EFFECTS OF TEMPERATURE GRADIENT ON COOLING EFFECTIVENESS OF PCM VESTS IN AN EXTREMELY HOT CLIMATE

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INTRODUCTION

When exposed to extremely hot environments combined with physical work and thick protective clothes such as fire fighting and military drills, human body may suffer thermal physiological strain resulting in reduced working performance, and increased risk of heat illness since the only way of heat dissipation from the body by evaporation is severely resisted by the multi-layer clothing (Holmér et al 2006). One of the measures to reduce such adverse effects and increase work performance is to use personal cooling equipment to improve the microclimate around human body.

Passive cooling systems apply phase change materials (PCM), e.g., ice, frozen gel, salt, wax, etc. (Bennett et al 1995, Webster et al 2005, Carter et al 2007, Reinertsen et al 2008, Choi et al 2008, Chou et al 2008) in the vest and clothing. Using passive methods are more flexible and convenient to carry out tasks. Microcapsules of PCMs in clothing have been reported to provide a small, temporal heating/cooling effect during environmental transients between warm and cold chambers (Shim et al 2001). Frozen gel was tested by Pimental et al (1992), Bennett et al (1995), and Choi et al (2008) as being effective in reducing thermal strain. Gelled coolants in ice vests were studied by Webster et al (2005) worn prior to and after exercise in the heat (37 °C and 50% RH) as being able to enhance endurance and reduce heat strain of athletes. Ice and frozen gel vests need a cold environment for storage and transport. The usage of salt vests, on the other hand, is more practical.

Our previous studies have shown that PCM (mainly sodium sulphate, melting at 28 °C) cooling vest have effects both on manikins and on subjects (Gao et al, 2007, Gao et al, 2009). However, Carter et al (2007) has reported that the similar vest does not have cooling effects on core, mean skin, and even local scapular skin temperatures during and at the end of fire fighting. Many factors affect the cooling rate and cooling efficiency of a PCM cooling device. The effects of different skin temperature and temperature gradient (between skin temperature and PCM melting temperature) might have been the factors that are accountable for the insufficient cooling effects (Gao et al, 2009). The majority of the simulated environment in previous studies on the cooling effect of personal cooling equipment in heat was at about 30-37 °C (e.g. Bennett eat al 1995, Webster et al 2005, Choi et al 2008, Chou et al 2008). However, the cooling effect of salt based PCM vests in a more extremely hot environment has only been recently studied by Carter et al (2007) at air temperature 170 °C in a firehouse, and found no effect on heat strain. Little research has been carried out on the effects of temperature gradient on the PCM cooling effectiveness on subjects.

The objective of this study was to investigate if the effect of temperature gradient on the cooling rate of PCM vests at two melting temperatures (24 and 28 °C) observed on the thermal manikin could be validated on human subjects in extreme heat.

METHODS

PCM cooling vests

The cooling vest is made of polyester and separate pockets containing 21 PCM packs. The PCMs are patented products. The main ingredients are salt mixtures including sodium sulphate and water (sodium sulphate decahydrate $Na_2SO_4 \cdot 10H_2O$ known as Glauber's salt), and additives. In this study, PCMs tested were with two melting temperatures 24, and 28 °C, which are also referred to as vest24 and vest28, representing two levels of latent heat of fusion 108.0, and 126.0 J/g respectively. Before and after the tests, the vests were kept at 20 °C overnight for solidifying and preparing for re-use. The weight of PCM in the vests was 1734 and 1743 g respectively. The total weight of the vest was about two kilograms.

Clothing

Clothing and equipment worn by the subjects were Swedish RB90 fire fighting ensembles. These include T-shirt, briefs, RB90 underwear and outerwear, socks, safety boots, gloves, and equipment (pulse belt and watch, skin and rectal temperature sensors, helmet, mask, self-contained breathing apparatus). The cooling vest was worn between T-shirt and RB90 underwear. Total weight of clothes and equipment (with vest) was 22 kg. Thermal insulation without the vest was 2.78 clo (0.431 m^2 ºC/W).

Subjects

Six healthy male fire fighting trainees volunteered to participate in the study. A briefing was given and a written consent was obtained before they participated in the experiments. Their average age was (mean±SD) 29.8±8.1 years old, height 1.78±0.05 m, weight 79.7±9.8 kg. Each subject performed each test condition (control, vest24 and vest28) on a separate day. They were asked not to drink alcohol 24 hours before the experiment, not to smoke, eat and drink tea or coffee for at least 2 hours before the experiment. The test order was fully randomized. One of the subjects did an extra baseline test at 20 ºC with all other variables being kept the same. The same subject also did a two-bout test at 55 ºC with 35 min resting at 20 ºC in-between to simulate a different fire fighting scenario, and to check if rectal temperature can be recovered before the 2nd bout and if the rectal temperature still increases during the 2nd resting period as observed in previous studies (Holmér et al, 2006, Gao et al, 2007).

Experimental procedure

The procedure followed the study by Holmér et al (2006). The rectal temperature (T_{rec}) sensor was inserted by the subjects at a depth of 10 cm behind the anal sphincter. Skin temperature (T_{sk}) sensors were taped on forehead and left side chest, scapula, forearm, thigh and calf. After preparation, the subject cycled on a cycle ergometer at 50 W for 20 minutes at room temperature to simulate preparation work and to warm up before smoke diving. T_{rec} and T_{sk} were recorded by a Labview program at 15 seconds interval. After cycling, the subject was equipped with compressed air apparatus and gloves, and entered the climatic chamber (T_a=55 °C, RH=30%, P_a=4 725 Pa, and v_a=0.4 m/s), and walked on the treadmill (5 km/h). Mean skin temperature ($\overline{T_{sk}}$)

was calculated according to modified equation ($\overline{T_{sk}}$ = 0.07$T_{forehead}$ + 0.175($T_{scapula}$ + T_{chest}) + 0.19 ($T_{forearm}$ + T_{thigh}) + 0.2T_{calf}). Mean torso temperature was calculated according to formula (T_{torso}= 0.5T_{chest} + 0.5$T_{scapula}$).

Criteria to terminate the heat exposure were when: 1) 30 minutes of heat exposure was reached, 2) subjects felt the condition was intolerable and wanted to quit, 3) T_{rec} reached 39.0 °C, 4) test leader decided to terminate the exposure based on the observation of the subject. After the exposure the subject was sitting and resting on a chair simulating real work situations until the rectal temperature started dropping.

RESULTS

Local cooling effect on torso skin temperature

The alleviation of the local skin (torso) temperature increase is most effective as shown in Figure 1. When the ambient air temperature was 55 °C, the torso (chest and scapula) temperature reached 39.8 °C at the end of the test without the cooling vest, whilst it was 36.8 and 37.1 °C when worn the vest28 and 24 respectively. The torso temperature was about 3 °C lower at the termination of the tests with vests than that without vest. The difference among the three conditions is statistically significant ($F=16.6$, $p<0.01$). The cooling effect of vest24 is stronger than that of vest28, which largely mirrors and validates the results observed on the manikin tests (Gao et al, 2009). Without the vests, the torso temperature increased linearly and sharply with the time of the exposure and exercise in the extreme heat. With the vests, however, the temperature increase was significantly attenuated throughout the whole period, so that at the termination of the exposure, torso temperature stayed at the same level as in the baseline test at 20 °C (Fig. 1).

There are also pre-cooling effects on the torso as shown in Fig. 1 in the preparation period (about 5-10 minutes), which can be clearly seen when comparing with baseline level at 20 °C. Frozen gel vests (807 g) have shown to reduce abdomen skin temperature to 1 °C during two hours simulated red pepper harvest work at WBGT 33 °C and relative humidity 65% (Choi et al 2008). However, it is surprising to notice that the study by Carter et al (2007) did not show significant alleviations of core, mean skin, and local scapular skin temperature using similar PCM vests during and at the end of simulated fire fighting, although there was a trend of local temperature reduction, which might be explained by the fact that, in this study, the heat stress was higher, the total exposure time was longer and skin temperature rise was greater at the end of heat exposure. As a result, the temperature gradient between subject's skin and PCM melting temperature was greater and therefore more effective.

Rectal temperature increase and recovery

The rectal temperature changes at the end of heat exposure were not statistically significant among the three conditions ($F=2.18$, $p>0.05$). However, after the termination of the heat exposure and physical activity, T_{rec} was still increasing for 10~13 minutes during resting and recovery phase in the room temperature environment. The peak rise without the cooling vests compared to the start of cycling reached up to 2.5 °C, then gradually dropping. The average peak rectal temperature without the cooling vests reached about 39.7 °C, whilst with vests reached about 39.3 °C during recovery. The peak rectal temperature during recovery was statistically different among the three conditions (F=6.06, p=0.01). Nevertheless it was not significantly different between the two conditions with the cooling vests.

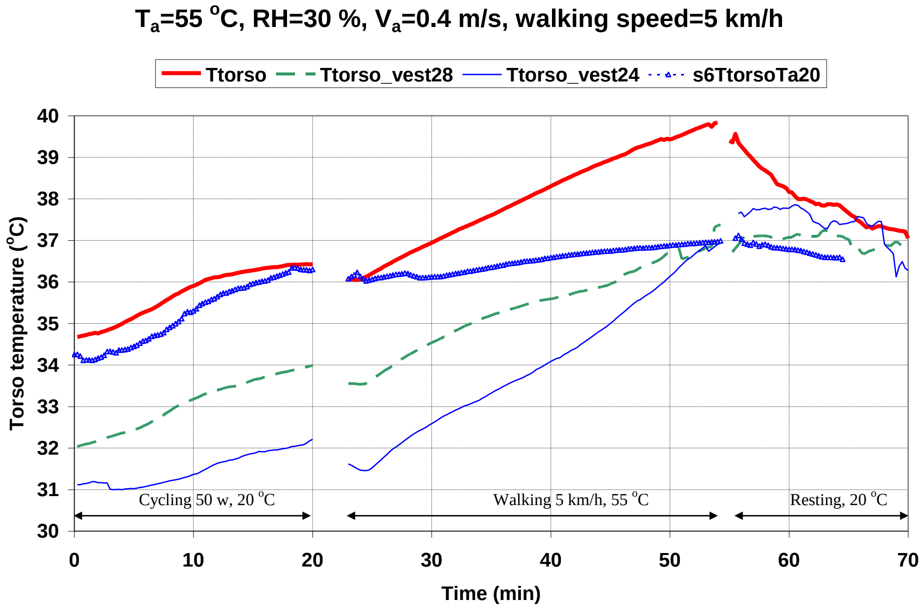

Figure 1. The cooling effects of the vest28 and 24 on the torso (chest and scapula) skin temperature and the torso skin temperature in the baseline test at 20 °C.

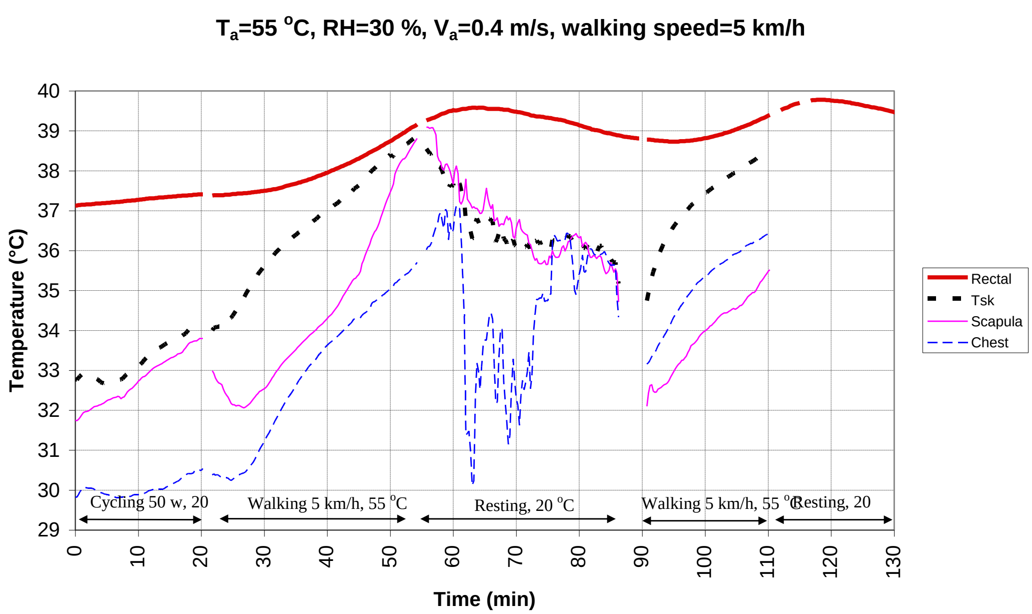

Figure 2. Chest, scapula, mean skin and rectal temperatures in the two-bout test

Two-bout test

The chest, scapula, mean skin and rectal temperatures in the two-bout test of one subject are shown in Fig. 2. The subject wore vest24 in the 1st exposure and the vest with 13 packs of

PCM24 and 8 packs of PCM28 in the 2nd exposure. The chest and scapula skin temperature increases were attenuated by the vest and therefore were lower than the mean skin temperature. After the 1st resting period (about 35 min), both mean skin (35.2 °C) and rectal temperature (38.8 °C) were not fully recovered to the level at the start (32.9 and 37.1 °C respectively). The peak rectal temperature during the 2nd resting period was even higher than that in the 1st resting period. Caution should be taken when planning a second bout in fire fighting. Further studies with more subjects are needed.

CONCLUSIONS

The PCM vest with lower melting temperature (24 °C) has stronger and faster cooling effect on the torso than that with higher melting temperature (28 °C). Vest24 produced more effective local cooling due to a higher temperature gradient. However, the cooling duration is shorter, which is determined by PCM mass and the total latent heat. In order to achieve a more effective cooling effect, temperature gradient is more critical than mass and total latent heat when choosing a personal PCM cooling product.

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