Eur J Appl Physiol (2008) 104:369–374
DOI 10.1007/s00421-007-0665-7

ORIGINAL ARTICLE

Physiological and subjective responses to cooling devices on firefighting protective clothing

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Accepted: 20 December 2007 / Published online: 8 February 2008

Abstract The aim of the present study was to examine the effectiveness of ice-packs (ICE) and phase change material (PCM) cooling devices in reducing physiological load based on subjects' physiological and subjective responses while the subjects exercised on a bicycle ergometer while wearing firefighting protective clothing in a relatively high temperature environment (30°C, 50%RH). Subjects were eight graduate students, aged 25.9 years (SD 3.2). Each subject participated in four 50-min exposures: control (CON), ICE, PCM of 5°C [PCM(5)] and 20°C [PCM(20)]. Each subject rested in a pre-test room for 10 min before entering the test-room where they rested for another 10 min, followed by 30 min-exercise and a 10 min-recovery period. The exercise intensity was set at 55%VO_{2max}. Cooling effects were evaluated by measuring rectal temperature (Tre), mean skin temperature (Tsk), body weight loss and subjective responses. An increase in Tre for PCM(5) and PCM(20) which was less than that for CON and ICE was observed. The increases in Tsk were depressed using cooling devices, but the cooling effects of PCMs were greater than ICE. The subjects with CON felt hotter and wetter than those in the other conditions. The larger surface cooling area, higher melting temperature and softer material of PCMs which reduces absorption capacity caused a decrease in Tre and Tsk for PCM(5) and PCM(20) which was more than that for CON and ICE. Furthermore, PCM(20) does not require refrigeration. These results suggest that PCM(20) is more effective than other cooling devices in reducing the physiological load while wearing firefighting protective clothing.

Keywords Thermal comfort · Cooling device · Body temperatures · Firefighting protective clothing

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Introduction

An exterior thermal load is added to the heat stock from the metabolism of the body and that causes an excessive heat load on firefighters. While the functions of firefighting protective clothing have been improved, there is the possibility that the physiological load on the firefighters may be increased. Furthermore, it has been reported that physiological stress is caused by impermeable garments, which increase skin temperature, heart rate and core temperature (Bishop et al. 1994; Duncan et al. 1979; Faff and Tutak 1989). Tochihara et al. (2005) conducted a questionnaire study on 792 firefighters, and reported that 48.7% had experienced feeling very ill because of heat during the previous summer. Therefore, it is important to examine the methods for reduction of thermal stress on firefighters from firefighting protective clothing.

It is known that using a cooling vest with ice-packs (ICE) can reduce heart rate, skin temperature and sweat rate (Muir et al. 1999; Webster et al. 2005). Recently, the use of phase change materials (PCM, a highly productive thermal storage medium) is being applied in many fields, such as in garments, home furnishing and cooling products.

Pause (2003) and McLellan and Frim (1998) reported that a protective suit with PCM could slow down the rate of the increase in the user's temperature and prevent heat stress.

Although many studies have been conducted on the application of PCM in ordinary clothing fibers, few of them have investigated its application in preventing heat stress on firefighters. To the knowledge of the researchers, no published research is available that investigates the use of ICE and PCM cooling devices on firefighting protective clothing.

The aim of the present study was to examine ICE and PCM cooling devices for reducing physiological load based on subjects' physiological and subjective responses under the condition of exercising on a bicycle ergometer while wearing firefighting protective clothing in a relatively high temperature environment.

Methods

Subjects

The subjects in this investigation were eight graduate students. They were informed of all details of experimental procedures and the associated risk and discomforts. Each subject gave informed consent before participation. The mean (SD) physical characteristics of the subjects were as follows: age 25.9 years (SD 3.2); height 168.3 cm (SD 4.4); weight 62.5 kg (SD 9.2); body mass index 23.0 kg m^{-2} (SD 2.6) and VO_{2max} 45.8 ml min^{-1} kg^{-1} (SD 2.2).

Determination of VO_{2max}

The maximal rate of oxygen consumption (VO_{2max}) was measured in a room at 30°C (50% RH) using AE300s: MINAT conducted on an ergometer (Aerobike 75XL, Combi Co. Ltd., Japan). VO_{2max} protocol was calculated using continuous incremental loading based on Fitchett (1985). The protocol was divided into four phases of 4 min duration, each for a total of 16 min. Heart rate was monitored continuously using a Dynascope DS-2151 (Fukuda Denshi Co. Ltd., Japan).

Clothing ensembles and cooling devices

The cooling devices contained two types of cooling materials. All subjects participated in four conditions, namely: (1) no cooling devices; control (CON), (2) ice-packs (ICE), (3) PCM of 5°C [PCM(5)], and (4) PCM of 20°C [PCM(20)] administered in random order. During this experiment, subjects wore firefighting protective clothing (1.53 clo) and basic undergarments: A T-shirt, trousers, underwear, socks, boots, gloves and helmet were worn.

The ICE condition included five ice-packs (refrigerant) inserted into a mesh vest. The ICE was 1,050 g (two on chest and three on back) frozen in a freezer. The total ICE with vest weight was 1,203 g. The PCM condition included 16 packs of PCM (CoolVest^{TM}, Nippon Blower Co., Ltd) inserted into a mesh vest with a total weight of 1,694 g. The PCM(5) was 1,344 g (six on front torso and ten on back) cooled in a 5°C refrigerator. The PCM(20) condition included 16 packs of PCM kept at 20°C.

The melting temperature of the PCM was 28°C. The melting heat and specific heat of the materials of PCMs were 35.1 and 0.69 cal °C^{-1} g, respectively. The melting heat and specific heat of the materials of ICE were 79.5 and 1.0 cal °C^{-1} g, respectively.

Cooling devices ICE and PCM contain water and paraffin, respectively. When the temperature of ice or paraffin rises to 37°C (body temperature), theoretical heat absorption capacity of cooling materials is as follows: ICE at 302.2 kJ m^{-2}, PCM(5) at 190.0 kJ m^{-2} and PCM(20) at 155.6 kJ m^{-2}.

The total surface areas of the cooling materials for the ICE and PCMs were 1,310 and 1,792 cm^2, respectively (Table 1).

Experiment procedures and measurements

The cooling effects were evaluated using rectal temperature (Tre), mean skin temperature (Tsk), heart rate (HR), body weight loss (BWL), body heat storage (S) and subjective responses. Figure 1 shows the experiment protocol and measurement. The pre-test room as control was set with an air temperature (T_a) of 25°C and relative humidity (RH) of 50–60%. The test-room was set with an T_a of 30°C and RH of 50%. The cooling devices were worn under the firefighting protective clothing. The duration of each condition was 50 min. The subjects initially rested in a pre-test room for 10 min before entering the test-room where they rested for another 10 min, followed by 30 min 55%VO_{2max} exercise on a bicycle ergometer and 10 min recovery period.

Nakahashi et al. (2003) reported that in a typical Japanese wooden house, in the case of semi-destruction by fire, it takes about one hour to extinguish the fire, and the average actual fire-fighting time is about 30 min. Based on this reference, the exercises in our study were set for 30 min in the four conditions.

They inserted a thermistor to a depth of 150 mm inside the rectum. The skin thermistors were placed on the right side of the body (head, abdomen, chest, back, forearm, hand, thigh, calf, and foot). Tsk was calculated using Hardy

Table 1 Specifications of the cooling devices

Condition	ICE	PCM(5)	PCM(20)
Cooling devices	  	 	
Quantity	5	16	
Weight (g) and size of a piece (cm)	210, 15.5 × 16.9 × 2.0	84, 8 × 14 × 0.6	
Total weight with a vest (g)	1,203	1,694	
The melting heat (cal °C^{-1} g)	79.5	35.1	
Specific heat of the materials (cal °C^{-1} g)	1.0	0.69	
Total surface area of cooling materials (cm^2)	1,310	1,792	
Materials and melting temperature (°C)	Water, 0	Paraffin, 28	

and DuBois's equation (Hardy and DuBois 1938). The mean rectal temperature and the mean skin temperature were collected on a portable data logger (Gram, LT-8A). Heart rate was monitored using a Dynascope DS-2151 (Fukuda Denshi Co. Ltd., Japan). Body weight loss (BWL) was determined using change in body/clothing weight (±1 g accuracy) (ID2, Mettler Instruments) before and after the experiment. Body heat storage (S) was calculated using Eq. (1) (Burton 1935):

$$S = (3.48\,\mathrm{Wt}\,A^{-1}) \cdot (\Delta\mathrm{Tb}), \qquad (1)$$

where 3.48 is the average specific heat of body tissues (in kJ kg^{-1} °C^{-1}), A is the body surface area (m^{-2}). ΔTb is the rate of increase in mean body temperature (in °C). The mean body temperatures (ΔTb) (in °C) were estimated from measurements of Tre and Tsk. (ΔTb = 0.8·Tre + 0.2·Tsk).

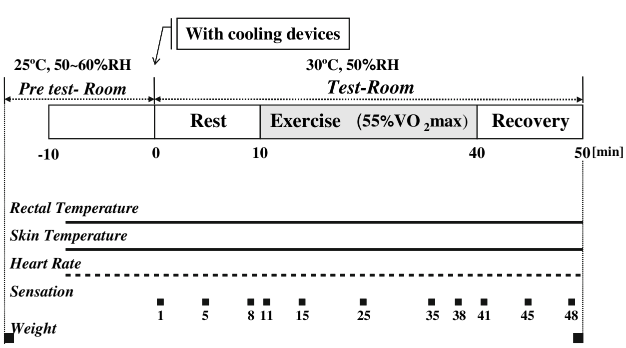

Fig. 1 Experiment protocol and measurement items

Subjective responses included thermal sensation and humidity. The scale of thermal sensation was from slightly cold to very hot. The scale of humidity sensation was from slightly dry to very wet. Subjects were also asked how well they found the cooling devices fit their bodies.

Statistical analysis

The cooling device-related effects on all measurements were examined by a two-way analysis of variances (ANOVA) with repeated measures for rest, period of exercise and recovery, separately [experimental conditions: CON, ICE, PCM(5) and PCM(20); time]. Scheffé's post-hoc comparisons were used to assess significant main effects using ANOVA. Statistical significance was set at $p < 0.05$.

Results

Physiological responses

The mean rectal temperature for eight subjects across time in the four conditions is shown in Fig. 2. Tre showed almost the same transition from beginning to end under all conditions, with a gradual increase following the start of the exercise. There was a significant difference in Tre

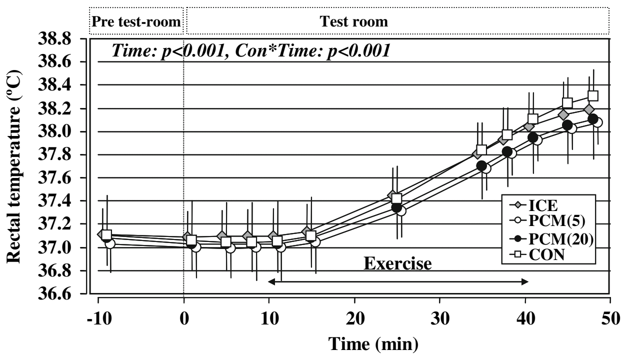

Fig. 2 Time courses of the mean rectal temperature (Tre) of *CON*, *ICE*, *PCM(5)*, and *PCM(20)*. Values are means and SD. "Time: $p < 0.001$" indicates a significant main effect of time. "Con × time: $p < 0.001$" indicates a significant interaction between conditions and time

between condition and time towards the end of the experiment. The result of the experiment showed an increase in Tre for PCM(5) and PCM(20) which was less than that for CON and ICE.

Mean skin temperature over time in all conditions showed a significant difference between CON and PCM as shown in Fig. 3. The results of the experiment showed a lower increase in Tsk in PCM(20) compared to CON from 5 min after starting the rest until the end of the experiment ($p < 0.05$–0.01). During the latter half of the exercise, the significant differences observed in Tsk in PCM(5) were lower than CON ($p < 0.05$). The difference between CON and ICE were smaller than between CON and PCMs.

Heart rate was almost the same from the beginning to the end of the exercise under all conditions. However, after the exercise PCM(5) was significantly lower than CON in recovery.

The mean (SD) values of BWL were greatest in CON at 670 g (SD 105), followed by ICE at 591 g (SD 101),

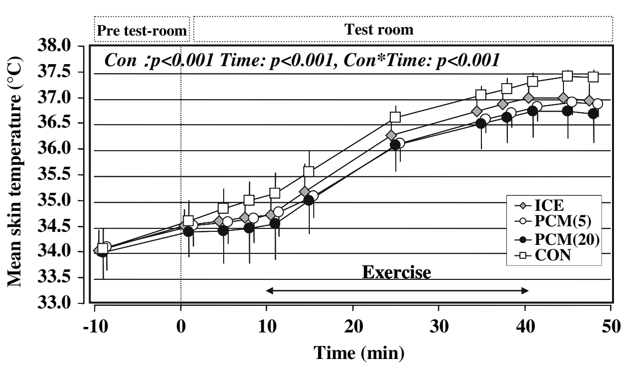

Fig. 3 Time courses of the mean skin temperature (Tsk). Values are means and SD. "Con: $p < 0.001$", indicates a significant main effect of conditions. "Time: $p < 0.001$" indicates a significant main effect of time. "Con × time: $p < 0.001$" indicates a significant interaction between conditions and time

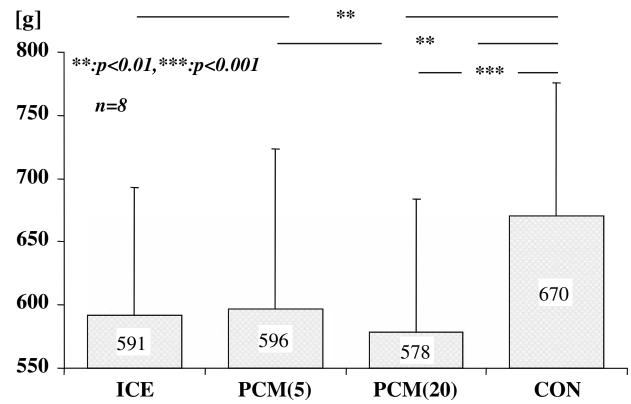

Fig. 4 Body weight loss observed in each of the four test trial conditions. Values are means and SD. "**: $p < 0.01$", indicates a significant differences between *CON* and *ICE*. "**: $p < 0.01$", indicates a significant differences between *CON* and *PCM(5)*. "***: $p < 0.01$", indicates a significant differences between *CON* and *PCM (20)*

PCM(5) at 596 g (SD 126) and PCM(20) at 578 g (SD 105) as shown in Fig. 4. The BWL of CON was significantly greater than the other three conditions. However, there were no significant differences observed among the cooling device conditions.

Subjective responses

Figure 5 shows the time course of the whole body thermal sensation under four conditions. There were significant ($p < 0.001$) differences in whole body thermal sensation, which showed that the subjects with CON felt hotter than other conditions after entering the room. Similarly, there were significant differences ($p < 0.05$) in humidity sensation at the end of the exercise period, which indicates that CON was wetter than the other conditions. All subjects reported that the PCM cooling devices fit their bodies better than the ICE.

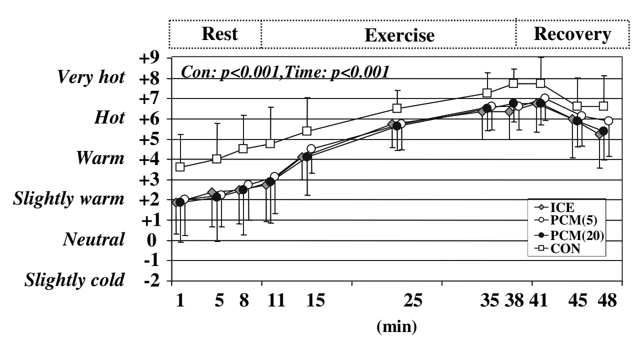

Fig. 5 Time courses of the whole body thermal sensation. Values are means and SD. "Con: $p < 0.001$", indicates a significant main effect of conditions. "Time: $p < 0.001$" indicates a significant main effect of time

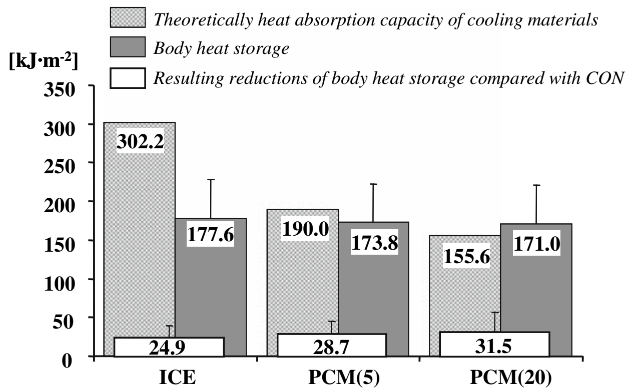

Fig. 6 Theoretical heat absorption capacity of *ICE*, *PCM(5)*, and *PCM(20)*. Body heat storage and resulting reductions of body heat storage compared with *CON*. The values are means and SD

Cooling devices for body heat storage

Figure 6 shows theoretical heat absorption capacity of cooling devices and calculated mean body heat storage for 50 min exposure at ICE, PCM(5) and PCM(20). Resulting mean reductions in body heat storage compared with CON are also shown. Body heat storage was greatest in the CON at 202.5 kJ m^{-2}, followed by ICE at 177.6 kJ m^{-2}, PCM(5) at 173.8 kJ m^{-2} and PCM(20) at 171.0 kJ m^{-2}. There were no significant differences in body heat storage among the four conditions.

Discussion

The aim of the present study was to examine ICE and PCM cooling devices for reducing physiological load based on subjects' physiological and subjective responses under the condition of exercising on an ergometer while wearing firefighting protective clothing in a relatively high temperature environment.

Muir et al. (1999) reported that using an ice-cooling devices compared with no ice cooling devices can reduce heart rate, skin temperature and rectal temperature during light exercise while wearing protective clothing. Also, Webster et al. (2005) reported that a light-weight cooling vest can enhance performance of athletes and lower heart rate, skin temperature and rectal temperature in the heat. In this study, compared with the condition without cooling devices (CON), ICE, PCM(5) and PCM(20) also reduce heat stress when wearing firefighting protective clothing as shown in Figs. 2–5. Although the physiological differences are small among the cooling devices, Tsk at CON is significantly higher than those at PCE(5) and PCM(20) as shown in Fig. 3.

McLellan and Frim (1998) measured physiological and subjective responses during prolonged exercise of to 3 h at 40°C (30%RH) while wearing NBC clothing. They evaluated cooling effects of liquid/air cooling system and PCM to reduce heat stress, and reported that cooling ability of PCMs was less than that of liquid/air cooling systems, but still useful when exercise time was not excessive. Since use of cooling systems is not practical during firefighting work, PCM may be a more practical alternative for firefighting over a relatively short time.

The theoretical heat absorption capacity of cooling materials is as follows: ICE at 302.2 kJ m^{-2}, PCM(5) at 190.0 kJ m^{-2} and PCM(20) at 155.6 kJ m^{-2}. Theoretically ICE has a greater absorption capacity for cooling than PCMs. However, resulting reductions in body heat storage for ICE, PCM(5) and PCM(20) were 24.9, 28.7 and 31.5 kJ m^{-2}, respectively. Although the difference was not significant, resulting mean reductions in body heat storage of ICE were smaller than those of PCMs. The actual cooling efficiency of the heat absorption capacity of cooling devices was greatest in PCM(20) at 20.2%, followed by PCM(5) at 15.1%, and ICE at 8.2%. There are several reasons why the ICE has smaller heat stress reduction, although ICE has greater absorption capacity for cooling. First, PCM(5) and PCM(20) are cooling devices with six PCM inserted in the chest and back portion of a vest with a surface area of 1,792 cm^2. On the other hand, ICE is a cooling device with two ice bags placed in the chest and another three in the back portion of a mesh net vest, and with a surface area of 1,310 cm^2. Bennett et al. (1995) used four (425 g each) and six (765 g each) frozen gel thermostrips and proposed that the physiological burden decreased with an increase in the cooling area in contact with the body. Since the cooling area covered with PCM(5) and PCM(20) was greater than the area covered with ICE, it seemed that PCM(5) and PCM(20) limited more the increase of accumulation of heat in the body. Secondarily, due to the lower melting temperature of ICE and its thickness (2.0 cm), ICE is still hard even when it begins to melt. On the other hand, PCMs soon become soft after it begin to melt. Due to this softness, PCMs become more pliable and are able to touch the skin more easily and thus absorb the body heat effectively. The increase in heat storage in the body can be suppressed. Furthermore, all subjects reported protective clothing with PCM(5) and PCM(20) fit their bodies better than ICE. Finally, since the surface temperature of ICE reaches 0°C when it was frozen, wearing ordinary cooling materials on T-shirts may lead to not only body overcooling but possibly frostbite. Thus, ICE is a covered by a 1 mm polyurethane foam laminated with aluminum sheets to protect the user. This insulation may influence the absorption effect of ICE.

There are no differences in heat stress reduction between PCM(5) and PCM(20), although PCM(5) has theoretical greater heat absorption capacity for cooling. Since PCM(5) requires refrigeration during storage, PCM(20) is much easier to use in real situations for firefighting work. In summary, the larger surface cooling area of PCMs, the higher melting temperature and softer material of PCMs and lack of a cover which reduces absorption capacity cause a decrease in Tre and Tsk for PCM(5) and PCM(20) which was more than that for CON and ICE. Furthermore, PCM(20) does not require refrigeration. These results suggest that PCM(20) is more effective than other cooling devices in reducing the physiological load while wearing firefighting protective clothing.

Our results suggest that PCMs are effective in reducing heat stress for 30 min during high-intensity exercise in our experiment condition but new materials need to be developed for widespread use in actual firefighting with the following characteristics: (1) a high melting temperature (about 30°C) but with a greater latent heat capacity like ice, (2) non-flammability, and (3) low production costs.

Acknowledgments The authors appreciate the special advice given by Dr. Takako Fukazawa. We would like to acknowledge and express our gratitude to the Japan Fire Retardant Association (JFRA) and a Grant-in-Aid for Scientific Research (No.16107006) from the Japan Society for the Promotion of Science(JSPS).

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