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Optimizing the Performance of Phase-Change Materials in Personal Protective Clothing Systems

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Phase-change materials (PCM) can be used to reduce thermal stress and improve thermal comfort for workers wearing protective clothing. The aim of this study was to investigate the effect of PCM in protective clothing used in simulated work situations. We hypothesized that it would be possible to optimize cooling performance with a design that focuses on careful positioning of PCM, minimizing total insulation and facilitating moisture transport. Thermal stress and thermal comfort were estimated through measurement of body heat production, body temperatures, sweat production, relative humidity in clothing and subjective ratings of thermal comfort, thermal sensitivity and perception of wetness. Experiments were carried out using 2 types of PCM, the crystalline dehydrate of sodium sulphate and microcapsules in fabrics. The results of 1 field and 2 laboratory experimental series were conclusive in that reduced thermal stress and improved thermal comfort were related to the amount and distribution of PCM, reduced sweat production and adequate transport of moisture.

phase-change materials (PCM)   protective clothing   thermal stress

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1. INTRODUCTION

Protective clothing limits body heat dissipation and may lead to thermal stress and discomfort even at moderate exposure temperatures. Phase-change materials (PCM) can be used to reduce thermal stress and provide improved thermal comfort for wearers of protective clothing.

PCM are characterized by their ability to absorb energy when they change from a solid to a liquid state and to release heat as they return to the solid phase. PCM used in clothing go through the phase change at temperatures close to the thermally neutral temperature of the skin, 28–32 °C. During the phase change, the temperature does not change, and thus PCM can stabilise body temperature. The cooling effect of PCM depends on the capacity to absorb heat during periods when external heat load or body heat production exceeds heat loss. The net effect of PCM in practical use is reduced by the fact that PCM in clothing add to the total weight of the wearer and thus increase metabolic heat production. PCM also represent an extra barrier to evaporative heat loss and moisture transport through the clothing layers. Therefore, the potential cooling contribution provided by PCM should be identified and evaluated as part of the total heat exchange mechanism through the clothing system, together with the capacity of the body to maintain thermal neutrality and comfort.

Body temperatures must be maintained within narrow ranges in order to ensure optimal body functions. Cognitive performance is negatively affected when body core temperature increases by more than 1 ºC [1]. The rates of heat production and heat loss must be equal if body temperature is to remain constant. Our temperature-regulating system aims to maintain the core temperature (T_{core}) constant and skin temperatures (T_{skin}) within a range of ±2 ºC. The system (a) is responsive to fluctuations in body temperatures, (b) integrates information from both peripheral and central temperature receptors, and (c) permits proportionality between input information from multiple temperature receptors in the body core and in the skin, and our various effector mechanisms. Effector responses act in a direction opposite to disturbances of the body temperatures. Dilatation of peripheral blood vessels and sweating are effector mechanisms that facilitate heat loss, while vasoconstriction and increased heat production preserve body heat. T_{skin} or T_{core} must cross an effector-specific threshold in order to activate or inactivate effector mechanisms. Once the threshold temperature has been passed, the effector responses are proportional to the difference between actual T_{skin} and the activation threshold temperature. In many real-life situations, T_{skin} is assumed to generate the decisive afferent input [2]. T_{skin} plays an exclusive role in temperature sensation [3, 4], which, in contrast to thermal comfort, is independent of T_{core}. Thus, changes in T_{skin} alone activate both autonomic and behavioural effector mechanisms so that deviations in T_{core} are reduced or avoided. Different skin regions have different thermosensitivity and importance [5, 6]. The face, chest, neck and lower back are more sensitive to changes in temperature than, e.g., the thigh and leg. The afferent signals from skin temperature receptors are highly sensitive to the rate of change in temperature as well as to absolute temperature. The direction of temperature change affects the response; a change in the direction of normal temperature evokes less receptor response than an equivalent change away from normal temperature.

Protective clothing worn in situations of external heat stress or intensive physical work may challenge the body’s temperature regulating system to such an extent that heat balance is no longer possible, wich will result in heat storage and, consequently, the development of hyperthermia. PCM can provide a solution to this problem by absorbing heat during the phase change from solid to liquid. The use of PCM in this study was based upon knowledge of human temperature regulation, thermal comfort, temperature and moisture transport through clothing layers, and of the mechanisms by which PCM work. Our aim was to optimize the cooling performance of PCM in protective clothing in simulated work situations, characterized by heat stress resulting from moderate metabolic heat production and heat exposure. We hypothesized that careful positioning of PCM, giving due regard to the characteristics of human thermoregulation and mechanisms of heat and moisture transport through clothing layers, would improve the wearer's thermal comfort. We predicted that the new design would reduce the temperature of selected skin areas, reduce sweat production and water absorbed in the clothing and thus improve subjective thermal comfort during periods of heat stress.

2. MATERIALS AND METHODS

This report presents the results of pilot studies that provide a knowledge basis for our further research on PCM and the design of protective clothing.

Our study comprised protective clothing for two different working situations: surgery in an operating theatre and well-insulated protective clothing to be used in moderately warm conditions. Neither of these situations allows the wearer to make any adjustments of the clothing during the working period. Case studies in the operating theatre together with a laboratory test provided knowledge about positioning PCM in protective clothing. Based upon the experience from this study, PCM were carefully integrated into well-insulated protective clothing (a PCM suit). The effect of PCM in clothing was studied in the operating theatre, using subjects who simulated relevant work situations under controlled laboratory conditions. The subjects were informed of the procedures and potential risks of the experiments, and the experimental procedures were approved by the Ethics Review Committee of the Faculty of Medicine at the Norwegian University of Science and Technology.

2.1. PCM

Experiments were carried out using two types of PCM; the crystalline decahydrate of sodium sulphate or Glauber's salt (Climsel C28, C31 Climatro AB, Sweden) and microcapsules in fabrics (Outlast® 341 Clemmons; Outlast Europe GmbH, Germany). The effect of Glauber's salt is three times that of Outlast® (microcapsules and fabric), 180 and 60 kJ·kg^{-1}, respectively.

2.2. Clothing

2.2.1. Surgery

The regular clothing worn by the surgeon in the operating theatre consisted of shoes, socks, cotton underwear including a t-shirt, cotton trousers and a surgeon's protective smock (clothing A). Heat stress produced when this clothing was worn was compared with the situation when a commercially available cooling vest completely covered with Glauber's salt elements (ComfortCooling, Sweden;

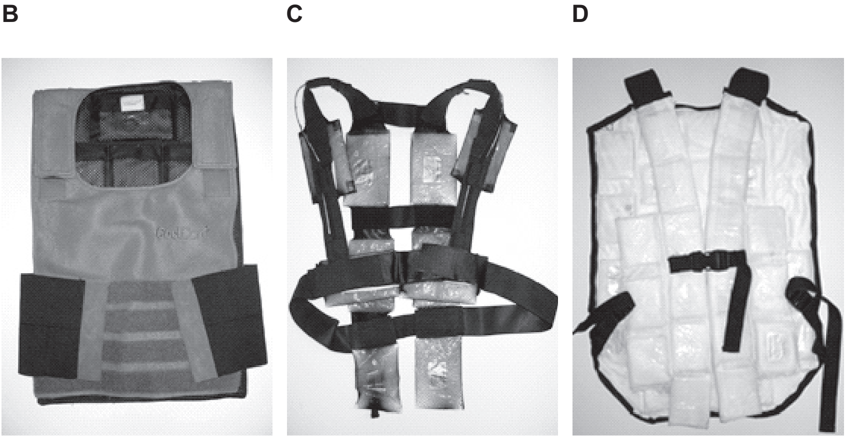

Figure 1. The three cooling vests worn by the surgeon during trials in the operating theatre: B—commercially available vest, C—initial experimental vest concept and D—final vest concept. Glauber's salt elements (Climsel C28, C31 Climatro AB, Sweden) were used as phase-change material.

total weight 2 kg) was added to the protective clothing system (clothing B, Figure1). Clothing with two experimental cooling vest concepts (C and D, Figure 1) were compared with clothing A and B. The C and D vest concepts were the result of a product design process based upon a number of trials in the operating theatre [7]. For the design of a new cooling vest, all excess fabric was removed from the existing vest. Then, the number and position of the elements were systematically changed, while the effect on heat stress and freedom of movement was evaluated. The cooling vest concept C was worn directly on the skin under the surgical shirt. In order to examine the effect of different positioning and amount of PCM on physiological responses, laboratory tests under controlled environmental conditions were also performed. The design of the final vest concept D (total weight 1.8 kg) was chosen on the basis of the results from the operating theatre and the laboratory.

2.2.2. Well-insulated protective clothing

Underneath the suit, the 6 subjects were dressed in cotton underwear, cotton shirt and trousers, a woollen sweater and woollen socks. The regular suit (a placebo) was compared with a new suit with PCM. By careful selection of lining material, we achieved identical insulation values (3.30 clo) for both the placebo and PCM suits. Following the same design methodology as for the surgeon's protective clothing system, various amounts of Outlast® were integrated into the suit at selected body sites in order to facilitate the cooling of the most thermally sensitive body areas and to aid moisture transport. The results showed measurements of the placebo suit and of the final prototype PCM suit. The total weight of the Outlast® material used in the final prototype suit was 450 g.

2.3. Measurements

2.3.1. Physiological parameters

Metabolic heat production was calculated from oxygen uptake (analysed with a Vmax29; SensorMedics Corporation, USA), heart rate (Polar Sport Tester heart rate recorder, Polar Electro OY, Finland), 13 skin temperatures (YSI-400 thermistors, accuracy ±0.15 °C, Yellow Spring Instruments, USA), rectal temperature (YSI-700 thermistors, accuracy ±0.15 °C, Yellow Spring Instruments, USA) and body weight before and after the experiments (Mettler ID1 Multirange, Mettler Toledo, USA). Mean skin temperature was calculated using the average of all measured skin temperatures.

2.3.2. Clothing physiological parameters

Temperature (YSI-400 thermistors, accuracy ±0.15 °C, Yellow Spring Instruments, USA) and moisture (relative humidity, RH; moisture sensors HIH-3605-B-CP, Honeywell, USA) between clothing layers, sweat accumulated in the clothing (weight increase during experiment).

2.3.3. Subjective evaluation

Thermal sensation (body, feet, hands, head, back and neck), thermal comfort, wetness of skin and clothing [8]. Ratings for thermal sensation: 0—*neutral*, 1—*slightly warm*, 2—*warm*, 3—*hot*, 4—*very hot*, 5—*extremely hot*. Ratings for thermal comfort: 0—*neutral*, 1—*comfortable*, 2—*slightly uncomfortable*, 3—*uncomfortable*, 4—*very uncomfortable*, 5—*extremely uncomfortable*. Ratings for wetness of skin and clothing: 1—*more dry than normal*, 2—*normal dryness*, 3—*chest and back slightly wet*, 4—*chest and back wet*, 5—*body wet*, 6—*body wet, clothing sticks to the skin*.

2.4. Experimental protocols

Heat balance and thermal comfort during work are affected by metabolic heat production, clothing insulation and ventilation properties as well as exposure, which is characterised by temperature, RH, radiation and relative velocity of the ambient air. The laboratory experiments were performed in a climatic chamber: temperature +40 to –30 ± 0.5 °C, 10–90 ± 5% RH, air velocity 0.3 $m \cdot s^{-1}$. Before the laboratory experiments were performed, exposure characteristics, clothing properties and work intensities (heart rate) were assessed for real work situations for the surgeon in the operating theatre during laparoscopic surgery at St. Olavs Hospital, Trondheim [7]. Heat production relevant to the actual work situation for the surgeon was achieved by walking on a treadmill (Woodway, Germany, PP55 sport-I-climate). To evaluate the well-insulated protective clothing with or without PCM (a PCM or a placebo suit, respectively), the test protocol comprised 120-min rest in a sitting position.

Before the subjects entered the climatic chamber they were fitted with clothing and equipment for measuring temperature, heart rate and moisture. In order to stabilise their temperature, they first rested in a sitting position under thermally neutral conditions for 20 min.

2.4.1. Surgery

The vest with PCM elements was put on by the subject immediately on entering the climatic chamber (air temperature 23 ºC, 50% RH, air velocity 0.3 $m \cdot s^{-1}$). The test protocol comprised 20-min moderate treadmill exercise followed by 20 min of performing different tasks relevant for laparoscopic surgery, followed by another 20-min treadmill exercise. Temperature, moisture and heart rate were recorded every minute. Subjective evaluations of thermal sensation, thermal comfort and wetness were recorded every 10 min.

2.4.2. Well-insulated protective clothing

The subjects (6 males) were dressed in the protective clothing (a placebo or a PCM suit) immediately upon entering the climatic chamber (air temperature 27 ± 0.5 ºC, 50 ± 5% RH, air velocity 1.5 $m \cdot s^{-1}$). Heat production was measured every 15 min. Temperature, RH and heart rate were recorded every minute. Subjective evaluations of thermal sensation, thermal comfort and wetness were recorded every 5 min.

2.4.3. Evaluation criteria

Before a new clothing design was chosen, a set of user requirements was established for the actual work situations. The following criteria were given high priority: (a) effective cooling, (b) freedom of movement during work, (c) sufficient moisture transport, and (d) thermal comfort.

2.5. Statistics

The clothing concepts of the operating theatre were evaluated using only 1 (in the operating theatre) or 2 (in the laboratory) subjects; statistical treatment was therefore not applicable. The effects of PCM in the well-insulated protective clothing on physiological parameters and subjective evaluations were assessed with analysis of variance (ANOVA) for repeated measures. When this analysis revealed a significant main effect (within-subjects effect) a paired *T* test was used as a post-hoc test to locate significant differences between means during the experimental period.

3. RESULTS

3.1. Surgery

A 55-year-old male surgeon was the test subject for the four experiments in the operating theatre. Table 1 shows the results of subjective evaluations of thermal comfort, thermal sensation and skin wetness. Since the clothes were evaluated during real operations, the duration of the exposures varied. The results are therefore shown only for 90 min, which was the shortest duration. Compared with regular clothing (clothing A) the subjective ratings of thermal comfort and sensation, and also skin wetness, improved when cooling vests with PCM were introduced into the clothing. While perceived skin wetness increased with time for clothing A, it was stable throughout exposure when clothing C was worn. Also values after 90-min exposure were reduced for clothing with PCM, shown by ratings 6 (*body wet, clothing sticks to the skin*, 4 (*chest and back wet)* and 3 (*chest and back slightly wet*) for clothing A, B and C, respectively.

It was apparent from the clinical trials that regular clothing generated serious discomfort related to wetness and temperature. The

TABLE 1. Subjective Evaluations* of Thermal Comfort, Thermal Sensation and Skin Wetness for a Surgeon Wearing Protective Clothing A, B, C or D. Values are Means and Standard Deviations of Measurements Made Every 10 min During the First 90 min of the Operations. Values in Parentheses Denote Ratings at 90 min

	Clothing			
Subjective Ratings	**A**	**B**	**C**	**D**
Thermal comfort	2.6 ± 1.3 (4)	2.5 ± 0.8 (3)	2.2 ± 1.3 (3)	1.0 ± 0.6 (1)
Thermal sensation	3.3 ± 0.5 (4)	2.5 ± 0.5 (3)	2.3 ± 0.5 (3)	2.0 ± 0.0 (2)
Skin wetness	4.7 ± 1.0 (6)	3.4 ± 0.5 (4)	3.0 ± 0.0 (3)	3.0 ± 0.0 (3)

Notes. *—ratings for thermal comfort: 0—*neutral*, 1—*comfortable*, 2—*slightly uncomfortable*, 3—*uncomfortable*, 4—*very uncomfortable*, 5—*extremely uncomfortable*. Ratings for thermal sensation: 0—*neutral*, 1—*slightly warm*, 2—*warm*, 3—*hot*, 4—*very hot*, 5—*extremely hot*. Ratings for wetness of skin and clothing: 1—*more dry than normal*, 2—*normal dryness*, 3—*chest and back slightly wet*, 4—*chest and back wet*, 5—*body wet*, 6—*body wet*, *clothing sticks to the skin*.

experience from the operating theatre encouraged further improvements in the use of PCM in the surgeon's protective clothing. The effect of PCM on subjective evaluations of wetness was noticeable when the commercially available cooling vest (B) and the initial experimental vest concept (C) were worn. However, the surgeon stated that vest B was not acceptable because it reduced freedom of movement and was stiff. Our challenge was to design a cooling vest in which the freedom of movement that had been achieved by vest concept C was maintained and which also contained a sufficient number of cooling elements to maintain satisfactory cooling capacity. It was also a challenge to provide spacing between the cooling elements and thus reduce the barriers to the evaporation of sweat.

Two experimental vest concepts were developed in order to evaluate the effect of the number of cooling elements and the positioning of the elements under controlled environmental conditions in the laboratory. The effects of cooling elements covering the whole trunk (vest concept α) or the upper trunk (vest concept β) were compared (Figure 2). In concept α, 14 elements were attached to the trunk, six on the front surface and eight on the back. In concept β, the elements were reduced to nine. They were attached to the upper part of the trunk, with four on the front and five on the back (Figure 2). Although mean skin temperature fell more and stayed at the lower level for a longer period when concept α was used than concept β, the subject rated thermal comfort and thermal sensation more positively for clothing β than for clothing α (results not shown). RH was 20% lower in clothing β than in α. Moreover, less sweat was produced and more sweat evaporated through clothing β than clothing α (217 and 189 g, respectively; measured as a difference between total sweat production and the amount of sweat accumulated in the clothing).

The final experimental vest concept (D, see Figure 1) was designed using a permeable,

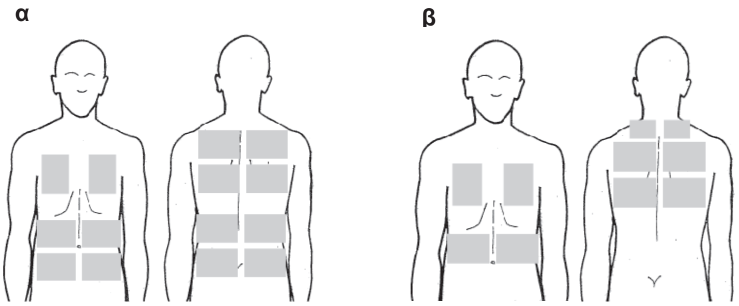

Figure 2. The two experimental cooling vests worn by the surgeon during the laboratory trials: (α) 14 cooling elements, six on the front and eight on the back, cover the whole trunk and (β) 9 elements, four on the front and five on the back, cover the upper trunk. Glauber's salt elements (Climsel C28, C31 Climatro AB, Sweden) were used as phase-change material.

thin material that facilitates heat and moisture transport. The vest was closely fitting since there were no PCM elements on the sides of the trunk, providing better freedom of movement. The elements were configured in strips, with three or four elements in a row and small spaces between them. They were positioned on areas of high thermal sensitivity and where body heat transport could be facilitated by regulating blood flow through variations in vasomotoric tonus. Clothing D was evaluated during a gastric bypass operation that lasted almost 4 hrs. After 90-min exposure perceived sweat rate was *chest and back slightly wet* (rating 3), thermal sensation was perceived as *warm* (rating 2) and thermal comfort was perceived as *comfortable* (rating 1) (Table 1).

3.2. Well-Insulated Protective Clothing

The PCM suit produced a slower rise in back skin temperatures, which were maintained at a lower value compared with the placebo suit between 20 and 40 min ($n = 6$, $p < .04$) (Figure 3). RH (back) between the woollen sweater and the suit, increased at a slower rate until 70–80 min before it increased and approached the measurements of RH for the trials with the placebo suit ($n = 6$) (Figure 4). The duration of the stable period varied between individuals. Examinations of the results from single–person measurements showed that this dynamic pattern was pronounced (Figure 5). While RH in the placebo suit rose sharply at 30 min and reached 90% at 60 min, it was fairly stable at 40% until it started to increase at 80 min and approached 90% after 120 min. Thermal sensation of the back was significantly different between the placebo suit and the PCM suit between 60 and 80 min ($n = 6$, $p < .05$) (Figure 6). Interestingly, the time course of the rise in RH between the clothing layers of the back, followed the time course of thermal sensation of the back rising from *neutral* to *warm*, for the PCM suit, both demonstrating a marked change in the rate of increase at 80 min into the trial (Figures 4, 5 and 6).

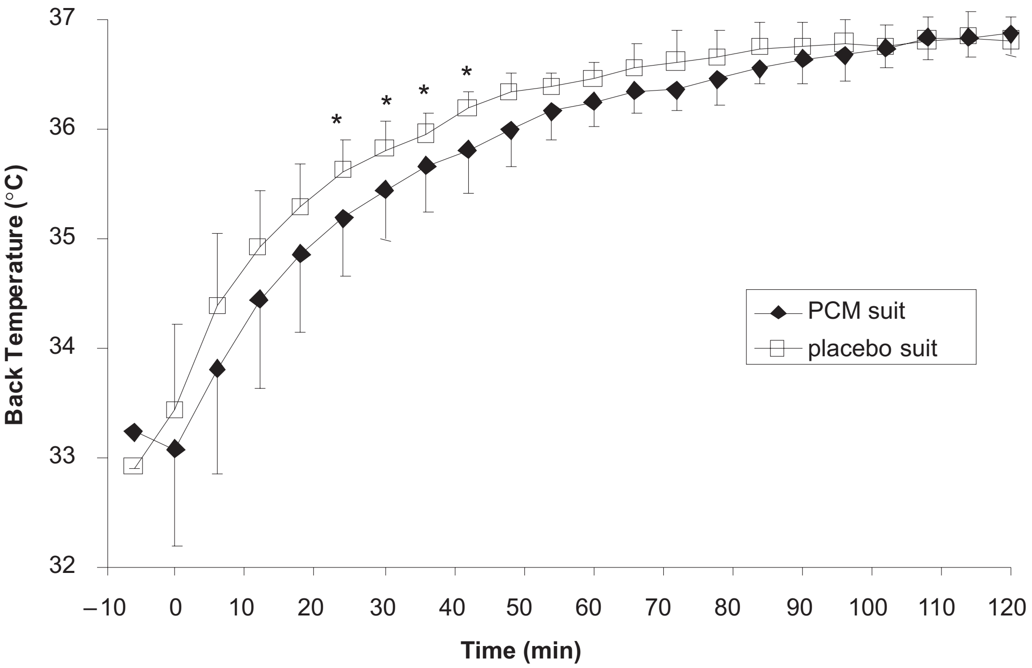

Figure 3. Time courses for skin temperatures (back) while a well-insulated phase-change material suit (filled symbols) or a placebo suit (open symbols) were worn in moderately hot conditions. The values are means (6 subjects) and standard deviations. Asterix denotes statistical differences between the two conditions ($p < .04$). Microcapsules in fabrics (Outlast® 341 Clemmons; Outlast Europe GmbH, Germany) were used as phase change material. Environmental conditions: air temperature 27 ± 0.5°C, 50 ± 5% RH, air velocity 1.5 m·s^{-1}.

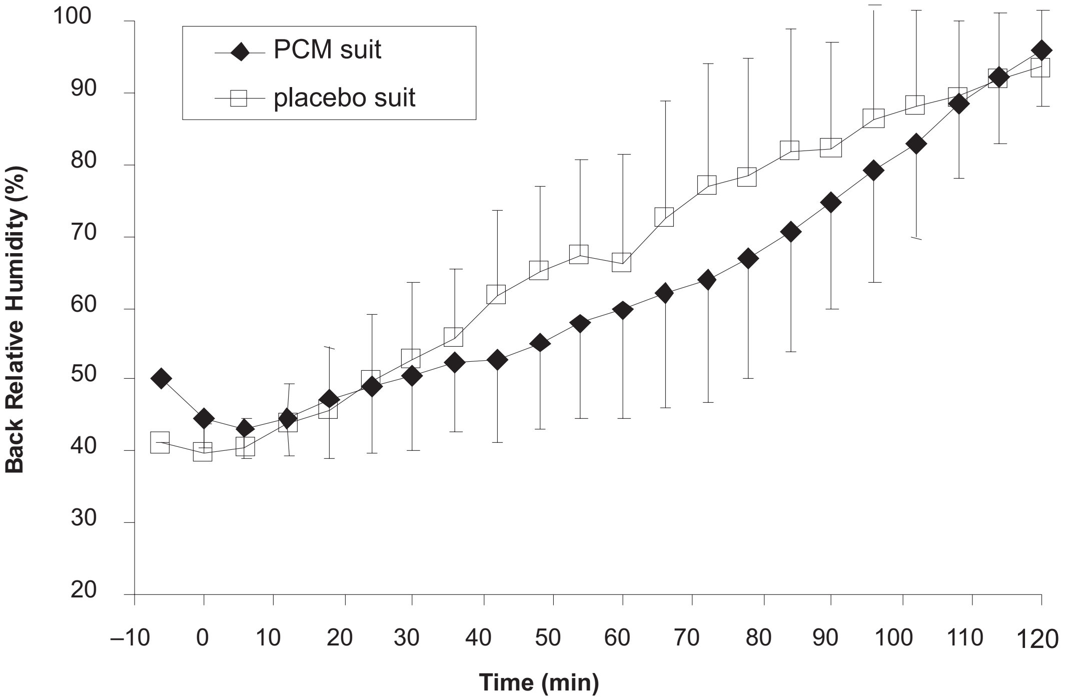

Figure 4. Time courses for relative humidity (back) while a well-insulated phase-change material suit (filled symbols) or a placebo suit (open symbols) were worn in moderately hot conditions. The values are means (6 subjects) and standard deviations. The humidity sensor was positioned between the woollen sweater and the suit. Microcapsules in fabrics (Outlast® 341 Clemmons; Outlast Europe GmbH, Germany) were used as phase-change material. Environmental conditions: air temperature 27 ± 0.5 °C, 50 ± 5% RH, air velocity 1.5 m·s^{-1}.

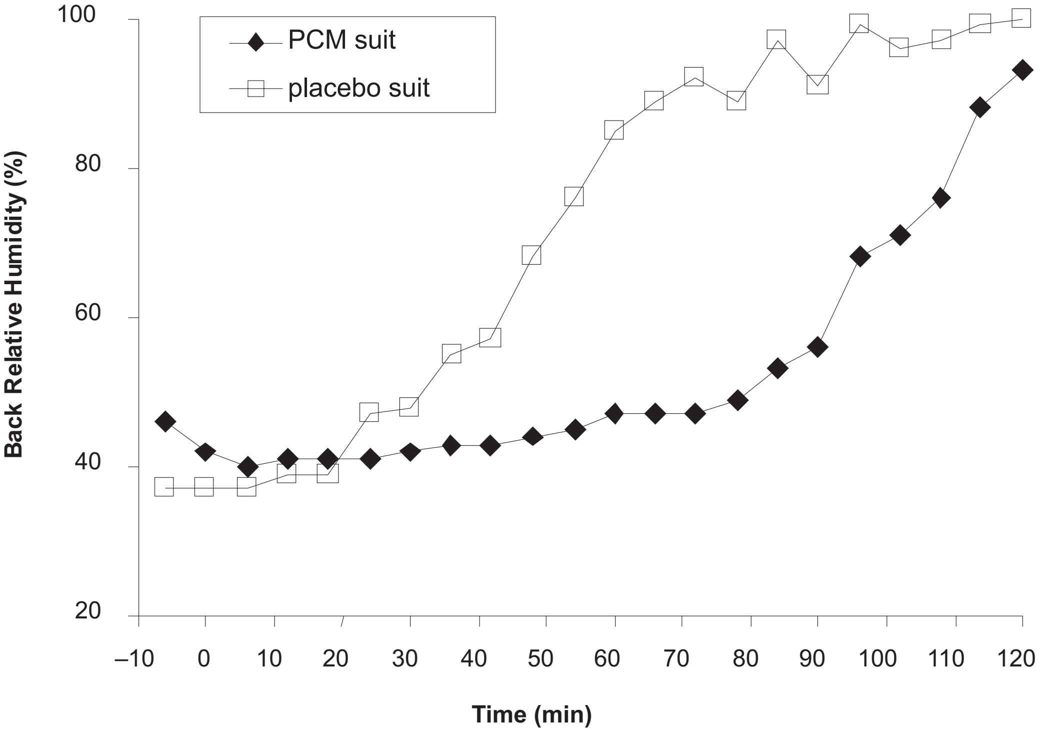

Figure 5. Time courses for relative humidity (back) while a well-insulated phase-change material suit (filled symbols) or a placebo suit (open symbols) were worn in moderately hot conditions. The values are for 1 subject. The humidity sensor was positioned between the woollen sweater and the suit. Microcapsules in fabrics (Outlast® 341 Clemmons; Outlast Europe GmbH, Germany) were used as phase-change material. Environmental conditions: air temperature 27 ± 0.5 °C, 50 ± 5% RH, air velocity 1.5 m·s^{-1}.

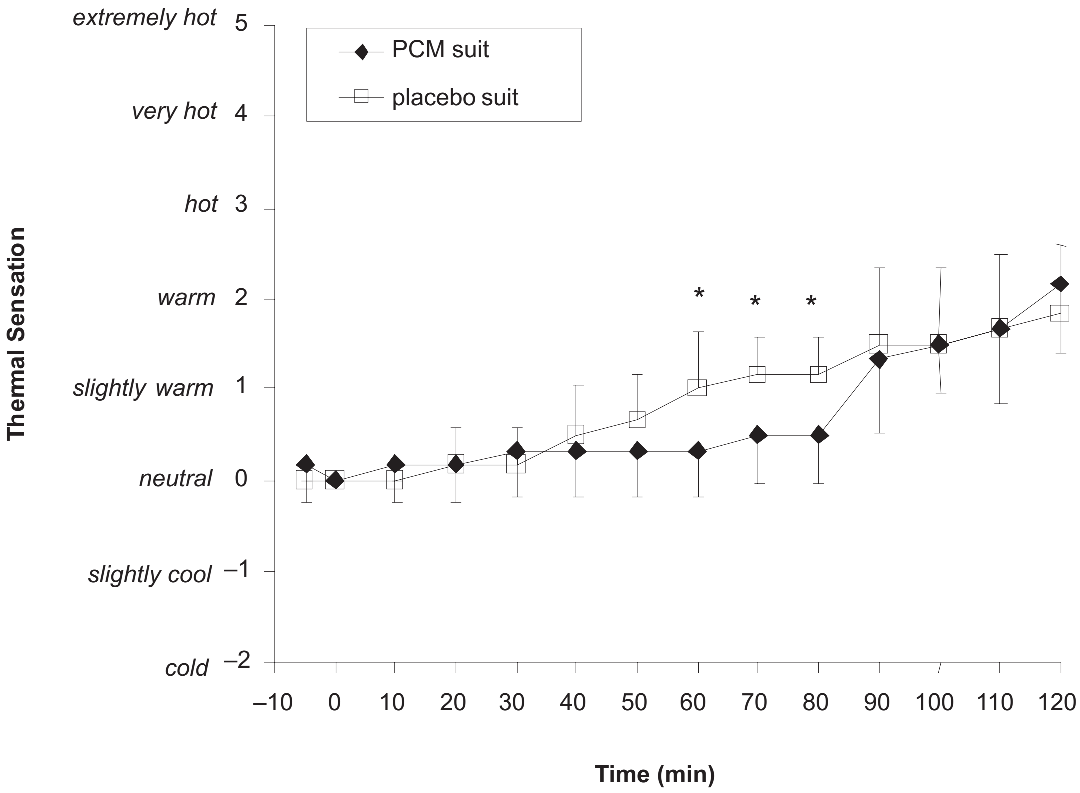

Figure 6. Time courses for subjective ratings of thermal sensation (back) while a well-insulated phase-change material suit (filled symbols) or a placebo suit (open symbols) were worn in moderately hot conditions. The values are means (6 subjects) and standard deviations. The asterisk denotes statistical differences between the two conditions ($p < .05$). Microcapsules in fabrics (Outlast® 341 Clemmons; Outlast Europe GmbH, Germany) were used as phase-change material. Environmental conditions: air temperature 27 ± 0.5 °C, 50 ± 5% RH, air velocity 1.5 m·s^{-1}.

4. DISCUSSION

We investigated the effect of two different PCM in protective clothing. We wished to study whether it would be possible to optimize cooling performance of PCM in clothing by using a design that focused on careful positioning of PCM, minimizing total insulation and facilitating moisture transport.

The final experimental cooling concept for the surgeon (C) resulted in improved subjective evaluations of perceived wetness of skin and clothing, improved thermal sensation of clothing and improved thermal comfort, compared with the surgeon's regular clothing. The trunk was cooled sufficiently to reduce the activation of sweating. The resulting improved perceived thermal comfort has also been observed in other studies that have demonstrated an inverse relationship between perception of sweatiness and thermal comfort [9, 10]. The cooling elements provided even distribution of temperature over the whole trunk, while skin temperature varied between different areas of the trunk in the regular suit. Such uniform distribution of skin temperature is perceived as more thermally comfortable than nonuniform temperature distribution [11]. The total weight of fabric and Glauber's salt elements of the final vest concept (D) was only slightly reduced compared with that of the commercially available cooling vest (B), 1.8 and 2.0 kg, respectively. Although the commercially available vest also provided improved thermal sensation and thermal comfort, the final vest concept D allowed improved moisture transport and evaporation. This was achieved through spacing between the cooling elements and the use of materials with improved moisture permeability. The design provided a close fit between the cooling elements and the skin in order to facilitate heat transport. A recent study has also demonstrated the significance of fit on the effect of cooling garments [12].

Since the cooling capacity of Outlast® used in the PCM suit was only 30% of that of Glauber's salt, it was of great importance to be aware of body areas with high thermal sensitivity, great potential for heat exchange through adjustments of vasoconstriction and vasodilatation, and sweat production. Selected areas of the back represent such body areas [13]. The results as regards back skin temperature, RH in the clothing and subjective evaluations of the thermal sensation of the back, all demonstrate an effect of the PCM. The lowering of back skin temperature may have delayed skin-temperature-dependent afferent inputs to evoke thermal sweating as indicated by the lower values of RH measured in the back of the PCM suit, resulting in significantly better ratings of thermal sensation for the PCM suit. Typically, subjective evaluations of thermal sensation remain stable throughout the period of phase change of the material, and this is reflected by the stable periods seen in measurements of RH. It is evident that the capacity of the PCM employed in the PCM suit is not sufficient for a warming period of 2 hrs under these conditions. For ergonomic reasons, it is not desirable to add more material into the suit; therefore we see a clear need for a more efficient textile-based PCM.

5. CONCLUSION

The results from the field and laboratory experiments were conclusive in that reduced thermal stress and improved thermal comfort were related to the amount and distribution of PCM, reduced sweat production and adequate transport of moisture to the outer clothing shell. The subjects rated the lowering of skin temperatures positively, even though body core temperature did not fall.

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