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

3

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12       **Running head**

13       Protective ensembles, work tolerance time and cooling

14

15 **Abstract**

16 **Objectives**

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

20 **Methods**

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

27 **Results**

28 Tolerance time was extended in PCM (46 [36, 56] min,  $P = 0.018$ ), SLIV (56 [46, 67]  
29 min,  $P < 0.001$ ) and WPS (62 [53, 70] min,  $P < 0.001$ ), compared with control (39  
30 [30, 48] min). Tolerance time was longer in SLIV and WPS compared with both IV  
31 (48 [39, 58 min]) and PCM ( $P \leq 0.011$ ). After 20 min of work, HR was lower in SLIV  
32 (121 [105, 136] beats·min<sup>-1</sup>), WPS (117 [101, 133] beats·min<sup>-1</sup>) and IV (130 [116,  
33 143] beats·min<sup>-1</sup>) compared with control (137 [120, 155] beats·min<sup>-1</sup>) (all  $P < 0.001$ ).  
34 PCM (133 [116, 151] beats·min<sup>-1</sup>) did not differ from control.

35 **Conclusion**

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

39 **Key words**

40 Heat stress; cardiovascular strain; thermal strain; thermoregulation; body cooling;

41 occupational.

42

43 **Introduction**

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

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

62 Due to the plethora of cooling methods available, choosing the most appropriate may  
63 not always be an easy choice. For example, trying to extend work tolerance time  
64 may require different cooling strategies compared to only wanting to reduce  
65 physiological strain during work (28). Considering the many cooling methods  
66 available, studies that compare one or two cooling methods with control of no cooling

67 limit the possible recommendations to end-users. Further, when deciding their choice  
68 of cooling strategy end-users need to consider other factors, such as work location,  
69 CBRN ensemble in use and available resources.

70 Although previous studies used cooling methods during work (per-cooling),  
71 individuals may also take advantage of cooling before work (i.e. pre-cooling). This  
72 approach has received less attention, though positive results are reported (29–31).  
73 We recently showed in a Class 3 National Fire Protection Association (NFPA) CBRN  
74 ensemble (32) that per-cooling successfully extended work tolerance time similarly to  
75 pre- and per-cooling (28). However, it is unknown whether the cooling methods that  
76 extended work tolerance time in the Class 3 ensemble translate to the heavier Class  
77 2 ensemble. Therefore, this study aims to investigate whether a combination of pre-  
78 and per-cooling further reduces physiological strain and extends tolerance time  
79 compared with pre-cooling only in Class 2 ensembles.

## 80 **Methods**

81 The present study was approved by the Queensland University of Technology  
82 Human Research Ethics Committee (#1700001026) and complied with standards set  
83 in the Declaration of Helsinki (2013). The participants were made aware of the  
84 purpose, procedures and risks of the study before giving their informed written  
85 consent. A total of eight male participants volunteered. Their physical characteristics  
86 were as follows [mean (SD)]: 24 (4) years of age; height of 180.2 (7.5) cm; body  
87 mass of 77.1 (6.8) kg; body fat of 13.8 (5.9) %; maximal oxygen uptake ( $VO_{2max}$ ) of  
88 51.0 (3.5)  $mL \cdot kg^{-1} \cdot min^{-1}$ . All participants were non-smokers and free from any  
89 vascular, blood and respiratory conditions.

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

## 96 **Familiarisation Session**

97 Participants' height, nude body mass and body fat were measured before performing  
98 a progressive incremental running test to exhaustion on a motorised treadmill to  
99 ascertain their  $VO_{2max}$ . Body composition was measured using dual-energy X-ray  
100 absorptiometry (Lunar Prodigy, GE Healthcare Lunar, USA) and analysed using  
101 dedicated software (enCORE, version 9, GE Healthcare Lunar, USA). Following a  
102 warm-up period, participants were fitted with expired gas analysis equipment (Parvo  
103 Medics TrueOne 2400, USA) and a heart rate (HR) monitor (Polar Team<sup>2</sup>, Finland).  
104 The test started at a speed of  $\sim 8 \text{ km} \cdot \text{h}^{-1}$  and a 1 % grade. On every minute, the

105 speed was increased by  $1 \text{ km}\cdot\text{h}^{-1}$  until a speed the participant could maintain for at  
106 least two minutes was achieved. After, the grade was increased by 1 % every minute  
107 until volitional exhaustion. The variables used for the determination of  $\text{VO}_{2\text{max}}$  -  
108 followed the standard laboratory procedure (28,34). Following this, participants were  
109 familiarised with the CBRN ensemble; this involved donning all equipment and  
110 walking on the treadmill (described below) for 15 minutes.

### 111 **Experimental Sessions**

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

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

124 Standard termination criteria were applied during each trial in accordance with the  
125 ASTM guidelines (F2668-07, 2007) which included: (1) deep body temperature  $>39.0$   
126  $^\circ\text{C}$ , (2) 120 minutes of work, (3)  $\text{HR} \geq 90$  % of maximum, or (4) fatigue or nausea  
127 (self-termination). Following the attainment of one of the termination criteria, the  
128 participant exited the climate-controlled chamber.



129 ***Personal Cooling Garments and Protocols***

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

133 *Per-Cooling, Cooling Vests (IV, PCM)*

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

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

139 Thirty minutes before walking commenced, participants ingested 7.5 g·kg<sup>-1</sup> of ice  
140 slushy (-2 °C) at a rate of 1.25 g·kg<sup>-1</sup> every five minutes (36,37). Each drink was  
141 prepared using a slushy machine (Model SSM-180, ICETRO, South Korea) with the  
142 same flavouring used (The Slushie Specialists, Australia). Following this, participants  
143 donned IV (as above).

144 *Per-Cooling, Water-perfused Suit (WPS)*

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

152 **Measurements and Calculations**

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

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

$$\bar{T}_{msk} = 0.28T_{neck} + 0.28T_{scapula} + 0.16T_{hand} + 0.28T_{shin}$$

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

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

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

### 173 **Statistical Analyses**

174 A one-way repeated-measures analysis of variance was used to compare tolerance  
 175 time and sweat rate between trials. A two-way repeated-measures analysis of  
 176 variance was used to compare  $T_{\text{rec}}$ ,  $\bar{T}_{\text{msk}}$ , and HR between trials at baseline, minute  
 177 5, 10, 15, 20 of work and upon participant termination. The data were only analysed  
 178 during work to 20 minutes as participants began to terminate from 21 minutes. When  
 179 statistically significant interactions were observed, differences between trials were  
 180 assessed using a paired sampled *t*-test. Multiple comparisons were corrected using  
 181 Tukey's test. An  $\alpha$  of 0.05 was used to determine statistical significance. Statistical  
 182 analyses were conducted using GraphPad Prism (version 7, GraphPad Software,  
 183 USA). Effect sizes were calculated for pairwise comparisons using an unbiased  
 184 Cohen's *d* ( $d_{\text{unb}}$ ) and calculated as (40):

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

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

185 Where  $M_{\text{diff}}$  is the difference in means between two trials, and SD1 and SD2 are the  
 186 SD of the two trials. Effect sizes were interpreted as small (0.20–0.49), moderate  
 187 (0.50–0.79) or large ( $\geq 0.80$ ) (41,42). Data are presented as mean and 95 %  
 188 confidence intervals (CI).

189 **Results**

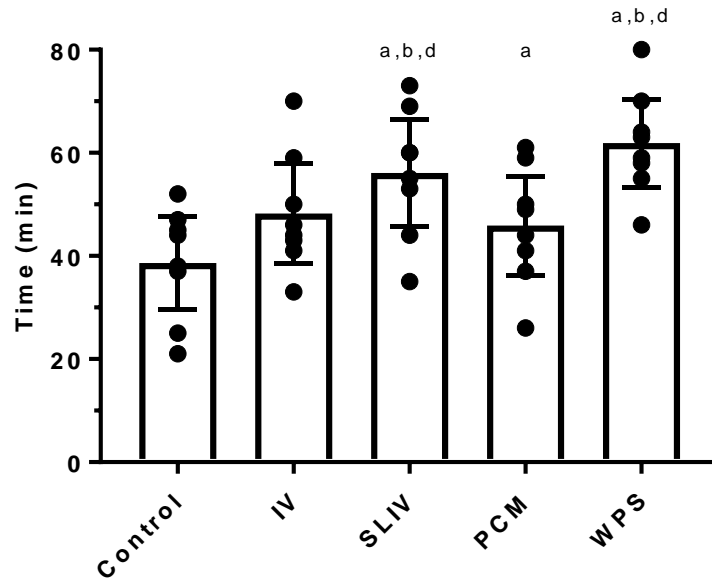
190 **Tolerance Time**

191 There was a statistically significant main effect between trials for tolerance time  
192 (Figure 1,  $P < 0.001$ ). While IV (48 [39, 58] min) did not statistically differ from control  
193 (39 [30, 48] min,  $P = 0.078$ ,  $d_{unb} = 0.77$ ), tolerance time was longer, compared with  
194 control, in SLIV (56 [46, 67] min,  $P < 0.001$ ,  $d_{unb} = 1.33$ ), PCM (46 [36, 56] min,  $P =$   
195  $0.018$ ,  $d_{unb} = 0.58$ ) and WPS (62 [53, 70] min,  $P < 0.001$ ,  $d_{unb} = 1.97$ ). Tolerance time  
196 was also longer in SLIV compared with both IV ( $P = 0.011$ ,  $d_{unb} = 0.58$ ) and PCM ( $P$   
197  $= 0.005$ ,  $d_{unb} = 0.76$ ). Similarly, tolerance time was longer in WPS compared with  
198 both IV ( $P < 0.001$ ,  $d_{unb} = 1.12$ ) and PCM ( $P = 0.001$ ,  $d_{unb} = 1.31$ ). Most participants  
199 terminated as a result of either high  $T_{rec}$  ( $>39.0$  °C) or reaching a HR  $\geq 90$  % of  
200 maximum (Table 1).

201 Table 1. Termination criteria for each condition

	HR ( $\geq 90$ % 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	-
<b>Total</b>	<b>22</b>	<b>17</b>	<b>1</b>	<b>0</b>

202



203

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

205 <sup>a,b,d</sup> Statistical difference compared with control, IV, PCM, respectively ( $P < 0.05$ ).

## 206 Physiological Variables

207 For  $T_{rec}$ , there was a statistically significant main effect for trial ( $P < 0.001$ ), time ( $P <$   
 208  $0.001$ ) and interaction (Table 2, Figure 2A,  $P < 0.001$ ). Pairwise comparisons of the  
 209 interaction revealed  $T_{rec}$  was lower in SLIV compared with all trials from baseline  
 210 until 20 min of work ( $P < 0.001$ ,  $d_{unb} \leq 1.92$ ). Upon termination,  $T_{rec}$  was lower in  
 211 control ( $P = 0.039$ ,  $d_{unb} = 0.45$ ) and WPS ( $P = 0.003$ ,  $d_{unb} = 0.67$ ) compared with  
 212 SLIV.

213 For  $\bar{T}_{msk}$ , there was a statistically significant main effect for trial ( $P < 0.001$ ), time ( $P$   
 214  $< 0.001$ ) and interaction (Table 3, Figure 2B,  $P < 0.001$ ). Pairwise comparisons of  
 215 the interaction revealed,  $\bar{T}_{msk}$  was cooler throughout work in IV ( $P < 0.001$ ,  $d_{unb} \leq$   
 216  $6.19$ ), SLIV ( $P < 0.001$ ,  $d_{unb} \leq 7.30$ ), PCM ( $P < 0.001$ ,  $d_{unb} \leq 2.68$ ) and WPS ( $P \leq$   
 217  $0.024$ ,  $d_{unb} \leq 4.04$ ) compared with control. Up to 20 min of work,  $\bar{T}_{msk}$  was cooler in  
 218 IV ( $P < 0.001$ ,  $d_{unb} \leq 2.03$ ) and SLIV ( $P < 0.001$ ,  $d_{unb} \leq 2.54$ ) compared with PCM.

219 Similarly,  $\bar{T}_{\text{msk}}$  was cooler in IV ( $P < 0.001$ ,  $d_{\text{unb}} \leq 3.00$ ) and SLIV ( $P < 0.001$ ,  $d_{\text{unb}} \leq$   
220 3.82) compared with WPS. On termination,  $\bar{T}_{\text{msk}}$  was cooler in IV compared with  
221 control ( $P < 0.001$ ,  $d_{\text{unb}} = 1.94$ ), SLIV ( $P = 0.036$ ,  $d_{\text{unb}} = 0.35$ ), PCM ( $P = 0.001$ ,  $d_{\text{unb}}$   
222  $= 0.60$ ) and WPS ( $P < 0.001$ ,  $d_{\text{unb}} = 1.26$ ). In addition,  $\bar{T}_{\text{msk}}$  was cooler in SLIV ( $P <$   
223  $0.001$ ,  $d_{\text{unb}} = 0.60$ ) and PCM ( $P = 0.013$ ,  $d_{\text{unb}} = 0.61$ ) compared with WPS.

224 For HR, there was a statistically significant main effect for trial ( $P = 0.003$ ), time ( $P <$   
225  $0.001$ ) and interaction (Table 4, Figure 2C,  $P < 0.001$ ). After 20 min of work, HR was  
226 lower in SLIV compared with control ( $P < 0.001$ ,  $d_{\text{unb}} = 0.75$ ), IV ( $P < 0.001$ ,  $d_{\text{unb}} =$   
227  $0.47$ ) and PCM ( $P < 0.001$ ,  $d_{\text{unb}} = 0.57$ ). Similarly, HR was lower in WPS compared  
228 with control ( $P < 0.001$ ,  $d_{\text{unb}} = 0.89$ ), IV ( $P < 0.001$ ,  $d_{\text{unb}} = 0.63$ ) and PCM ( $P < 0.001$ ,  
229  $d_{\text{unb}} = 0.71$ ).

230 Sweat rate was similar ( $P > 0.05$ ) between control (0.99 [0.71, 1.26] L·h<sup>-1</sup>), IV (0.99  
231 [0.71, 1.26] L·h<sup>-1</sup>), PCM (1.07 [0.83, 1.31] L·h<sup>-1</sup>), SLIV (0.82 [0.49, 1.16] L·h<sup>-1</sup>) and  
232 WPS (1.00 [0.82, 1.18] L·h<sup>-1</sup>).

233

234 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)

235 <sup>a,b,d,e</sup> Statistical difference compared with control, IV, PCM, WPS, respectively ( $P < 0.05$ ).

236 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

237 <sup>b,c,d,e</sup> Statistical difference compared with IV, SLIV, PCM, WPS, respectively ( $P < 0.05$ ).

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239

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

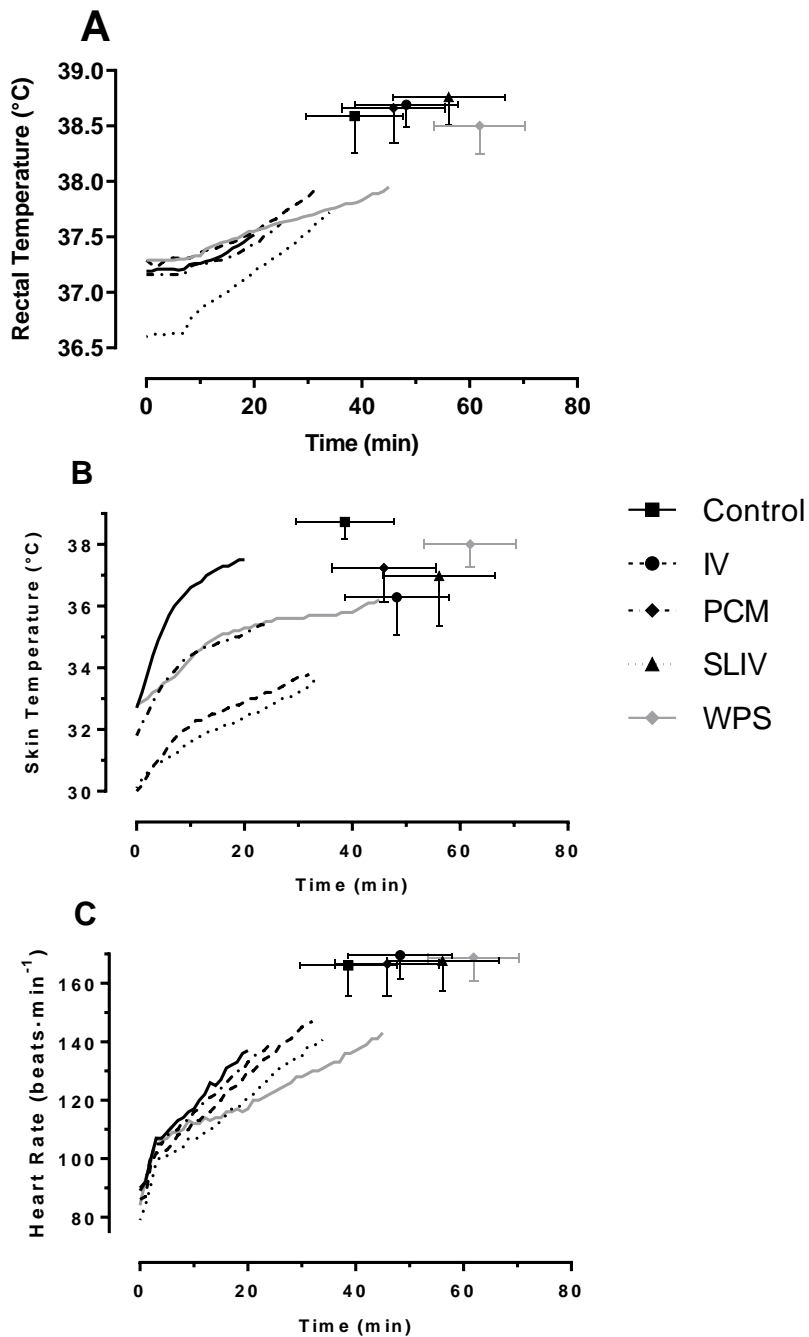
	Heart Rate (beats·min <sup>-1</sup> )				
	Control	IV	SLIV	PCM	WPS
<b>0</b>	89 (80, 97)	86 (75, 98)	79 (68, 89) <sub>a,b,d,e</sub>	90 (80, 99)	84 (71, 97)
<b>5</b>	109 (95, 123)	103 (94, 112) <sub>a</sub>	101 (91, 111) <sub>a,d,e</sub>	108 (97, 119)	107 (95, 119)
<b>10</b>	117 (102, 133)	113 (103, 123)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

241 <sup>a,b,d,e</sup> Statistical difference compared with control, IV, PCM, WPS, respectively ( $P < 0.05$ ).

243

244





245  
 246 Figure 2. Mean (95 % CI) (A) rectal temperature, (B) skin temperature and (C) heart  
 247 rate for each trial during work

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

250 **Discussion**

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

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

267 There is a redistribution of blood flow to the working muscles and cutaneous  
268 circulation during work in the heat. It is proposed that in young healthy adults, the  
269 two vascular beds are adequately perfused to meet demands (47); that is, mean  
270 arterial pressure is not compromised but working in the heat dressed in CBRNE  
271 ensembles will, however, place a significant demand on the heart to maintain cardiac  
272 output (1). As a result, heart rate rises rapidly, eventually rising to maximal levels.  
273 Cooling methods have shown to reduce cutaneous blood flow (48,49), which may

274 benefit the cardiovascular system by attenuating the rise in heart rate during work.  
275 Supporting this, the present study showed the addition of slushy ingestion to IV  
276 further reduced thermoregulatory strain (Table 2, Figure 2A) which benefited the  
277 cardiovascular system (Table 4, Figure 2C).

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

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

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

306 While the duration of work may be governed by breathing apparatus capacity,  
307 conducting work while wearing a cooling garment after it has lost its cooling capacity  
308 will add to an individual's thermal strain. For example, the WPS loses its cooling  
309 capacity after ~60 minutes of work in the heat. After this, the additional layer of  
310 clothing and mass of equipment associated with the WPS only increases thermal  
311 insulation and metabolic cost of work. First-responders should exercise caution  
312 choosing a portable WPS when work time in the heat is predicted to be longer than  
313 60 minutes. For simplicity, when working in Class 2 NFPA ensembles workers  
314 should opt for SLIV over the WPS when wanting to extend work tolerance times in  
315 the heat.

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

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

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

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