Eur J Appl Physiol (2013) 113:1223–1231
DOI 10.1007/s00421-012-2534-2

ORIGINAL ARTICLE

The impact of a phase-change cooling vest on heat strain and the effect of different cooling pack melting temperatures

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Received: 24 November 2011 / Accepted: 17 October 2012 / Published online: 16 November 2012

Abstract Cooling vests (CV) are often used to reduce heat strain. CVs have traditionally used ice as the coolant, although other phase-change materials (PCM) that melt at warmer temperatures have been used in an attempt to enhance cooling by avoiding vasoconstriction, which supposedly occurs when ice CVs are used. This study assessed the effectiveness of four CVs that melted at 0, 10, 20 and 30 °C (CV_0, CV_{10}, CV_{20}, and CV_{30}) when worn by 10 male volunteers exercising and then recovering in 40 °C air whilst wearing fire-fighting clothing. When compared with a non-cooling control condition (CON), only the CV_0 and CV_{10} vests provided cooling during exercise (40 and 29 W, respectively), whereas all CVs provided cooling during resting recovery (CV_0 69 W, CV_{10} 66 W, CV_{20} 55 W and CV_{30} 29 W) ($P < 0.05$). In all conditions, skin blood flow increased when exercising and reduced during recovery, but was lower in the CV_0 and CV_{10} conditions compared with control during exercise (observed power 0.709) ($P < 0.05$), but not during resting recovery (observed power only 0.55). The participants preferred the CV_{10} to the CV_0, which caused temporary erythema to underlying skin, although this resolved overnight after each occurrence. Consequently, a cooling vest melting at 10 °C would seem to be the most appropriate choice for cooling during combined work and rest periods, although possibly an ice-vest (CV_0) may also be appropriate if more insulation was worn between the cooling packs and the skin than used in this study.

Communicated by George Havenith.

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Keywords Heat strain · Cooling vest · Phase-change cooling

Abbreviations

ANOVA	Analysis of variance
CON	Control condition
CV_0	Cooling vest (melting at 0 °C)
CV_{10}	Cooling vest (melting at 10 °C)
CV_{20}	Cooling vest (melting at 20 °C)
CV_{30}	Cooling vest (melting at 30 °C)
LDF	Laser Doppler flowmetry
HR	Heart rate
O_2	Oxygen
CO_2	Carbon dioxide
PCM	Phase-change material
SD	Standard deviation
SkBF	Skin blood flow
$\overline{T}_b$	Mean body temperature
T_{sk}	Skin temperature
$\overline{T}_{msk}$	Mean skin temperature
WBGT	Wet bulb, globe temperature

Introduction

Military, emergency service and industrial personnel often experience uncompensable heat strain, which limits their physical endurance and ultimately either operational capability or industrial productivity. The main contributory factor to exertional heat strain is generally considered to be physical exercise coupled with the restriction to evaporation of sweat that is caused by wearing multiple or impermeable clothing layers (e.g. fire or chemical protective clothing). When such uncompensable heat strain occurs, and it is not feasible to loosen or remove clothing or to reduce the work rate, the only method of extending safe working times and operational endurance is to provide additional cooling. This can be achieved either by enhancing evaporative cooling within or under the clothing, or by direct conductive cooling. There is a multitude of equipment commercially available performing one of these two cooling techniques, with a variety of technologies, both powered and unpowered. In many situations, the only cooling technique that could be used in practice is a 'phase-change' cooling vest (hereafter described as 'CV'); liquid- or air-cooled systems are often generally too complex, heavy or restrictive to mobility[1] and are also expensive to procure and maintain. Simple CVs, which contain a frozen substance, are commonly used as a simple technique for providing body cooling. The frozen substance absorbs body heat by an amount determined by its specific heat capacity (solid phase), its latent heat of fusion as it melts, and again by its specific heat capacity (liquid phase). The rate of cooling is determined by the temperature gradient between the skin and the frozen, melting, or melted substance. Generally, the greatest amount of heat is absorbed during the melting phase with the latent heat of fusion being much larger than the specific heat capacity of the substance in either the solid or liquid phases. As a consequence, the majority of cooling occurs at the temperature at which the substance melts and such substances are generally termed phase-change materials (PCM); ice is such a material.

Water/ice-based CVs have been shown to be beneficial in reducing heat strain in a large number of studies relating to industrial and military uses when thermoregulation is otherwise compromised by clothing (Strydom et al. 1974; Holmer 1989; Banta and Braun 1992; Engel et al. 1984; Bennett et al. 1995; House 1996; Cadarette et al. 2002; House et al. 2003). In contrast, other studies have shown that such cooling vests are inappropriate for the use by athletes trying to cool post-exercise (Lopez et al. 2008; Barwood et al. 2009) as the vest impedes evaporation of sweat from the lightly clad torso, which would otherwise provide significant evaporative cooling. Some performance benefits have been demonstrated when athletes use CVs to pre-cool prior to performing in warm or humid conditions (Arngrímson et al. 2003; Hunter et al. 2006; Ückert and Joch 2007) or between bouts during competition in tetraplegic athletes with compromised thermoregulation (Webborn et al. 2010). Bogerd et al. (2010) demonstrated a reduced skin blood flow when cooling the torso with only *mild cooling* (water evaporation cooling shirt) or *strong cooling* (ice-vest) when attempting to pre-cool volunteers with a normal core temperature. However, most heat was extracted using the ice-vest irrespective of the reduced skin blood flow, presumably by direct conduction through the tissues.

The coolant used as a PCM is not always ice, other substances are used which melt at a greater temperature, primarily long-chain alkanes, such as hexa- and tetra-decane, and these have two supposed advantages. First, the PCM can be re-charged (solidified) without a freezer, e.g. a substance that melts at 20 °C can be re-charged without a freezer, in air cooler than 20 °C, or more quickly in water below this temperature. Secondly, a substance which melts at 20 or 30 °C would seem less likely to cause a peripheral vasoconstriction in underlying skin than an ice-based system melting at 0 °C. This advantage is widely reported by manufacturers of non-ice-based PCM cooling systems, who also report an increased subsequent physiological cooling power, but without any evidence to confirm such assertions. Tests on a thermal manikin (Gao et al. 2010) indicate that cooling power is greater with a larger differential between the coolant melting temperature (in the range 24 to 32 °C) and the skin, although this did not take into account any effects on the peripheral circulation which may be compromised, particularly when much colder coolants, such as ice, are used (Wyss et al. 1974; Johnson and Park 1979). Reducing the peripheral circulation under a CV may reduce its effectiveness; with cooling of deep tissues relying on slow conduction through the tissues, rather than faster mass heat transfer by the circulation. In human tests, Gao et al. (2011) demonstrated that the torso cooling effect was stronger using a CV melting at 24 °C compared to a CV melting at 28 °C, but that neither attenuated the rate of rise of rectal temperature during exercise in the heat, although they both reduced the peak rectal temperature reached during resting recovery. Gao et al. (2011) recommended that similar investigations be conducted with CVs that have a lower melting temperature.

This study was conducted to measure the effectiveness of cooling using a CV with cooling packs that melt at either 0, 10, 20 or 30 °C as compared to a non-cooling control condition. It was hypothesised that, in humans wearing clothing, which restricts evaporative cooling, and who are suffering from an uncompensable heat strain:

All cooling vests would attenuate the rise in heat strain during exercise, and would accelerate the reduction in heat strain during resting recovery.

The ice-based cooling vest could afford the greatest physiological cooling benefit, having the greatest physical cooling capacity, per kilogram of coolant.

[1] The wearer must either carry their power supply, pump and coolant (heavy) or have these supplied by umbilical (mobility restriction).

All vests would cause an initial vasoconstriction on the torso when first donned at the start of each test when the participants were normothermic and the CV cooling packs having just been removed from the freezer.

Skin blood flow would be lower in the vest conditions compared to the control, and would be less with the vests melting at a lower temperature.

Methods

Following approval from the Ministry of Defence Research Ethics Committee, ten male volunteer participants were recruited and provided their written informed consent. An independent medical officer conducted a medical assessment of volunteers prior to the study, and volunteers with a history of cold induced illness, heat illness or intolerance, history of collapse on exertion, anaemia, vascular disease or who had donated blood in the week prior to the study were excluded. The 10 participants were a mean (SD) 28.8 (6.9) years old, of height 180.3 (6.3 cm) and mass of 82.4 (6.2) kg.

The experiment was conducted in an environmentally controlled chamber, set to a climate of 40 °C dry bulb (T_{db}), and 29.5 °C wet bulb (T_{wb}) [46 % relative humidity (rh)]. The participants completed five test conditions, one at the same time each day on five consecutive days, on each day undertaking a stepping exercise for 45 min, followed by a post-exercise seated recovery period (also 45 min). The five conditions were control (Con), and CV with cooling packs melting at one of four different temperatures, CV_0, CV_{10}, CV_{20} and CV_{30}, melting at 0, 10, 20 or 30 °C, respectively. The order of presentation of conditions was a counterbalanced Latin square design to minimise any acclimation/habituation effects.

The four CV conditions used identical torso tabard-style vests, each comprising a cotton outer with a cotton mesh liner into which a cooling pack was inserted into the front tabard and one into the rear tabard. Each of the coolant packs (ice, or PCM melting at 10, 20, or 30 °C) contained 1 kg of coolant, thus each CV condition comprised 2 kg of coolant. The cooling packs were also of identical design and had the same coolant surface area approximately 1,750 cm^2 per CV. The latent heat of fusion (Q) and specific heat capacity (C) of the CVs were as follows: CV_0 (Q 334 kJ kg^{-1}; C 4.18 kJ kg^{-1}); CV_{10} (Q 203 kJ kg^{-1}; C 2.61 kJ kg^{-1}); CV_{20} (Q 212 kJ kg^{-1}; C 2.66 kJ kg^{-1}); CV_{30} (Q 222 kJ kg^{-1}; C 2.74 kJ kg^{-1}).

Procedure

Prior to each test, participants had abstained from alcohol for at least 24 h, and from caffeine for at least 2 h prior to testing. Participants, wearing underwear and socks, were instrumented, and then donned a t-shirt, a double-layered cotton coverall and a fire fighting coverall and shoes. The coveralls were worn initially on the lower body with the upper part of the coveralls tied around the waist, so that the torso was covered only by a t-shirt. The participants then moved into the environmental chamber where they rested seated and data collection commenced. After 5 min of rest, the participants stood-up and donned the appropriate CV and the upper-body section of the two coveralls, which were then fastened; in the Control condition, no CV was worn. Participants then remained standing for 5 min from the start of donning the vest, they then commenced stepping on a 22.5 cm box at a rate of 12 complete steps per minute for 45 min, after which they were seated for a recovery period of 45 min, with the clothing remaining fastened.

During the experiment participants were provided with tap water *ad libitum* and were actively encouraged to drink. The temperature of the water consumed was not controlled, and was approximately 14 °C when supplied in 1 L water bottles which was replaced when the water was consumed; the temperature of the water would have risen from when the participants were first given their water bottle, until when it was fully consumed. No measure of the final temperature of the water in the water bottles was taken.

Each participant undertook each of their five experiments at the same time of day each day. Half of the group undertook their experiments in the morning and the other half in the afternoon.

Measurements

Deep body temperature was estimated from rectal temperature using a thermistor self-inserted to 15 cm beyond the anal sphincter. Mean skin temperature ($\overline{T}_{msk}$) was estimated from skin temperature (T_{sk}) recorded by thermistors at four sites (shin, thigh, upper arm and chest) according to Ramanathan (1964); an additional skin thermistor was placed on the abdomen, positioned so that it would be directly underneath any CV worn. Environmental temperature was monitored using a wet, bulb, globe thermometer (WBGT). All thermistors and the WBGT monitor were supplied by Grant Instruments (Cambridge) Ltd (UK). The data from these instruments were recorded at 1-min intervals on an electronic data logger (*Squirrel* 1200 series) supplied by the same company. Heart rate (HR) was monitored continuously using a 3-lead electrocardiogram telemetry system (MIE Medical Research Ltd, Leeds). Metabolic work rate was determined from the rate of oxygen uptake ($\dot{V}O_2$) calculated by collecting expired air in 'Douglas' bags for three, 5-min samples starting at approximately 10, 20 and 30 min into the exercise period.

The volume of the collected gas was measured using a dry-gas meter (Harvard Inc., USA) and the oxygen (O_2) and carbon dioxide (CO_2) content using gas analysers (Series 1400, Servomex Ltd, UK). Temperature of the gas (Grant Instruments Ltd, UK) and barometric pressure (F54 Fortin Barometer, Russell Scientific Instruments Ltd, UK) were also measured.

Skin blood flow measurements were made by laser Doppler flowmetry (LDF) (MoorLab, Moor Instruments Ltd, UK), recording digitally into a computer (PowerLab, ADInstruments Ltd, UK). In each experiment, a laser Doppler probe was attached to the left chest of each participant adjacent to the chest T_{sk} thermistor, but ensuring that its position was underneath one of the CV cooling packs (where worn). After each participant had completed all experimental conditions, they were asked to rank order their preference for conditions.

The mass of fluid consumed by each participant was measured by weighing each water bottle provided pre-and post-consumption throughout each experiment. Naked and clothed body masses pre-and immediately post-testing were measured using an electronic balance (Industrial Electronic Weight Indicator, Model I10, Ohaus Corporation, NJ, USA).

Calculations and data analysis

Masses of sweat produced and evaporated were be calculated from differences in nude and clothed body mass, corrected for fluid intake and any urine output.

Mean skin temperature ($\overline{T}_{msk}$) was calculated as follows (Ramanathan 1964):

$$\overline{T}_{msk} = 0.3T_{chest} + 0.3T_{arm} + 0.2T_{thigh} + 0.2T_{calf}$$

Mean body temperature ($\overline{T}_b$) was calculated according to the following equation (Colin et al. 1971):

$$\overline{T}_b = 0.8T_{re} + 0.2_{msk}\ (^\circ C)$$

From values of $\overline{T}_b$ changes in body heat storage (ΔS) were calculated according to the following equation (adapted from Burton 1935)[2]:

$$(\Delta S) = C\ m\ \Delta T_b\ (kJ)$$

where $C = 3.470$ (kJ kg^{-1} °C^{-1}), m mass of participant (kg), ΔS was calculated and is presented separately for exercising and resting recovery periods. The mass used for the calculation of $\overline{T}_b$ was the mean of pre- and post-experiment naked body masses.

Although the above method of estimating ΔS is known to have errors compared with partitional calorimetry, these errors are assumed to be equal between conditions and thus the effects of the CVs on S (compared to Con) can still be calculated by this method (Vallerand et al. 1992).

The absolute values of T_{re}, $\overline{T}_b$, HR and skin blood flow were determined at the start and end of the work and rest periods. These were examined using analysis of variance (ANOVA) techniques and *post hoc* testing using the Newman–Keuls test. A one-way repeated measures ANOVA was used to assess the differences between conditions. Time of the day was included in the model to reduce error variance in the model. Two-way ANOVA included a between participants factor (am/pm) at two levels and the model tested for the interaction between CV and am/pm and also CV and order of conditions. The results are presented at 5 % level of significance ($P < 0.05$) unless stated otherwise. The subjective preference ranking data was examined using a Wilcoxon's matched pairs test.

Results

All 10 participants completed each work and rest period in each condition. There were no order or time of day effects detected by ANOVA.

Mean $\dot{V}O_2$ during the stepping exercise was not different between conditions: ($P = 0.42$) Con (0.96 [0.12]) L min^{-1}, CV_0 (0.89 [0.16]) L min^{-1}, CV_{10} (0.94 [0.14]) L min^{-1}, CV_{20} (0.98 [0.07]) L min^{-1} and CV_{30} (0.94 [0.15]) L min^{-1}.

Mean T_{re} during the experiment is shown in Fig. 1.

At the end or exercise T_{re} was lower in CV_0 compared to the control. T_{re} in the CV_{10}, CV_{20} and CV_{30} conditions were intermediate to the CV_0 and control conditions, and not significantly different from either. At the end of the recovery period, T_{re} was lower in all CV conditions compared with the control. In addition, T_{re} was lower in the CV_0, CV_{10} and CV_{20} conditions compared with CV_{30}.

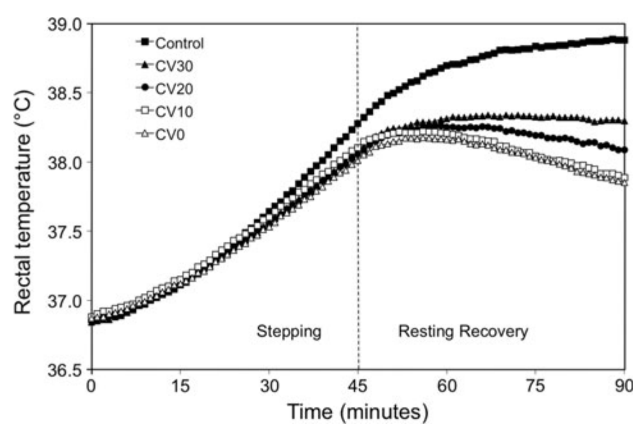

Fig. 1 Mean rectal temperature when wearing different cooling vests under fire-fighting clothing during stepping and resting recovery ($n = 10$)

[2] Burton originally included body surface area and quoted S in J/m^2.

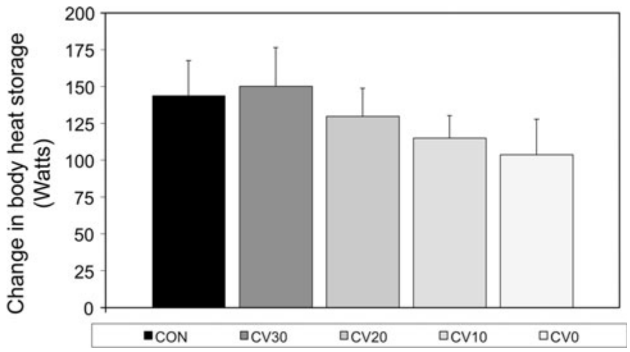

Fig. 2 Mean (SD) change in body heat storage whilst stepping ($n = 10$)

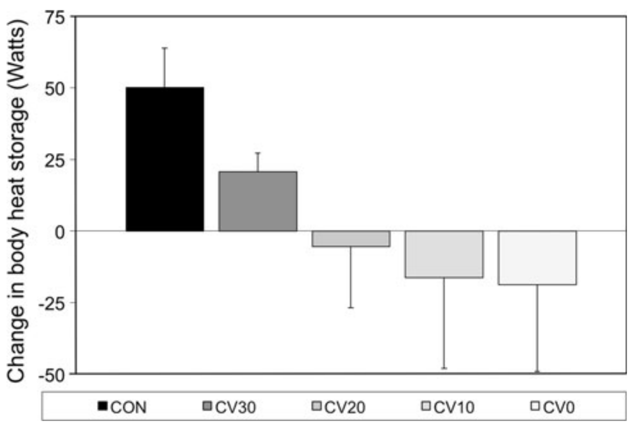

Fig. 3 Mean (SD) change in body heat storage during resting recovery ($n = 10$)

Change in body heat storage

The rates of change of body heat storage during exercise in each condition are shown in Fig. 2, and during recovery in Fig. 3.

Body heat rose at similar rates during the stepping exercise in the control, CV_{30} and CV_{20} conditions, and rose less quickly (was attenuated) in CV_{10} and CV_0 (Fig. 2).

During resting recovery, total body heat content rose less quickly than the control (CV_{30}), or fell compared with the control (CV_{20}, CV_{10} and CV_0) ($P < 0.01$); in addition, the reduction in body heat content was greater in CV_0 and CV_{10} when compared with CV_{20} and CV_{30} ($P < 0.01$) (Fig. 3).

Differences in the rates of change of body heat content indicate that the CV_0 and CV_{10} conditions provided 40 and 29 W of cooling, respectively, during exercise, and 69 and 66 W during recovery. The recovery cooling powers for the CV_{20} and CV_{30} were 55 and 29 W, respectively.

Heart rate

There were no differences in mean (SD) HR at the start of the exercise period. At the end of exercise, HR was lower

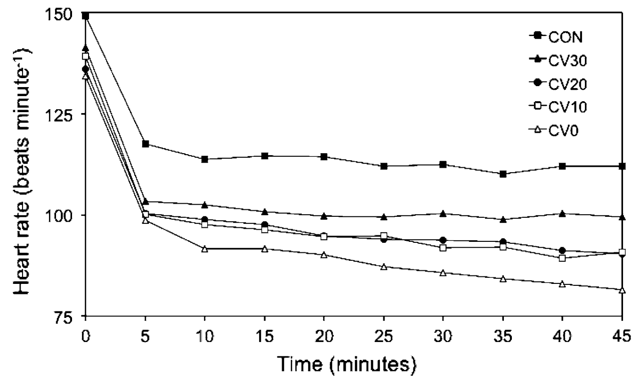

Fig. 4 Mean heart rate when wearing different cooling vests under fire-fighting clothing during resting recovery ($n = 10$)

in the CV_0 [134 (15) beats min^{-1}] and CV_{20} [136 (16) beats min^{-1}] conditions compared to the control [149 (14) beats min^{-1}] ($P < 0.01$). There was only marginal evidence that HR was lower in CV_{10} [139 (20) beats min^{-1}] as compared to the control ($P < 0.06$). HR was not reduced as compared to the control when wearing the CV_{30} [141 (17) beats min^{-1}].

Mean recovery HR data are shown in Fig. 4.

After 5 min, and throughout the remainder of the rest period, HR was lower in all vest conditions compared to the control ($P < 0.05$). After 15 min of rest, and thereafter, HR was lower in CV_0 compared to CV_{30}. After 25 min of rest and thereafter HR was lower in the CV_0 compared to the CV_{20}. At the end of the rest period, HR was lower in the CV_0 compared to all other vest conditions. In addition, at the end of the rest period HR was lower in the CV_{10} compared to the CV_{30} condition.

Subjective preferences

When requested to rank the order of preference of each of the five conditions, all vest conditions were preferred to the control ($P < 0.005$). In addition the CV_{10} condition was preferred over the other three vest conditions, CV_{30}, CV_{20} and CV_0 ($P < 0.001$). The participants commonly reported that the CV_0 condition was "too cold". In addition, cold-induced erythema was usually apparent at the end of the experiment for participants in the CV_0 condition in areas of contact between the t-shirt covered torso and the CV_0. Participants reported that the erythema persisted throughout the day, but had subsided by the following morning.

Abdomen and chest temperatures

A graph of mean abdomen T_{sk} during the work period and the effect of the four cooling vests is shown in Fig. 5, and for the chest in Fig. 6.

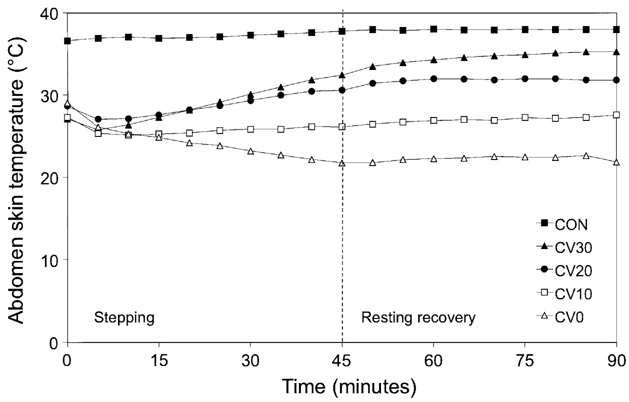

Fig. 5 Mean abdomen skin temperature when wearing different cooling vests under fire-fighting clothing whilst stepping and during resting recovery ($n = 10$)

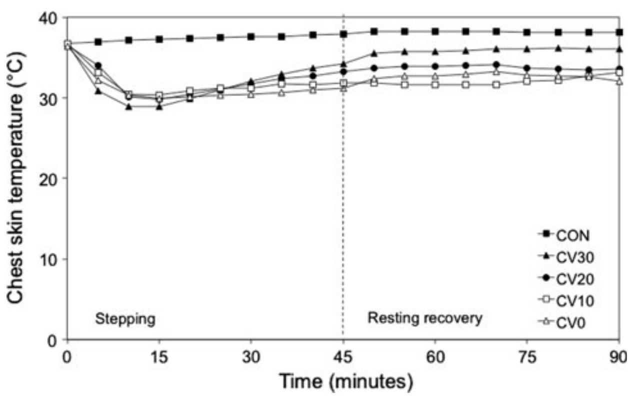

Fig. 6 Mean chest skin temperature when wearing different cooling vests under fire-fighting clothing whilst stepping and during resting recovery ($n = 10$)

Abdomen temperature was lower in all vest conditions compared to the control throughout exercise and recovery, and was lower for the CV_0, CV_{10} and CV_{20} conditions compared to CV_{30} during recovery only. Whilst the mean abdomen temperature did not fall below 20 °C, the lowest individual abdomen temperature recorded was 9.5 °C (CV_0).

Chest temperature responses were similar to that of the abdomen, but approximately 5 °C warmer than the abdomen temperatures (for the CV conditions), with mean chest skin temperature having a lowest value of 28.8 °C, with the lowest individual value recorded being 17.8 °C (CV_0).

Chest skin blood flow

There were no differences in chest skin blood flow between conditions before the vests were donned, or after the vests had been donned before stepping, although the observed powers were low (0.667 and 0.217, respectively). SkBF was increased during the 5-min vest-donning period compared to the 5 min pre-donning period in all four vest conditions, but not the control. Chest skin blood flow during the exercise and rest periods is shown in Fig. 7.

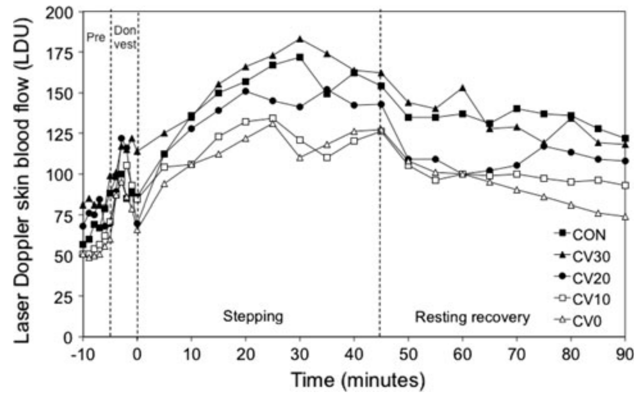

Fig. 7 Mean chest laser Doppler skin blood flow when wearing different cooling vests under fire-fighting clothing during stepping exercise and resting recovery ($n = 10$)

In all conditions, skin blood flow was greater at the end of the work period compared to the start and lower at the end of the recovery period that at the end of work/start of recovery. Skin blood flow was lower in the CV_0 and CV_{10} conditions compared to the control during exercise (observed power 0.709), but not during resting recovery (observed power 0.55). Overall, skin blood flow was greater in the exercise period, as compared to the resting recovery period.

Sweat production and evaporation and fluid balance

More sweat was produced in the Con (1.78 [0.39] L) compared to the CV_0 (1.32 [0.27] L) and CV_{10} (1.48 [0.26] L). Sweat production in the CV_{20} (1.52 [0.24] L) was not different from any other condition, whilst that in the CV_{30} (1.60 [0.27] L) was not different from Con, CV_{20} or CV_{10}, but was greater than that for CV_0. Sweat evaporation was not significantly different between conditions: Con (0.51 [0.23] L); CV_{30} (0.56 [0.19] L); CV_{20} (0.48 [0.08] L); CV_{10} (0.47 [0.05] L) and CV_0 (0.48 [0.13] L). Fluid intake was not significantly different between conditions: Con (1.83 [0.75] L); CV_{30} (1.54 [0.49] L); CV_{20} (1.28 [0.29] L); CV_{10} (1.29 [0.65] L) and CV_0 (1.30 [0.57] L). Changes in naked body mass uncorrected for fluid intake, indicating fluid gain or loss, were not different between conditions and were Con (0.05 [0.75] L); CV_{30} (−0.06 [0.48] L); CV_{20} (−0.24 [0.44] L); CV_{10} (−0.19 [0.74] L) and CV_0 (−0.02 [0.52] L).

Discussion

Wearing the vests had no measureable effect on oxygen uptake, indicating no significant increase in heat production due to having to carry the mass of the vest in four of the five conditions, or any shivering occurring.

Recovery from the imposed heat strain, as indicated by changes in T_{re}, $\overline{T}_b$ and HR, was improved when wearing any of the cooling vests compared with the non-vest control. However, only the CV_0 condition caused an attenuation of the rise of T_{re}, $\overline{T}_b$ and HR during exercise, with CV_{10} attenuating only $\overline{T}_b$ whilst CV_{20} attenuated $\overline{T}_b$ and HR. Thus, the first hypothesis can be partially accepted, that all cooling vests accelerate the reduction in heat strain during resting recovery, but that only the CV_0 attenuates the rise in heat strain (as indicated by T_{re}) during exercise, although CV_{10} and CV_{20} do slow the rate of rise of $\overline{T}_b$ during exercise also. These data and the above findings also support the second hypothesis that the ice-based vest (CV_0) would provide a greater physiological cooling benefit than the other vests that melt at a greater temperature.

In neither 5 min pre-vest-donning or vest-donning periods did we detect any difference in skin blood flow between conditions, although we did detect a transient increase in SkBF in all four CV conditions (but not control) as the CVs were donned. This, presumably, was due to movement artefact on the Doppler probes and fibreoptic cables. Although skin blood flow measures were disrupted during the short period when the vests were first donned (Fig. 7), we did not detect a difference in chest skin blood flow between conditions at the start of exercise, but that SkBF increased in all four vest conditions whilst donning compared to the 5 min pre-donning period. We therefore must suppose that the vest had no direct vasoconstrictor effect and consequently, we found no evidence to support our third hypothesis, that the vests would cause vasoconstriction when first donned; the increase in SkBF we found on donning was most likely due to movement artefact, which declined in the two minutes pre-exercise. Although the different vests melted at different temperatures, when initially removed from the freezer (−18 °C) the surface temperatures of the packs were likely to be similar, irrespective of their melting temperatures. Not until after some period had elapsed would enough heat have been donated to the cooling packs to raise the frozen coolant to its melting temperature, and then for it to melt. Consequently, the vests in all four conditions will have been at a similar temperature at least for the early part of each test. The packs, generally, were completely melted (CV_0, CV_{10} and CV_{20}), or almost completely melted (CV_{30}) by the end of the 90-min test period. This suggests that the packs, for the majority of each experiment, were at their melting temperature or greater (after completely melting). Of the packs that had not completely melted, it was apparent that the inner (next to the skin) surface of the packs had melted first. Nevertheless, consideration should be given to repeating this experiment with the cooling packs being cooled to just below their freezing temperatures; this may give a fairer assessment of the value of coolants that melt at a greater temperature than ice. Given that cooling all the CV coolant packs to −18 °C gives an additional heat sink capacity to the CV_{10}, CV_{20} and CV_{30} vests, it may be that cooling the vests to just below their melting temperature will greater differentiate the cooling capabilities of the different vests. The CV_0 also does not need to be frozen to −18 °C, but it was felt that this is the most likely way such a vest would be used, in a domestic freezer, rather than in a custom chill cabinet designed to chill the packs to just below their melting temperature, say −1 °C.

Despite the proximity of the frozen vests to the skin, separated only by the thin mesh lining of the CV waistcoat and a thin cotton t-shirt, chest skin blood flow was seen to rise in response to the increasing heat strain, and decline during resting recovery. There was some evidence that skin blood flow was slightly compromised in CV_0 and CV_{10} conditions during exercise, but this difference was not apparent during resting recovery. Therefore, we partially accept our fourth hypothesis with some amendment, that skin blood flow under the vest is marginally compromised during exercise, for the vests with the coldest melting temperature (CV_0 and CV_{10}), but not for the vests which melt at a warmer temperature (CV_{20} and CV_{30}) or for any vest during resting recovery. However, by the start of the resting recovery period, the vest would have risen in temperature to their melting temperature, and had partially melted. Thus, the lack of identified vasoconstrictor effect during resting recovery may be related to a lesser cold stimulus to the skin, and a similar response to that seen for the exercise period (marginal vasoconstrictor effect for the coldest vests) may have been seen had the vests been worn for recovery only, or had the frozen packs been changed for fresh ones at that point. However, the observed power for the statistical analysis of the skin blood flow data was relatively low, and it may be that more differences between conditions may have been apparent with a greater powered study, particularly for the resting recovery data where differences may have been detected in line with the apparent visual differences shown in Fig. 7.

Why chest T_{sk} was greater than abdomen T_{sk} is not known. In the absence of any significant upper body exercise (perhaps resulting in greater heat generation in the chest than abdomen musculature), it is considered that abdomen T_{sk} may be greater than chest T_{sk} due to greater heat generation in the abdomen (liver and intestine). However, given the large cooling effect of the CVs, this would seem unlikely, and opposite to what we found. Perhaps, the more pliable abdomen allows for better contact with the initially rigid CV cooling packs when first donned as compared to the more rigid chest, or that the T_{sk} thermistor just happened to be positioned under the groove (between sections) of the cooling pack more often for the chest as compared to abdomen.

The claim by manufacturers that traditional ice-vests cause widespread vasoconstriction, and that vests that melt at greater temperatures do not, is not supported by this study. In contrast to Kellong et al. (1993) who reported that skin blood flow is primarily controlled by deep body temperature rather than skin temperature when the former is raised, this study presents some evidence that skin blood flow was reduced with the colder vest (CV_0 and CV_{10}) during exercise but not during rest. However, in all conditions, skin blood flow did rise in response to the increasing heat strain. Irrespective of the effects on skin blood flow, it is clear that vest with the lowest melting temperature did not compromise cooling; indeed, cooling was greatest with the colder melting vests. This finding indicates that in terms of heat extraction alone, the vest with the lowest melting temperature (CV_0) provided the greatest cooling power. Presumably, this occurred because of the enhanced gradient between deep body temperature and skin temperature, whilst skin blood flow was generally maintained (even if reduced slightly), and also due to conduction through the tissues, as heat transfer will not be restricted to convective/mass heat transfer through the circulation alone. Gao et al. (2010) also reported that the cooling rate of CVs was directly proportional to the cooling gradient between the CV and the skin, i.e. greater cooling effect with colder CV melting temperature, although this was tested initially only on a manikin (where such a finding would be expected), and with a much smaller temperature range with PCM vests melting at 24, 28 and 32 °C. Gao et al.'s (2012) subsequent study on humans confirmed that CVs with a lower melting temperature do indeed have a stronger cooling effect, but this was tested only in the range 24 to 28 °C. The findings of this study support Gao et al.'s (2012) findings, and extend the conclusion for CVs with a much larger range of melting temperature. This study demonstrates that CVs with melting temperatures of between 0 and 10 °C (or at least lower than 20 °C) provide the most effective cooling benefit.

The participants preferred all of the vests compared to the no-vest control condition, and additionally preferred the CV_{10} compared to the other three vests, and generally reported that the CV_0 felt too cold. The cold-induced erythema seen following the use of the CV_0 suggest that the CV_0 should not be used without additional insulation between the skin and the cooling packs. Alternatively, a CV_{10} vest could be used instead. That erythema occurred was surprising considering that mean abdomen T_{sk} did not fall below 20 °C even when the CV_0 was worn although some individuals had colder abdomen temperature (9.5 °C). Whether such vests would be appropriate for situations with mild thermal discomfort, but without a substantial heat strain response (i.e. without an increasing deep body temperature) has not been tested. A CV with a melting temperature of 21 °C has been shown to provide benefits in thermal sensation (more comfortable) and reduce torso skin temperature by up to 3 °C whilst undertaking seated office work in 34 °C air with 60 % rh (Gao et al. 2012). It would seem likely that a colder vest (CV_0 or CV_{10}) may invoke too much of a cooling stimulus with a risk of erythema when at rest without a rising (or raised) deep body temperature.

Although cooling vests are effective at extracting heat during exercise (CV_0 and CV_{10}) and post-exercise recovery (all CVs), it is not clear why greater cooling occurred during the resting–recovery period. One explanation could be a reduced skin blood flow during exercise as compared to recovery, or alternatively due to the CVs being colder during exercise than recovery (after they have absorbed considerable heat energy), causing a further reduction in skin blood flow. Certainly, when deep body temperature is raised to 38 °C, skin blood flow is much reduced during exercise, compared to when passively heated (Brengelmann et al. 1977) due to a withdrawal of active vasodilation, likely linked to blood pressure regulation (Kellogg et al. 1993). However, in all conditions in this study, deep body temperature (T_{re}) was raised above 38 °C, and spent longer at or above this level during recovery as compared to exercise. How soon after the cessation of exercise the attenuation of vasodilation is reversed is not clear. Kellogg et al.'s data (1993) show an increased skin blood flow 5 min after the cessation of exercise, due to active vasodilation although this occurs as deep body temperature (oesophageal) was falling, although the absolute value was just above 38 °C. Our data show the reverse, with rising skin blood flow during exercise (as T_{re} rose) and gradually falling skin blood flow during recovery (as T_{re} reduced) (Fig. 7), with the overall skin blood flow being greater during exercise compared to recovery.

It is concluded that a cooling vest can provide a worthwhile enhanced reduction in heat strain during resting recovery in conditions (clothing and/or climate) where thermoregulation is otherwise compromised. It is further concluded that the greatest benefit in cooling during resting recovery occurs with the coldest coolant temperature, in the range 0 to 30 °C, with no apparent vasoconstriction occurring under any of the vests, in contrast to some manufacturers' claims. The attenuation of heat strain during exercise was restricted to the cooling vests with the lowest melting temperature (CV_0 and CV_{10}). In the conditions of this study, participants preferred the CV_{10} vest, primarily because the CV_0 felt too cold and caused torso erythema, although this was no longer visible the following day. Consequently, a cooling vest melting at 10 °C would seem to be the most appropriate choice for cooling during combined work and rest periods, although possibly an ice-vest may also be appropriate if more insulation was worn between the cooling packs and the skin than in this study, thereby avoiding erythema.

Acknowledgments The authors greatly acknowledge the volunteer participants who gave up their time and thermal comfort to undertake this experiment. We are also grateful for the independent medical support provided by Dr Howard Oakley and Mr David Grist, and Dr Shaun Kilminster for his help undertaking the statistical analysis, all of the Institute of Naval Medicine. Thanks are also due to Professor Mike Tipton (University of Portsmouth) and Dr Adrian Allsopp (Institute of Naval Medicine) for their critical review of this manuscript.

Conflict of interest The authors declare that they have no conflict of interest.

Ethical standard This study complies with the laws relating to human research in the United Kingdom and the European Union.

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