Extending work tolerance time in the heat in protective ensembles with pre- and per-cooling methods

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Running head

Protective ensembles, work tolerance time and cooling

Abstract

Objectives

Investigate whether a range of cooling methods can extend tolerance time and/or reducing physiological strain in those working in the heat dressed in a Class 2 chemical, biological, radiological, nuclear (CBRN) protective ensemble.

Methods

Eight males wore a Class 2 CBRN ensemble and walked for a maximum of 120 minutes at 35 °C, 50 % relative humidity. In a randomised order, participants completed the trial with no cooling and four cooling protocols: 1) ice-based cooling vest (IV), 2) a non-ice-based cooling vest (PCM), 3) ice slushy consumed before work, combined with IV (SLIV) and 4) a portable battery-operated water-perfused suit (WPS). Mean with 95 % confidence intervals are presented.

Results

Tolerance time was extended in PCM (46 [36, 56] min, $P = 0.018$), SLIV (56 [46, 67] min, $P < 0.001$) and WPS (62 [53, 70] min, $P < 0.001$), compared with control (39 [30, 48] min). Tolerance time was longer in SLIV and WPS compared with both IV (48 [39, 58 min]) and PCM ($P \leq 0.011$). After 20 min of work, HR was lower in SLIV (121 [105, 136] beats·min^{-1}), WPS (117 [101, 133] beats·min^{-1}) and IV (130 [116, 143] beats·min^{-1}) compared with control (137 [120, 155] beats·min^{-1}) (all $P < 0.001$). PCM (133 [116, 151] beats·min^{-1}) did not differ from control.

Conclusion

All cooling methods, except PCM, utilised in the present study reduced cardiovascular strain, while SLIV and WPS are most likely to extend tolerance time for those working in the heat dressed in a Class 2 CBRN ensemble.

Key words

Heat stress; cardiovascular strain; thermal strain; thermoregulation; body cooling; occupational.

Introduction

Undertaking physical activity in the heat may result in an impaired ability to regulate body temperature with concomitant performance reductions (1). The inability to regulate body temperature is further exacerbated when the ambient temperature is warmer than skin temperature (2), with accompanying high relative humidity (RH) reducing the capacity to evaporate sweat from the skin (3,4). The associated imbalance in thermal homeostasis is accelerated during physical roles necessitating the use of chemical, biological, radiological, or nuclear (CBRN) protective ensembles undertaken in thermally stressful environments (5–7). Protective ensembles are necessary for worker protection but the uncompensable microenvironments these workers experience may lead to shorter times to exhaustion in the heat (8–10).

Strategies designed to attenuate the increased physiological strain for those working in protective ensembles in the heat include heat acclimation, adequate hydration and appropriate work-rest cycles (11,12). If available, workers may utilise cooling methods during work to increase work tolerance time and/or reduce physiological strain (13,14,23–27,15–22). Despite the apparent efficacy of cooling interventions in alleviating thermal strain, the external validity of current evidence is debatable. Examples include those using water-perfused suits or air compressors that are not portable (15,17,25), or replenishing ice in cooling vests (13,14,19).

Due to the plethora of cooling methods available, choosing the most appropriate may not always be an easy choice. For example, trying to extend work tolerance time may require different cooling strategies compared to only wanting to reduce physiological strain during work (28). Considering the many cooling methods available, studies that compare one or two cooling methods with control of no cooling limit the possible recommendations to end-users. Further, when deciding their choice of cooling strategy end-users need to consider other factors, such as work location, CBRN ensemble in use and available resources.

Although previous studies used cooling methods during work (per-cooling), individuals may also take advantage of cooling before work (i.e. pre-cooling). This approach has received less attention, though positive results are reported (29–31). We recently showed in a Class 3 National Fire Protection Association (NFPA) CBRN ensemble (32) that per-cooling successfully extended work tolerance time similarly to pre- and per-cooling (28). However, it is unknown whether the cooling methods that extended work tolerance time in the Class 3 ensemble translate to the heavier Class 2 ensemble. Therefore, this study aims to investigate whether a combination of pre- and per-cooling further reduces physiological strain and extends tolerance time compared with pre-cooling only in Class 2 ensembles.

Methods

The present study was approved by the Queensland University of Technology Human Research Ethics Committee (#1700001026) and complied with standards set in the Declaration of Helsinki (2013). The participants were made aware of the purpose, procedures and risks of the study before giving their informed written consent. A total of eight male participants volunteered. Their physical characteristics were as follows [mean (SD)]: 24 (4) years of age; height of 180.2 (7.5) cm; body mass of 77.1 (6.8) kg; body fat of 13.8 (5.9) %; maximal oxygen uptake (VO_{2max}) of 51.0 (3.5) $mL \cdot kg^{-1} \cdot min^{-1}$. All participants were non-smokers and free from any vascular, blood and respiratory conditions.

Each participant attended the laboratory for one familiarisation trial and five experimental trials, each separated by 72 hours. Cooling intervention allocation and trial order was randomised using a random number generator (v4 Research Randomizer Form). Participants were instructed to refrain from alcohol, tobacco, caffeine and strenuous exercise, as well as to consume 45 mL of water per kg of body mass in the 24 hours preceding each visit to the laboratory (33).

Familiarisation Session

Participants' height, nude body mass and body fat were measured before performing a progressive incremental running test to exhaustion on a motorised treadmill to ascertain their VO_{2max}. Body composition was measured using dual-energy X-ray absorptiometry (Lunar Prodigy, GE Healthcare Lunar, USA) and analysed using dedicated software (enCORE, version 9, GE Healthcare Lunar, USA). Following a warm-up period, participants were fitted with expired gas analysis equipment (Parvo Medics TrueOne 2400, USA) and a heart rate (HR) monitor (Polar Team^2, Finland). The test started at a speed of ~8 $km \cdot h^{-1}$ and a 1 % grade. On every minute, the speed was increased by 1 km·h^{-1} until a speed the participant could maintain for at least two minutes was achieved. After, the grade was increased by 1 % every minute until volitional exhaustion. The variables used for the determination of VO_{2max} -followed the standard laboratory procedure (28,34). Following this, participants were familiarised with the CBRN ensemble; this involved donning all equipment and walking on the treadmill (described below) for 15 minutes.

Experimental Sessions

The experimental sessions involved walking in the CBRN ensemble for up to 120 minutes on a motorised treadmill at a speed of 4.5 km·h^{-1} with a 1 % gradient at air temperature and RH maintained at 35 °C, 50 %. Participants were blinded to the time elapsed.

The CBRN ensemble was a certified Class 2 NFPA 1994 (32) ensemble (MT94, Lion Apparel, USA), which consisted of a one-piece hooded jumpsuit, including inner gloves, booties, worn with outer gloves and a respirator and filter (Promask with a Pro2000 PF10 filter, Scott Safety, England). Participants also carried one full gas cylinder (L65C-77, Luxfer, Australia) mounted to a harness (ACSi2 Duo, Scott Safety, England). Participants did not breathe from this gas cylinder. The combined ensemble mass was 15.3 kg. Participants wore a base ensemble which consisted of a t-shirt, shorts, athletic shoes, socks and underwear.

Standard termination criteria were applied during each trial in accordance with the ASTM guidelines (F2668-07, 2007) which included: (1) deep body temperature >39.0 °C, (2) 120 minutes of work, (3) HR ≥90 % of maximum, or (4) fatigue or nausea (self-termination). Following the attainment of one of the termination criteria, the participant exited the climate-controlled chamber.

Personal Cooling Garments and Protocols

The information below describes the various cooling garments and protocols utilised. Where applicable, the cooling garment was applied over the participant’s base ensemble. All times were standardised between trials.

Per-Cooling, Cooling Vests (IV, PCM)

Two different cooling vests were tested: 1) an ice-based cooling vest (IV; ICEEPAK Australia, Australia; 1.3 kg), stored in a -18 °C freezer; 2) a non-ice-based cooling vest with a melting temperature of 14 °C (PCM; KewlFit, Model 6626-PEV, TechNiche, USA; 1.8 kg), stored in a 5 °C fridge.

Pre- and Per Cooling, Ice Slushy and Ice Vest (SLIV)

Thirty minutes before walking commenced, participants ingested 7.5 $g \cdot kg^{-1}$ of ice slushy (-2 °C) at a rate of 1.25 $g \cdot kg^{-1}$ every five minutes (36,37). Each drink was prepared using a slushy machine (Model SSM-180, ICETRO, South Korea) with the same flavouring used (The Slushie Specialists, Australia). Following this, participants donned IV (as above).

Per-Cooling, Water-perfused Suit (WPS)

Participants donned a three-piece portable battery-operated WPS (BCS4 Cooling System, Allen-Vanguard, Canada; 5.2 kg) that covered the entire body, except the hands and feet. The WPS consists of tubing sewn into a stretchable jacket, trousers and hood circulating water at ~375 $mL \cdot min^{-1}$ from a small portable pump (Delta Wing Pump, Allen-Vanguard, Canada) connected to a specially designed bottle which initially contained 90 % ice and 10 % water; this resulted in ~10 °C water entering the suit when first turned on.

Measurements and Calculations

Pre-trial hydration status was confirmed by urine specific gravity (PAL 10s, ATAGO, Japan) of ≤1.020 (38). If participants provided a sample >1.020, they were given an additional 500 mL of tap water, which was consumed >30 minutes before the commencement of the trial.

Environmental temperature and RH were measured using a wet-bulb globe thermometer (QUESTemp 36, 3M, USA). Deep body temperature was estimated from rectal temperature (T_{rec}) using a thermistor (YSI 400, DeRoyal, USA) self-inserted 12 cm beyond the anal sphincter and recorded using a wireless data logger (T-TEC 7, Temperature Technology, Australia). Mean skin temperature ($\overline{\mathrm{T}}_{\mathrm{msk}}$) was estimated using wireless iButton thermocrons (DS1922L-F50 iButtons, Maxim Integrated, USA) attached to four sites using a single piece of adhesive tape (Premium Sports Tape, AllCare, New Zealand) and calculated as (ISO 9886, 2004):

$$\overline{\mathrm{T}}_{\mathrm{msk}} = 0.28\mathrm{T}_{\mathrm{neck}} + 0.28\mathrm{T}_{\mathrm{scapula}} + 0.16\mathrm{T}_{\mathrm{hand}} + 0.28\mathrm{T}_{\mathrm{shin}}$$

T_{rec} and $\overline{\mathrm{T}}_{\mathrm{msk}}$ were recorded at 5-second intervals and averaged per minute. HR was recorded at 1-second intervals and averaged per minute.

Starting T_{rec}, $\overline{\mathrm{T}}_{\mathrm{msk}}$ and HR was an average of the first minute inside the climate-controlled chamber dressed in the CBRN and, if applicable, cooling garment. During this minute, participants straddled the treadmill and began walking on the next minute. For accurate sweat rate calculations, participants were towel-dried immediately before their start and end nude mass weighing (WB-110AZ, Wedderburn, Australia). Sweat rate calculation is shown below.

$$\text{Sweat rate } (\mathrm{L} \cdot \mathrm{h}^{-1}) = \frac{\text{Start nude mass} - \text{End nude mass}}{\text{Time elapsed (min)}} \times 60$$

Statistical Analyses

A one-way repeated-measures analysis of variance was used to compare tolerance time and sweat rate between trials. A two-way repeated-measures analysis of variance was used to compare T_{rec}, $\overline{\mathrm{T}}_{\mathrm{msk}}$, and HR between trials at baseline, minute 5, 10, 15, 20 of work and upon participant termination. The data were only analysed during work to 20 minutes as participants began to terminate from 21 minutes. When statistically significant interactions were observed, differences between trials were assessed using a paired sampled *t*-test. Multiple comparisons were corrected using Tukey's test. An α of 0.05 was used to determine statistical significance. Statistical analyses were conducted using GraphPad Prism (version 7, GraphPad Software, USA). Effect sizes were calculated for pairwise comparisons using an unbiased Cohen's *d* (d_{unb}) and calculated as (40):

$$d_{unb} = \left(1 - \frac{3}{4\,(df - 1)}\right) \times \left(\frac{\mathrm{M_{diff}}}{\mathrm{SD_{av}}}\right)$$

$$\mathrm{SD_{av}} = \sqrt{\frac{\mathrm{SD1}^2 + \mathrm{SD2}^2}{2}}$$

Where $\mathrm{M_{diff}}$ is the difference in means between two trials, and SD1 and SD2 are the SD of the two trials. Effect sizes were interpreted as small (0.20–0.49), moderate (0.50–0.79) or large (≥0.80) (41,42). Data are presented as mean and 95 % confidence intervals (CI).

Results

Tolerance Time

There was a statistically significant main effect between trials for tolerance time (Figure 1, $P < 0.001$). While IV (48 [39, 58] min) did not statistically differ from control (39 [30, 48] min, $P = 0.078$, $d_{unb} = 0.77$), tolerance time was longer, compared with control, in SLIV (56 [46, 67] min, $P < 0.001$, $d_{unb} = 1.33$), PCM (46 [36, 56] min , $P = 0.018$, $d_{unb} = 0.58$) and WPS (62 [53, 70] min, $P < 0.001$, $d_{unb} = 1.97$). Tolerance time was also longer in SLIV compared with both IV ($P = 0.011$, $d_{unb} = 0.58$) and PCM ($P = 0.005$, $d_{unb} = 0.76$). Similarly, tolerance time was longer in WPS compared with both IV ($P < 0.001$, $d_{unb} = 1.12$) and PCM ($P = 0.001$, $d_{unb} = 1.31$). Most participants terminated as a result of either high T_{rec} (>39.0 °C) or reaching a HR ≥90 % of maximum (Table 1).

Table 1. Termination criteria for each condition

	HR (≥90 % max)	T_{rec} (>39.0 °C)	Fatigue or nausea	Duration (120 min)
Control	5	3	-	-
IV	5	3	-	-
SLIV	3	5	-	-
PCM	4	4	-	-
WPS	5	2	1	-
Total	**22**	**17**	**1**	**0**

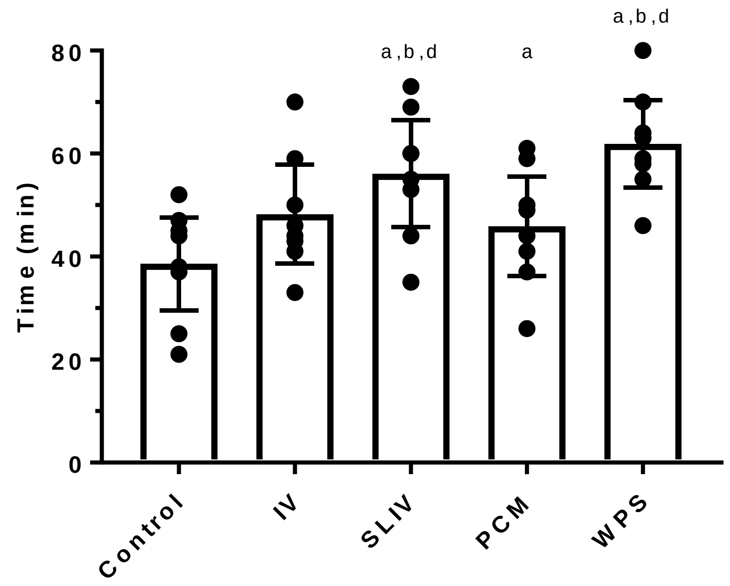

Figure 1. Mean (95 % CI) tolerance time for each trial

^{a,b,d} *Statistical difference compared with control, IV, PCM, respectively (P < 0.05).*

Physiological Variables

For T_{rec}, there was a statistically significant main effect for trial (P < 0.001), time (P < 0.001) and interaction (Table 2, Figure 2A, P < 0.001). Pairwise comparisons of the interaction revealed T_{rec} was lower in SLIV compared with all trials from baseline until 20 min of work (P < 0.001, d_{unb} ≤ 1.92). Upon termination, T_{rec} was lower in control (P = 0.039, d_{unb} = 0.45) and WPS (P = 0.003, d_{unb} = 0.67) compared with SLIV.

For $\overline{\mathrm{T}}_{\mathrm{msk}}$, there was a statistically significant main effect for trial (P < 0.001), time (P < 0.001) and interaction (Table 3, Figure 2B, P < 0.001). Pairwise comparisons of the interaction revealed, $\overline{\mathrm{T}}_{\mathrm{msk}}$ was cooler throughout work in IV (P < 0.001, d_{unb} ≤ 6.19), SLIV (P < 0.001, d_{unb} ≤ 7.30), PCM (P < 0.001, d_{unb} ≤ 2.68) and WPS (P ≤ 0.024, d_{unb} ≤ 4.04) compared with control. Up to 20 min of work, $\overline{\mathrm{T}}_{\mathrm{msk}}$ was cooler in IV (P < 0.001, d_{unb} ≤ 2.03) and SLIV (P < 0.001, d_{unb} ≤ 2.54) compared with PCM.

Similarly, $\overline{\mathrm{T}}_{\mathrm{msk}}$ was cooler in IV ($P < 0.001$, $d_{unb} \leq 3.00$) and SLIV ($P < 0.001$, $d_{unb} \leq 3.82$) compared with WPS. On termination, $\overline{\mathrm{T}}_{\mathrm{msk}}$ was cooler in IV compared with control ($P < 0.001$, $d_{unb} = 1.94$), SLIV ($P = 0.036$, $d_{unb} = 0.35$), PCM ($P = 0.001$, $d_{unb} = 0.60$) and WPS ($P < 0.001$, $d_{unb} = 1.26$). In addition, $\overline{\mathrm{T}}_{\mathrm{msk}}$ was cooler in SLIV ($P < 0.001$, $d_{unb} = 0.60$) and PCM ($P = 0.013$, $d_{unb} = 0.61$) compared with WPS.

For HR, there was a statistically significant main effect for trial ($P = 0.003$), time ($P < 0.001$) and interaction (Table 4, Figure 2C, $P < 0.001$). After 20 min of work, HR was lower in SLIV compared with control ($P < 0.001$, $d_{unb} = 0.75$), IV ($P < 0.001$, $d_{unb} = 0.47$) and PCM ($P < 0.001$, $d_{unb} = 0.57$). Similarly, HR was lower in WPS compared with control ($P < 0.001$, $d_{unb} = 0.89$), IV ($P < 0.001$, $d_{unb} = 0.63$) and PCM ($P < 0.001$, $d_{unb} = 0.71$).

Sweat rate was similar ($P > 0.05$) between control (0.99 [0.71, 1.26] $L \cdot h^{-1}$), IV (0.99 [0.71, 1.26] $L \cdot h^{-1}$), PCM (1.07 [0.83, 1.31] $L \cdot h^{-1}$), SLIV (0.82 [0.49, 1.16] $L \cdot h^{-1}$) and WPS (1.00 [0.82, 1.18] $L \cdot h^{-1}$).

Table 2. Mean (95 % CI) rectal temperature (°C) in each trial

	Rectal Temperature (°C)				
	Control	**IV**	**SLIV**	**PCM**	**WPS**
Resting	-	-	37.1 36.9, 37.3	-	-
0	37.2 (36.9, 37.5)	37.3 (37.1, 37.5)	36.6 (36.3, 36.9) a,b,d,e	37.2 (37.0, 37.3)	37.3 (37.0, 37.6)
5	37.2 (36.9, 37.5)	37.3 (37.1, 37.5)	36.6 (36.3, 36.9) a,b,d,e	37.2 (37.0, 37.3)	37.3 (37.0, 37.6)
10	37.3 (37.0, 37.6)	37.4 (37.1, 37.6)	36.8 (36.6, 37.0) a,b,d,e	37.3 (37.1, 37.4)	37.4 (37.1, 37.7)
15	37.4 (37.1, 37.6)	37.4 (37.2, 37.7)	37.0 (36.8, 37.2) a,b,d,e	37.3 (37.1, 37.5)	37.5 (37.2, 37.7)
20	37.5 (37.2, 37.8)	37.5 (37.3, 37.8)	37.2 (37.0, 37.4) a,b,d,e	37.4 (37.3, 37.6)	37.6 (37.3, 37.8)
Termination	38.6 (38.3, 38.9)	38.7 (38.5, 38.9)	38.8 (38.5, 39.0) a,e	38.7 (38.4, 39.0)	38.5 (38.3, 38.8)

[a,b,d,e] Statistical difference compared with control, IV, PCM, WPS, respectively ($P < 0.05$).

Table 3. Mean (95 % CI) mean skin temperature in each trial

	Mean Skin Temperature (°C)				
	Control	**IV**	**SLIV**	**PCM**	**WPS**
0	32.7 (32.1, 33.2) b,c,d	30.0 (29.6, 30.4)	30.1 (29.5, 30.8)	31.8 (31.0, 32.7) b,c,e	32.8 (32.0, 33.6) b,c
5	35.3 (34.8, 35.9) b,c,d,e	31.2 (30.6, 31.9)	31.0 (30.5, 31.6)	33.5 (32.4, 34.6) b,c	33.5 (32.9, 34.1) b,c
10	36.6 (36.1, 37.0) b,c,d,e	32.1 (31.4, 32.9)	31.6 (31.1, 32.2)	34.4 (33.3, 35.4) b,c	34.3 (33.8, 34.8) b,c
15	37.2 (36.8, 37.6) b,c,d,e	32.5 (31.9, 33.2)	32.0 (31.4, 32.7)	34.8 (33.8, 35.8) b,c	35.0 (34.5, 35.5) b,c
20	37.5 (37.2, 37.9) b,c,d,e	32.9 (32.2, 33.6)	32.4 (31.7, 33.1)	35.1 (34.2, 36.0) b,c	35.3 (34.8, 35.8) b,c
Termination	38.7 (38.3, 39.2) b,c,d,e	36.3 (35.1, 37.5) c,d,e	37.0 (35.4, 38.6)	37.2 (36.2, 38.3)	38.0 (37.3, 38.7) c,d

[b,c,d,e] Statistical difference compared with IV, SLIV, PCM, WPS, respectively ($P < 0.05$).

Table 4. Mean (95 % CI) heart rate in each trial

	Heart Rate (beats·min^{-1})				
	Control	**IV**	**SLIV**	**PCM**	**WPS**
0	89 (80, 97)	86 (75, 98)	79 (68, 89) [a,b,d,e]	90 (80, 99)	84 (71, 97)
5	109 (95, 123)	103 (94, 112) [a]	101 (91, 111) [a,d,e]	108 (97, 119)	107 (95, 119)
10	117 (102, 133)	113 (103, 123)	107 (93, 121) [a,b,d]	116 (102, 130)	112 (99, 125)
15	127 (110, 144)	120 (108, 132) [a]	113 (98, 128) [a,b,d]	124 (108, 139)	114 (100, 129) [a,b,d]
20	137 (120, 155)	130 (116, 143) [a]	121 (105, 136) [a,b,d]	133 (116, 151)	117 (101, 133) [a,b,d]
Termination	166 (156, 177)	170 (161, 178)	168 (157, 178)	167 (156, 178)	169 (161, 177)

[a,b,d,e] Statistical difference compared with control, IV, PCM, WPS, respectively (P < 0.05).

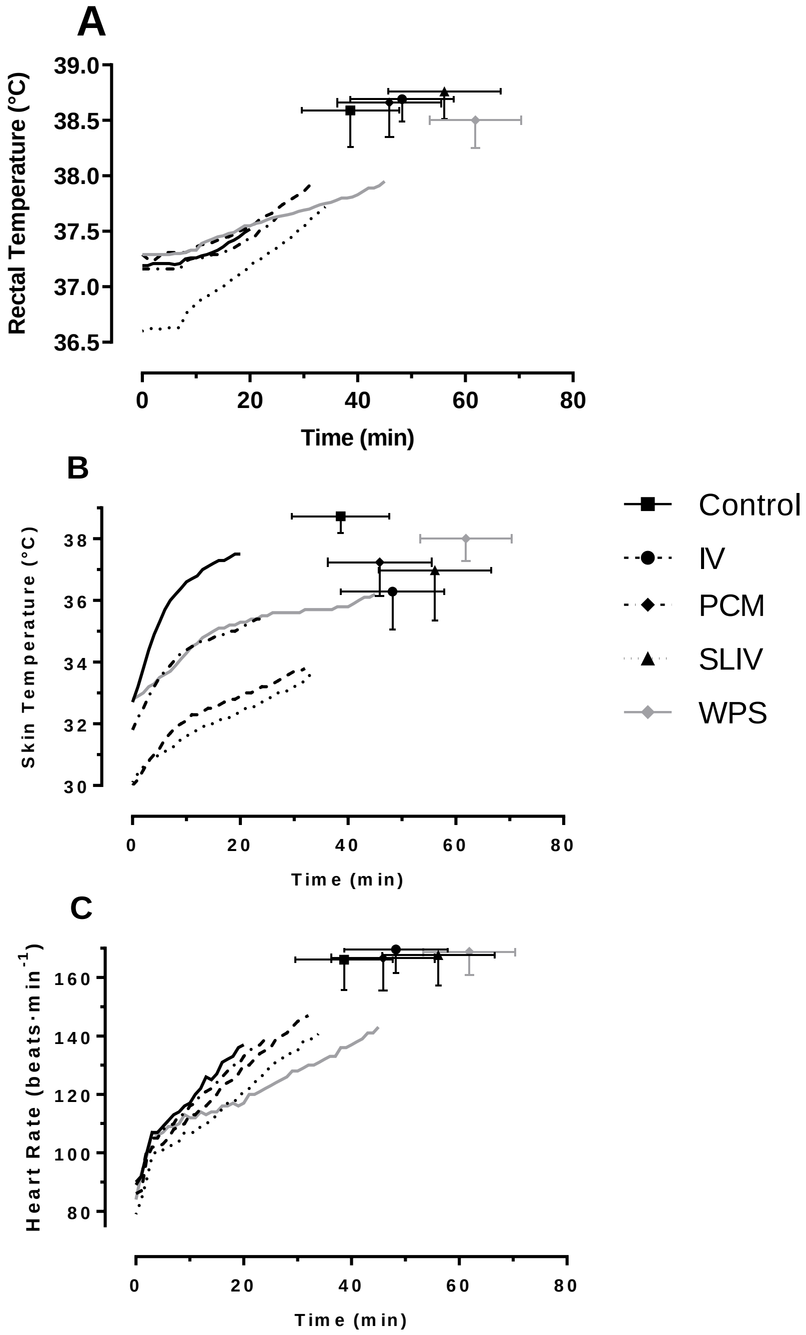

Figure 2. Mean (95 % CI) (A) rectal temperature, (B) skin temperature and (C) heart rate for each trial during work

Mean values are shown until one participant terminated. 95 % CI shown for final values only for reader clarity.

Discussion

The present study investigated a range of commercially available cooling methods and their effect on tolerance time and thermal strain in those working in the heat dressed in a Class 2 NFPA ensemble. The primary findings from this study were as follows: (1) SLIV, PCM and WPS statistically extended tolerance time compared with control (Figure 1); and (2) SLIV and WPS worked for longer compared with IV and PCM; and (3) IV, SLIV and WPS reduced cardiovascular strain compared with control during work (Table 4). To the authors' knowledge, this is the first study to highlight the positive use of a mixed-method cooling protocol (i.e. pre- and per-cooling) versus per-cooling only in those dressed in protective clothing.

External cooling reduces skin and deeper tissue temperature and may subsequently cool the cutaneous circulating blood and abate the rise in deep body temperature during work (43–46). Internal cooling involves an individual ingesting (e.g. ice slushy) a medium capable of cooling. Ingestion of an ice slushy takes advantage of the process whereby melting a substance requires energy, known as enthalpy of fusion. The reason for the extended tolerance time may be due to a reduced thermal strain in SLIV versus IV and, therefore, a more stable cardiovascular system.

There is a redistribution of blood flow to the working muscles and cutaneous circulation during work in the heat. It is proposed that in young healthy adults, the two vascular beds are adequately perfused to meet demands (47); that is, mean arterial pressure is not compromised but working in the heat dressed in CBRNE ensembles will, however, place a significant demand on the heart to maintain cardiac output (1). As a result, heart rate rises rapidly, eventually rising to maximal levels. Cooling methods have shown to reduce cutaneous blood flow (48,49), which may benefit the cardiovascular system by attenuating the rise in heart rate during work. Supporting this, the present study showed the addition of slushy ingestion to IV further reduced thermoregulatory strain (Table 2, Figure 2A) which benefited the cardiovascular system (Table 4, Figure 2C).

Despite the additional mass of the WPS (>3 kg heavier versus other cooling methods) this cooling method demonstrated the largest effect sizes for tolerance time. From the extensive work conducted at U.S. Army Research Institute of Environmental Medicine from 1976 to 1988, it is clear liquid-cooled garments are amongst the best cooling methods available (50). While SLIV enables individuals to start work with lower deep body temperature and work with cooler skin around the torso, the WPS covers most of the body. As a result of the greater surface area coverage with WPS, the cutaneous circulation demand may be lower than other cooling methods. Whether lowering starting deep body temperature with ice slushy or covering a larger body surface area with WPS the result is the same; that is, an attenuation in cardiovascular strain (Table 4, Figure 2C), resulting in an extended tolerance time (Figure 1).

Although tolerance time in IV was not statistically different from control, caution should be exercised when viewing this as an absence of a ‘positive’ response (51). Indeed, the mean difference in tolerance time was numerically greater in IV versus control (Figure 1, 9.6 minutes) compared with PCM versus control (7.3 minutes), with both cooling vests demonstrating medium effect sizes. Despite, the potential positive response from IV and PCM, it is clear these cooling methods are inferior to SLIV and WPS.

It is reported end-users do not utilise cooling methods before or during work as frequently as following work (52). Whether this is due to time and/or education is currently unknown, though logistics and time constraints are often cited as barriers to cooling method use (52). Consuming an ice slushy before work can be relatively quick, but the equipment and preparation needed may pose a barrier to its use. Though the WPS utilised in the present study is portable, it is expensive and heavier than other cooling methods and requires an extended time to don. Despite the superior performance of SLIV and WPS, these reasons could be barriers to their use during work.

While the duration of work may be governed by breathing apparatus capacity, conducting work while wearing a cooling garment after it has lost its cooling capacity will add to an individual's thermal strain. For example, the WPS loses its cooling capacity after ~60 minutes of work in the heat. After this, the additional layer of clothing and mass of equipment associated with the WPS only increases thermal insulation and metabolic cost of work. First-responders should exercise caution choosing a portable WPS when work time in the heat is predicted to be longer than 60 minutes. For simplicity, when working in Class 2 NFPA ensembles workers should opt for SLIV over the WPS when wanting to extend work tolerance times in the heat.

Considering cooling surface area coverage appears to be an important variable in extending tolerance time, cooling packs applied to thighs as well as wearing a cooling vest could be an addition for future work (24). Future work should focus on whether the use of cooling vests before and during work can extend tolerance times to similar values observed with SLIV and WPS.

The present study investigated the effect of different cooling strategies on work tolerance times whilst walking at a fixed intensity dressed in a Class 2 NFPA ensemble in a cohort of young healthy males. Therefore, caution should be applied when extrapolating these data. Whilst this study followed the criteria set out in the ASTM guidelines (F2300-10) (53) for assessing personal cooling devices, the authors recognise the limitations of this. Future studies may wish to utilise similar cooling methods in a group of older individuals more representative of the age of end-users. Further, future studies may wish to employ a range of work protocols in the field to gain more insight into the feasibility and efficacy of the cooling methods used in this study.

In conclusion, the cooling methods utilised in the present study may reduce cardiovascular and thermal strain for those performing work in the heat dressed in a Class 2 NFPA ensemble. Available resources, policies and other factors such as local fatigue may influence cooling method choice. These factors aside, the end-user should decide what they would like to achieve from a cooling method based on expected work time and intensity. If an end-user wants to extend work tolerance time, then they should opt for a WPS or SLIV method. Alternatively, if an end-user wants to only reduce physiological strain during <45 minutes of work in the heat, then an inexpensive cooling vest is sufficient.

Conflict of Interest & Funding

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References

1. Nybo L, Rasmussen P, Sawka MN. Performance in the heat-physiological factors of importance for hyperthermia-induced fatigue. Compr. Physiol. 2014;4(2):657–89.

2. Hardy JD, Du Bois EF. Basal metabolism, radiation, convection and vaporization at temperatures of 22 to 35° C. J. Nutr. 1938;15(5):477–97.

3. Cramer MN, Jay O. Biophysical aspects of human thermoregulation during heat stress. Auton. Neurosci. Basic Clin. Elsevier B.V.; 2016;196:3–13.Available from: http://dx.doi.org/10.1016/j.autneu.2016.03.001

4. Gagge AP, Gonzalez RR. Mechanisms of heat exchange: biophysics and physiology. In: Fregly MJ, Blatteis CM, editors. Handb. Physiol. Sect. 4 Environ. Physiol. New York: Oxford University Press; 1996. p. 45–84.Available from: http://onlinelibrary.wiley.com/doi/10.1002/cphy.cp040104/full

5. Muza SR, Banderet LE, Cadarette B. Protective uniforms for nuclear, biological, and chemical warfare: metabolic, thermal, respiratory, and psychological issues. In: Pandolf KB, Burr RE, editors. Med. Asp. Harsh Environ. Vol. 2 2nd ed. Washington, D.C: TMM Publications; 2001. p. 1084–187.

6. Eglin CM, Coles S, Tipton MJ. Physiological responses of fire-fighter instructors during training exercises. Ergonomics. Taylor & Francis; 2004 Apr 15;47(5):483–94.Available from: https://doi.org/10.1080/00140130310001075682

7. Eglin CM. Physiological Responses to Fire-fighting: Thermal and Metabolic

Considerations. J. Human-Environment Syst. 2007;10(1):7–18.

8. Carter BJ, Cammermeyer M. Emergence of real casualties during simulated chemical warfare training under high heat conditions. Mil. Med. 1985;150(12):657–63.

9. Stewart IB, Rojek AM, Hunt AR. Heat strain during explosive ordnance disposal. Mil. Med. 2011;176(8):959–63.

10. Cheung SS, McLellan TM, Tenaglia S. The thermophysiology of uncompensable heat stress. Physiological manipulations and individual characteristics. Sport. Med. 2000;29(5):329–59.Available from: http://link.springer.com/10.2165/00007256-200029050-00004

11. Taylor NAS. Overwhelming Physiological Regulation Through Personal Protection. J. Strength Cond. Res. 2015;29(11):111–8.

12. McLellan TM, Daanen HAM, Cheung SS. Encapsulated environment. Compr. Physiol. 2013;3(3):1363–91.

13. Cadarette BS, Levine L, Staab JE, Kolka MA, Correa MM, Whipple M, et al. Upper Body Cooling During Exercise-Heat Stress Wearing the Improved Toxicological Agent Protective System for HAZMAT Operations. AIHA J. Taylor & Francis; 2003 Jul 1;64(4):510–5.Available from: https://doi.org/10.1080/15428110308984847

14. Butts CL, Smith CR, Ganio MS, McDermott BP. Physiological and perceptual effects of a cooling garment during simulated industrial work in the heat. Appl. Ergon. Elsevier Ltd; 2017;59:442–8.

15. Glitz KJ, Seibel U, Rohde U, Gorges W, Witzki A, Piekarski C, et al. Reducing heat stress under thermal insulation in protective clothing: microclimate cooling by a “physiological” method. Ergonomics. 2015;58(8):1461–9.

16. House JR, Lunt HC, Taylor R, Milligan G, Lyons JA, House CM. The impact of a phase-change cooling vest on heat strain and the effect of different cooling pack melting temperatures. Eur. J. Appl. Physiol. 2013;113(5):1223–31.

17. Kim J-H, Coca A, Williams WJ, Roberge RJ. Effects of Liquid Cooling Garments on Recovery and Performance Time in Individuals Performing Strenuous Work Wearing a Firefighter Ensemble. J. Occup. Environ. Hyg. Taylor & Francis; 2011 Jul 1;8(7):409–16.Available from: https://doi.org/10.1080/15459624.2011.584840

18. Kenny GP, Schissler AR, Stapleton J, Piamonte M, Binder K, Lynn A, et al. Ice cooling vest on tolerance for exercise under uncompensable heat stress. J. Occup. Environ. Hyg. 2011;88(8):484–91.Available from: http://www.tandfonline.com/loi/uoeh20%5Cnhttp://dx.doi.org/10.1080/15459624.2011.596043%5Cnhttp://www.tandfonline.com/page/terms-and-conditions

19. Muir IH, Bishop PA, Ray P. Effects of a Novel Ice-Cooling Technique on Work in Protective Clothing at 28°C, 23°C, and 18°C WBGTs. Am. Ind. Hyg. Assoc. J. Taylor & Francis; 1999 Jan;60(1):96–104.Available from: https://doi.org/10.1080/00028899908984427

20. House JR. Reducing heat strain with ice-vests or hand immersion. In: Shapiro Y, Epstein Y, Moran D, editors. 7th Int. Conf. Environ. Ergon. Israel; 1996. p. 347–50.

21. Bennett BL, Hagan RD, Huey KA, Minson C, Cain D. Comparison of two cool vests on heat-strain reduction while wearing a firefighting ensemble. Eur. J. Appl. Physiol. Occup. Physiol. 1995;70(4):322–8.Available from: https://doi.org/10.1007/BF00865029

22. Carter JM, Rayson MP, Wilkinson DM, Richmond V, Blacker S. Strategies to combat heat strain during and after firefighting. J. Therm. Biol. 2007;32(2):109–16.Available from: http://www.sciencedirect.com/science/article/pii/S0306456506001306

23. Williamson R, Carbo J, Luna B, Webbon BW. A thermal physiological comparison of two HAZMAT protective ensembles with and without active convective cooling. J. Occup. Environ. Med. United States; 1999 Jun;41(6):453–63.

24. Kamon E, Kenney WL, Deno NS, Soto KI, Carpenter AJ. Readdressing personal cooling with ice. Am. Ind. Hyg. Assoc. J. United States; 1986 May;47(5):293–8.

25. McLellan TM, Frim J, Bell DG. Efficacy of air and liquid cooling during light and heavy exercise while wearing NBC clothing. Aviat. Space. Environ. Med. United States; 1999 Aug;70(8):802–11.

26. Quinn T, Kim J-H, Seo Y, Coca A. Comparison of Thermal Manikin Modeling and Human Subjects' Response During Use of Cooling Devices Under Personal Protective Ensembles in the Heat. Prehosp. Disaster Med. 2018/04/19. Cambridge University Press; 2018;33(3):279–87.Available from: https://www.cambridge.org/core/article/comparison-of-thermal-manikin-

modeling-and-human-subjects-response-during-use-of-cooling-devices-under-personal-protective-ensembles-in-the-heat/B749C202E66B095B664F4F614B2E8BF2

27. Quinn T, Kim J-H, Strauch A, Wu T, Powell J, Roberge R, et al. Physiological Evaluation of Cooling Devices in Conjunction With Personal Protective Ensembles Recommended for Use in West Africa. Disaster Med. Public Health Prep. 2017/03/17. Cambridge University Press; 2017;11(5):573–9.Available from: https://www.cambridge.org/core/article/physiological-evaluation-of-cooling-devices-in-conjunction-with-personal-protective-ensembles-recommended-for-use-in-west-africa/0BACB0B217F3F2FE57D67E805CB0FDB8

28. Bach AJE, Maley MJ, Minett GM, Zietek SA, Stewart KL, Stewart IB. An Evaluation of Personal Cooling Systems for Reducing Thermal Strain Whilst Working in Chemical/Biological Protective Clothing. Front. Physiol. 2019;10.

29. Watkins ER, Hayes M, Watt P, Richardson AJ. Practical pre-cooling methods for occupational heat exposure. Appl. Ergon. 2018;70:26–33.Available from: http://www.sciencedirect.com/science/article/pii/S000368701830019X

30. Tokizawa K, Sawada S, Oka T, Yasuda A, Tai T, Ida H, et al. Fan-precooling effect on heat strain while wearing protective clothing. Int. J. Biometeorol. 2014;58(9):1919–25.

31. Pryor RR, Suyama J, Guyette FX, Reis SE, Hostler D. The effects of ice slurry ingestion before exertion in Wildland firefighting gear. Prehospital Emerg. care. 2015;19(2):241–6.

32. National Fire Protection Association. NFPA 1994 – Standard on Protective Ensembles for First Responders to Hazardous Materials Emergencies and CBRN Terrorism Incidents [Internet]. Massachusetts: National Fire Protection Association; 2018.Available from: https://www.nfpa.org/codes-and-standards/all-codes-and-standards/list-of-codes-and-standards/detail?code=1994

33. European Food Safety Authority. Scientific opinion on dietary reference values for water. EFSA J. 2010 Mar;8(3):1459–507.Available from: http://doi.wiley.com/10.2903/j.efsa.2010.1459

34. Maley MJ, Costello JT, Borg DN, Bach AJE, Hunt AP, Stewart IB. An Overt Chemical Protective Garment Reduces Thermal Strain Compared with a Covert Garment in Warm-Wet but Not Hot-Dry Environments. Front. Physiol. 2017;8.Available from: http://journal.frontiersin.org/article/10.3389/fphys.2017.00913/full

35. ASTM Standard F2668-07. Determining the physiological responses of the wearer to protective clothing ensembles. West Conshohocken, PA; 2007.

36. Siegel R, Maté J, Brearley MB, Watson G, Nosaka K, Laursen PB. Ice slurry ingestion increases core temperature capacity and running time in the heat. Med. Sci. Sports Exerc. 2010;42(4):717–25.

37. Maley MJ, Minett GM, Bach AJE, Zietek SA, Stewart KL, Stewart IB. Internal and external cooling methods and their effect on body temperature, thermal perception and dexterity. PLoS One. 2018;13(1):e0191416.Available from: http://dx.plos.org/10.1371/journal.pone.0191416

38. Armstrong LE. Hydration assessment techniques. Nutr. Rev. 2005;63(6 Pt 2):S40–54.

39. International Organisation for Standardisation. ISO 9886: Ergonomics — Evaluation of thermal strain by physiological measurements. Geneva: International Organisation for Standardisation; 2004.

40. Cumming G. Understanding the new statistics: Effect sizes, confidence intervals, and meta-analysis. Routledge; 2013.

41. Cohen J. Statistical power analysis for the behavioral sciences. 2nd ed. Hillsdale, NJ: Erlbaum; 1988.

42. Cohen J. A power primer. Psychol. Bull. 1992;112(1):155–9.

43. Price MJ, Boyd C, Goosey-Tolfrey VL. The physiological effects of pre-event and midevent cooling during intermittent running in the heat in elite female soccer players. Appl. Physiol. Nutr. Metab. 2009;34(5):942–9.

44. Kay D, Taaffe DR, Marino FE. Whole-body pre-cooling and heat storage during self-paced cycling performance in warm humid conditions. J. Sports Sci. 1999;17(12):937–44.Available from: http://www.tandfonline.com/doi/abs/10.1080/026404199365326

45. Quod MJ, Martin DT, Laursen PB, Gardner AS, Halson SL, Marino FE, et al. Practical precooling: Effect on cycling time trial performance in warm conditions. J. Sports Sci. 2008;26(14):1477–87.Available from: http://www.tandfonline.com/doi/abs/10.1080/02640410802298268

46. Duffield R, Green R, Castle P, Maxwell N. Precooling can prevent the

reduction of self-paced exercise intensity in the heat. Med. Sci. Sports Exerc. 2010;42(3):577–84.

47. Kenney WL, Stanhewicz AE, Bruning RS, Alexander LM. Blood pressure regulation III: what happens when one system must serve two masters: temperature and pressure regulation? Eur. J. Appl. Physiol. 2014;114(3):467–79.

48. Price M, Maley MJ. The effects of ice vest pre-cooling on skin blood flow at rest and during exercise in the heat. Extrem. Physiol. Med. BioMed Central Ltd; 2015;4(Suppl 1):A127.Available from: http://www.extremephysiolmed.com/content/4/S1/A127

49. Bogerd N, Perret C, Bogerd CP, Rossi RM, Daanen HAM. The effect of pre-cooling intensity on cooling efficiency and exercise performance. J. Sports Sci. 2010;28(7):771–9.Available from: http://www.tandfonline.com/doi/abs/10.1080/02640411003716942

50. Speckman KL, Allan AE, Sawka MN, Young AJ, Muza SR, Pandolf KB. Perspectives in microclimate cooling involving protective clothing in hot environments. Int. J. Ind. Ergon. 1988;3(2):121–47.Available from: http://www.sciencedirect.com/science/article/pii/0169814188900157

51. Altman DG, Bland JM. Statistics notes: Absence of evidence is not evidence of absence. BMJ. 1995 Aug 19;311(7003):485.Available from: http://www.bmj.com/content/311/7003/485.abstract

52. Bach AJE, Maley MJ, Minett GM, Stewart IB. Occupational cooling practices of emergency first responders in the United States: A survey. Temperature.

2018;5(4):348–58.

53. ASTM Standard F2300-10. Standard test method for measuring the performance of personal cooling systems using physiological testing. West Conshohocken, PA; 2016.