EFFICACY OF A NOVEL PHASE CHANGE MATERIAL FOR MICROCLIMATE BODY COOLING

by

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The present study was conducted in order to evaluate the efficiency of personal body microclimate cooling systems based on a phase change materials and its effects on physiological strain in soldiers during exertional heat stress in hot environment. The results are obtained in the experiment conducted in the climatic chamber in the Institute of Hygiene, Military Medical Academy in Belgrade. Ten male soldiers were voluntarily subjected to exertional heat stress tests consisted of walking on treadmill (5.5 km/h) in hot conditions (40 °C) in climatic chamber. The subjects performed first test while wearing a field camouflage uniform without any cooling system (CONTROL group) and in second test they used additional microclimate cooling system with paraffin wax consist of n-hexadecane ($C_{16}H_{34}$), in a form of cooling packs (COOL group). As indicators of thermal strain, mean skin (T_{sk}) and tympanic (T_{ty}) temperature were determined. Simultaneously, thermal effects of phase change materials were measured by thermal imaging camera. The exercise in hot conditions induced a physiological response to heat stress, manifested through increased body core and skin temperatures. The results confirmed that the cooling vest worn over the field uniform was able to attenuate the physiological strain during exercise, compared to the identical exposure in the "control" group. The results of thermal imaging also indicate that heat generated inside the body is the main factor that will affect the phase change material melting time.

Key words: *phase change material, cooling vest, heat stress, thermal comfort, infrared thermography*

Introduction

The accumulation of heat, reflected by peripheral and core body temperature, occurs during heavy physical exertion, or exposure to warm and humid environment. Long-term accumulation of heat in a quantity of about 0.5 W/kg up to 2 hours, leads to an increase in body temperature that some people are unable to tolerate [1]. Heat stress may be compensated and uncompensated. Compensated heat stress (CHS) occurs when the heat loss is in balance with its production. Hence, it is possible to reach core temperature equilibrium (steady-state) at given

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physical activity. CHS is usually present in most of the activities related to the implementation of dedicated military tasks. Uncompensated heat stress (UCHS) occurs when demands for disclosure of heat (sweat evaporation) overcome the evaporative capacity of the environment. During uncompensed heat stress, the body cannot achieve steady state core temperature, so it rises until it reaches physiological limits. Heat exhaustion in terms UCHS occurs at relatively low value of core temperature. In cases of inadequate cooling (caused by insufficient evaporation of sweat), skin temperature remains high. Bloodstream is relocated to expanded skin vascular compartment in order to remove the heat from inside the body, which reduces the minute volume and increases heart rate. UCHS extremely reduces physical performance, so these conditions demand special regimes of work and rest cycles, with the use of active cooling during breaks [2].

Contemporary military activities request the best possible physiological comfort of soldiers. Considering this, different systems for body cooling have been developed so far, with a main purpose to increase comfort as well as to reduce thermal stress. Military applications of cooling systems bring numerous additional benefits, such as increased mission duration, decrease in hydration needs, improved mental acuity and maintained physical performance. Generally, cooling systems can be classified in five basic groups: evaporative cooling products, products based on phase change materials (PCM), compressed air systems, liquid circulation systems, and thermoelectric systems [3]. The application of particular cooling system type depends of many factors, such as cooling garment weight, readiness, cooling capacity, heat removal rate, compatibility, possibility for the monitoring and control by the wearer, environmental conditions, durability, and portability [4].

Video thermography techniques have actual and different interests in applications [5-11]. In our study, thermography is used to confirm the effectiveness of body cooling materials and experimental results obtained by medical acquisition devices. The focus of this survey was to investigate the efficiency of the cooling vest based on organic PCM cooling packs, combined with field uniform, on physiological strain during physical effort in hot environment. Experimental design was chosen to test the effectiveness of cooling vest, on heat stress indicators (body core and skin temperature) monitored by medical devices, as well as changes in temperature of the PCM cooling packs, measured by IR thermal imaging camera.

A number of studies dealing with the PCM application for various purposes, including in the body cooling systems, have been conducted so far. In the most studies, authors used thermal mannequins instead of human test subjects. This paper use novel and specific approach based precisely on volunteer's engagement, choosing specific type of PCM with a low melting point and application of the both methods – psychological measurements and IR recording simultaneously. Also, the study results can be useful for the further investigations of organic PCM applications in the body microclimate systems.

Experimental methods, equipment, and procedures

Subjects

The participants enrolled in this examination were 10 male soldiers (25.8 ± 2.4 years), with similar anthropometric characteristics (72 ± 10 kg, 182 ± 8 cm). Each participant read and signed an informed consent form, in accordance to standards of medical safety during examination in extreme hot or cold environment [12]. Procedures used in this study were approved by Ethical Committee in the Military Medical Academy, and correspond to the standards of thermal strain evaluation by psychological measurements [13].

In this study, experimental design based on exertional heat stress test protocol [14] was used. The investigation was conducted in climatic chamber in the Institute of Hygiene, Military Medical Academy in Belgrade, in the period from May to September 2011.

Thermal properties of the PCM in cooling vest

The cooling system tested in this study is based on usage of 4 two-parts '"cooling packs", inserted into specially designed pockets inside the vest. Cooling packs have special ability to melt on 18 °C, which automatically allows them to absorb excess body heat. Garment is designed to prevent the physiological rise of wearer's core temperature in respond to physical activity and/or exposure to heated environments. Cooling packs have to be removed from packaging material and either submerged completely in ice water for 20 minutes or placed flat without stacking in a freezer for about one hour. Fully charged (completely solid) packs, then should be inserted into garment internal pockets.

Table 1. Physical and thermal phase change properties of *n*-hexadecane

Thermo-physical properties	Value
Molecular formula	$C_{16}H_{34}$
Molar mass, [gmol^{-1}]	226.44
Melting point (T_m), [°C]	18.2
Boiling point, [°C]	287
Vapor pressure (Pa), at 105.3 °C	100
Latent heat of fusion, [kJkg^{-1}]	237,1
Density [gmol^{-1}], at 20 °C	0.77344
Thermal conductivity, [Wm^{-1}K^{-1}], at 30 °C	0,15
Latent heat of adsorption (DH), [Jg^{-1}]	235,2
Latent heat of emission (–DH), [Jg^{-1}]	236,6

Cooling packs are filled with alkane *n*-hexadecane ($C_{16}H_{34}$), paraffin wax compound, with characteristics of organic phase change material. Paraffins are considered as materials with strong heat storage capacity. They are also safe, not expensive and non corrosive. In our study, this type of paraffin was chosen for its high latent heat value, non-toxic characteristics and affordable price. General properties of *n*-hexadecane are given in tab. 1.

When the melting temperature of a PCM is reached during heating process, the material change its phase from solid to liquid. Typical differential scanning calorimetry (DSC) heating thermogram for *n*-hexadecane melting is schematically shown in fig. 1.

During this phase change, the PCM absorbs large quantities of latent heat from the surrounding area. The phase transition of *n*-hexadecane occurs between initial (T_{ip}) and final (T_{if}) melting point, while the corresponding latent heat of fusion is about 237 kJ/kg.

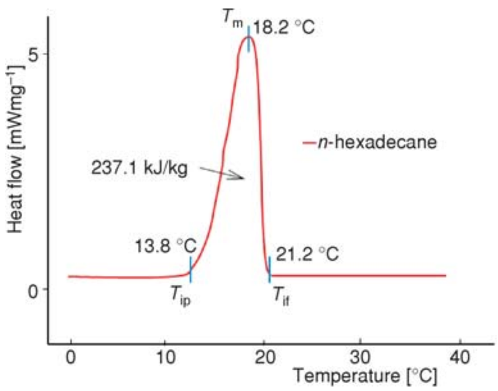

Figure 1. DSC heating thermogram of *n*-hexadecane

Clothing

During EHST, participants were dressed in standard combat uniform model M10 (boots, trousers, and shirt). Shirts are made of 67% cotton and 33% polyester fabric, 150 g/m^2

surface mass (±5%), with combed cotton yarn fineness of 20 tex in "right-left" interplacement. Surface mass of the knits with 8.5% humidity was 140 g/m^2 (± 5%). During EHST, participants wore the same type of underwear made of 100% cotton. All uniform parts have waterproof protection. The components of the uniform are made to protect the user from high temperatures up to +50 °C.

Experimental protocol

Each subject performed two tests. In both tests they were dressed in uniform, with and without cooling vest over it. Tests were performed under the same climatic conditions (air temperature 40 °C, relative humidity 58%, wind speed < 0,3 m/s). Maximal duration of test was initially limited on 45 minutes. Criteria for early termination were: achieving critical value of tympanic temperature (39 °C), or heart rate (190 bpm), or participant's subjective feeling of unbearable effort.

Skin and core temperatures were automatically monitored and recorded in real-time by physiological data monitoring system (Biopac Systems, Inc. USA) [15, 16]. System consists of MP150 acquisition unit, universal interface module (UIM100C) and four skin temperature amplifier modules (SKT 100C), single channel, with additional amplifier designed especially for core temperature monitoring. The UIM100C Universal Interface Module is the interface between the MP150/100 and external devices, while SKT100C employs the BIOPAC TSD202 series thermistor transducers (TSD202A and TSD202E type) for measuring tympanic and skin temperature [16]. The heart rate was monitored and recorded telemetrically (Quinton Instruments, USA).

Figure 2. Application of IR thermography with camera FLIR SC620

Concurrently with measuring of the thermal strain parameters, exercises on treadmill were discontinuously recorded by thermal imaging camera FLIR SC620 (fig. 2). High-quality pictures were produced using detector type focal plane area (FPA). The camera scans the field of view $24^{\circ} \times 18^{\circ}$, on the minimum focus distance of 0.3 m, with the current field of view IFOV (spatial resolution) 0.65 mrad. Thermal resolution is 0.04 °C (thermal sensitivity) at 30 ºC.

Footage analysis of the efficiency of cooling system is based on thermal imaging display of hot and cold zones on the vest and the torso area. The mean values of the surface temperature on four cooling packs filled with *n*-hexadecane were calculated in the 5th, 25th, and 45th minute of the EHST (AR01, AR02, AR03, and AR04), as well as skin temperature on the neck (SP01), the front of the right forearm (SP02) and left forearm (SP03).

Data are presented as mean values and standard deviations (±SD). Normal distribution was tested by Shapiro-Vilk's test. The differences between "cooling" and "control" groups were tested by Student's t-test. SPSS 17.0 was used to process statistical material and the 0.05 level of significance was used.

Measurement of body core and skin temperature

As a measure of core temperature, we used the temperature of tympanic membrane (eardrum), whose vascularisation is delivered in part by the internal carotid artery, which also supplies the hypothalamus. Thermal inertia of the eardrum is very low, due to its low mass and high vascularity; hence its temperature reflects the variations in arterial blood temperature, which influences the thermoregulation centers [13]. Tympanic temperature was measured by introducing TSD202A thermo-element into the auditive channel and placing it as close as possible to the eardrum. Tympanic temperature was measured continually, with data recording every 10 seconds.

Skin temperature varies widely over the body surface, especially in extreme ambiental conditions. Skin temperature results from thermal exchange by conduction, convection, radiation, and evaporation at the surface of the skin, but also depends on the intensity of skin blood flow and the temperature of the arterial blood reaching the particular part of the body [13].

In warm and hot environments (with the exception of intensive asymmetrical radiation heat source), local skin temperatures tend to be homogenous, so few measuring points may be used with accuracy [13]. Regarding this fact, we selected four measuring points, and calculated mean skin temperature according to their weighted values [13]. Local skin temperatures were continually measured, using transducer probe type TSD202E.

Subjective assessment of the comfort level was rated by each subject, using the scale of perceived exertion (RPE). Values in this scale range from 1 to 7, where 1 denotes "comfortable" and 7 denotes "extremely intolerable hot". The subjects were asked to point on the scale their subjective assessment every 5 minutes during the EHST.

Results and discussion

During EHST, not one participant showed any symptom of the heat stroke, or any disturbance related to serious type of heat illness. Tests lasted maximally 45 minutes, with the only 3 recorded cases of early completion, due to subjective report of intolerable effort (RPE level 7). There were no cases of early termination due to achieving limit values of tympanic temperature (39 °C) or heart rate (190 bpm).

Tympanic temperature

Comparable reviews of tympanic temperature values with a cooling system and without it are displayed in fig. 3.

The mean tympanic temperatures at the end of EHST (45th minute) in "control" group varied from 36.8 °C to 38.46 °C. In "cool" group, around the 15th minute temperature began to grow noticeably slower, so in 25th minute was lower by 0.49 ± 0.02 °C. Maximum diference of 0.81 ± 0.04 °C was recorded at the end of EHST ($p < 0.05$).

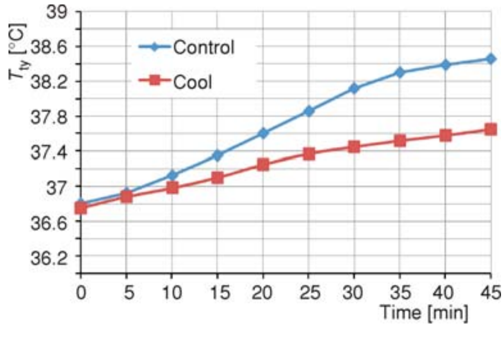

Figure 3. Mean tympanic temperatures during EHST in both groups

Body skin temperature

Figure 4. presents the changes in T_{sk} during EHST, with a cooling system and without it.

Body skin temperatures similarly increased in both groups, much faster in the first 15 minutes, then with slower rate. Maximum value of T_{sk} was achieved in 45th minute (36.41 ± 0.18 °C and 35.78 ± 0.14 °C in CONTROL and COOL group, respectively).

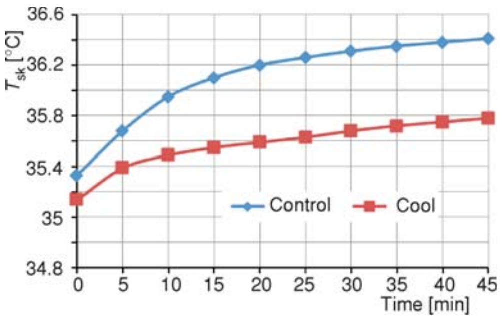

Figure 4. Mean body skin temperatures during EHST in both groups

At the two measuring points in the torso area (neck and scapula), significantly lower values of skin temperature were observed in COOL group compared to CONTROL group (1.12 ± 0.08 °C), as a direct consequence of cooling vest effects. Measured values of T_{sk} at the other two points (shin and hand) did not differ significantly between groups, as expected ($p > 0.05$).

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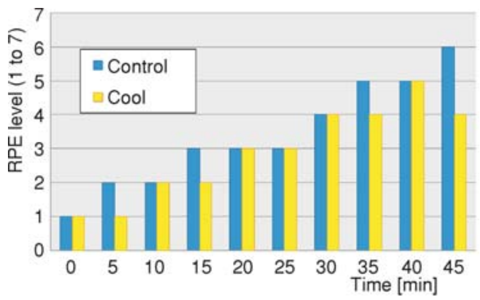

Figure 5. Comparison of the subjective assessment of the comfort level during EHST in both groups

Subjective assessment of comfort

For the most of the EHST duration, participants in COOL group reported less subjective discomfort by 1-2 grades then in CONTROL group. Subjective assessments of the comfort level during EHST, with cooling vest and without it, are showed in fig. 5.

IR camera measurements

The mean temperature on the PCM cooling packs surface measured by IR camera showed an upward trend from the beginning to the end of the test (fig. 6). Between the 5[th] and 25[th] minutes the temperature increased by 1.4 °C, while at the end of the test was 1.97 °C higher than at the beginning.

Increasing the temperature of PCM cooling packs is caused by the absorption of heat from the body. From the data obtained by thermal imager it can be concluded that the efficiency

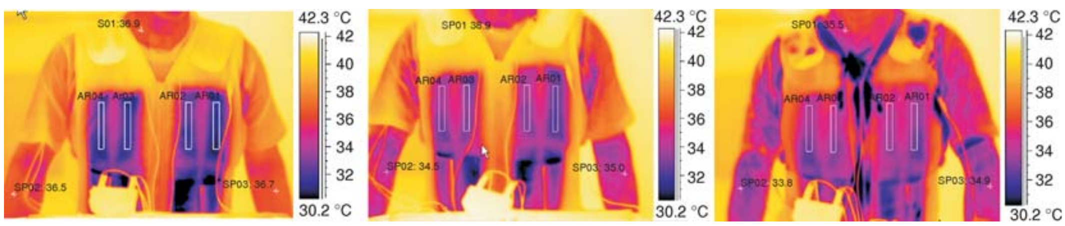

Figure 6. Vest snapshots recorded with IR camera in 5[th], 20[th], and 45[th] minutes of exercise

of PCM was the most pronounced in the first half of EHST, when the melting process was conducted much faster (fig. 7). Towards the end of EHST, the PCM capacity became reduced, and it can no longer maintain its temperature while storing the excess heat. Cooling packs should be removed for regeneration once they are 90% or more clear liquid.

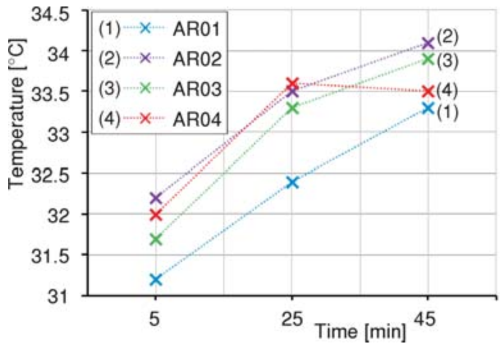

Figure 7. Mean temperatures of the PCM cooling packs surface during EHST

Data collected by measurements of physiological heat stress parameters (T_{ty}, T_{sk}, RPE), and data obtained by IR imaging are compatible and point to several key conclusions. Capacity of the paraffin based PCM, in this case *n*-hexadecane, to reduce user's body core temperature during heat stress has been experimentally proven. In the extreme test conditions (air temperature of 40 °C with intensive physical exertion), the effect of *n*-hexadecane did not last long. This can be explained by the *n*-hexadecane thermal properties (tab. 1) particularly its melting point of 18 °C. If there is a need for cooling during prolonged exposure, usage of PCM types with higher melting point (*e. g*. 30 °C) would be more efficient.

In the previous study, Jovanovic and coworkers investigated efficiency of cooling systems based on different types of PCM [17] . Among other, they used PCM "PhaseCore elements", installed into special vest pockets, which provide a cooling effect to the body's core by absorbing body heat. PhaseCore elements (salt mixture sealed inside an aluminum wrapper), have an activation point of 28 °C, much higher than *n*-hexadecane. The results showed that this type of PCM, compared to *n*-hexadecane, is less effective in absolute terms of attenuation the increased core temperature, but active time in reducing body temperature is significantly longer (for 15-20 min), under the same experimental conditions.

Many other studies also confirmed that cooling efficiency depends on the selected type of PCM and its thermal properties. Sharma *et al*. [18] found that use of a latent heat storage system based on phase change materials represents an effective way of storing thermal energy and has the advantages of high-energy storage density and the isothermal nature of the storage process. Mondal [19] evaluated concept of thermal comfort and working principle of the several PCM groups (hydrated inorganic salt, polyethylene glycol, fatty acids and their binary mixtures). He also explained phase change process with the liquid-solid phase diagram of the tetradecane C14H30 – hexadecane C16H34 binary mixtures system. The experimental studies conducted by Shen and Tan [20] have proved feasibity of using paraffin with 20 carbon atoms (*n*-eicosane) as PCM for application in thermal control of mobile devices.

Our results are consistent with the study of Fok *et al.* [21] who carried out the investigation of similar type of PCM (*n*-octadecane) to cool a motorcycle helmet. Paper presents the experimental investigations on the influence of the simulated solar radiation, wind speed, and heat generation rate on the cooling system. The results show that helmet cooled with the phase change material provide prolonged thermal comfort period compared to a normal helmet. Their findings also indicate that the heat generation from the head is the predominant factor affecting the PCM's melting time.

Some other authors used the same methodology to investigate effects of a cooling system with different functional principle. Bansevicius *et al*. [22] investigated body cooling system based on thermoelectric cooling method. They found that the most suitable cooling method is Peltier effect, considering its reliability, "green" technology, the absence of mechanical devices and possibility to use the same system for heating. Hadid and Yanovich [23] tested effects of the cooling system based on air circulation on exertional heat stress in soldiers. In this study, conducted by the same methodology, cooling was provided by personal ambient ventilation system worn under the ballistic vest. Twelve male volunteers were exposed to climatic conditions of 40 °C and 35 °C during a 115 min exercise routine, followed by 70 min resting recovery, while wearing a battle dress uniform and a ballistic vest, with cooling system and without it. Generally, in both climates, use of the cooling system reduced the physiological strain caused by physical exertion, with significant benefits in nearly all of the physiological parameters that were tested. McLellan [24] obtained similar results exploring the efficacy of an air-cooling vest to reduce thermal strain for Light Armour Vehicle (LAV) personnel. When cooling was provided, the rise in rectal temperature was minimal throughout the heat stress. It was concluded that micro-climate conditioning was an effective way to reduce the thermal strain of LAV crew.

Conclusions

Methodology used in this study and experimental protocols were carried out in accordance with contemporary standards in area of thermal strain evaluation by physiological measurements (ISO 9886), with respect to prescribed measures of medical supervision of subjects exposed to extreme hot environment (ISO 12894). At the same time, we used the results obtained by IR thermography. The results of physiological strain monitoring confirmed that body core temperature (measured as tympanic temperature) grew slower, and mean skin temperature remained lower during tests performed with cooling vests, compared to control conditions. Moreover, subjective assessment of comfort levels indicates better physiological suitability, which is very important result from the aspect of confidence and efficiency in fulfilling the given military missions. Results obtained by IR camera confirmed efficiency of the PCM contained paraffin wax in a limited time of exposure. Despite the good thermal conductivity, efficiency of the *n*-hexadecane during prolonged exposure was diminished by lower melting point compared to other types of PCM. Both methods show that higher body heat generation rate will shorten the PCM melting time. Considering the above, our results may be useful for further research activities related to PCM and its application in other areas.

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