47] |
| Air permeability l.s ⁻¹ .m ⁻² @100 Pa [l.min ⁻¹ acc. ISO9237: @100 Pa and 20 cm ²] | 1005 [121,0] | 487 [58,4] | 186 [22,3] | 15 [1,8] |
| Air permeability l.(min.cm ² .bar) ⁻¹ | 6050 | 2920 | 1115 | 88 |
| Vapour resistance incl. charcoal foam | 3,5 mm | 3,2 mm | 3,2 mm | 3,4 mm |