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1 **Exploring the Efficacy of a Safe Cryotherapy Alternative: Physiological Temperature**
2 **Changes from Cold Water Immersion vs Prolonged Phase Change Material Cooling**

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4 **Full names of the authors and institutional/corporate affiliations:** Susan Y. Kwiecien^{1,2},
5 Malachy P. McHugh^{1,2}, Stuart Goodall², Kirsty M. Hicks², Angus M. Hunter³, Glyn Howatson^{2,4}

6 ¹ Nicholas Institute of Sports Medicine and Athletic Trauma, Lenox Hill Hospital, New York,
7 NY, USA

8 ² Department of Sport, Exercise & Rehabilitation, Northumbria University, Newcastle upon
9 Tyne, UK

10 ³ Physiology, Exercise and Nutrition Research Group, University of Stirling, Scotland, UK

11 ⁴ Water Research Group, North West University, Potchefstroom, South Africa

12 **Contact details for the corresponding author:** Susan Y. Kwiecien; Nicholas Institute of Sports
13 Medicine and Athletic Trauma; MEETH, 210 East 64 Street, 5th Floor, NISMAT, New York,
14 New York, 10065, USA; 212-434-2752; 212-434-2687; susan@nismat.org

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20 **Abstract**

21 **Purpose:** To evaluate the effectiveness between cold water immersion (CWI) and phase change
22 material (PCM) cooling on intramuscular, core and skin temperature and cardiovascular
23 responses.

24 **Methods:** In a randomized, crossover design, 11 males completed 15 min of 15°C CWI to the
25 umbilicus and 2 h recovery or 3 h of 15°C PCM covering the quadriceps and 1 h of recovery,
26 separated by 24 h. Vastus lateralis intramuscular temperature at 1 and 3 cm, core and skin
27 temperature, heart rate variability and thermal comfort were recorded at baseline, and 15 min
28 intervals throughout treatment and recovery.

29 **Results:** Intramuscular temperature decreased ($P < 0.001$) during and after both treatments. A
30 faster initial effect was observed from 15 min of CWI (Δ : $4.3 \pm 1.7^\circ\text{C}$ 1 cm; $5.5 \pm 2.1^\circ\text{C}$ 3 cm;
31 $P = 0.01$). However, over time (2 h 15 min), greater effects were observed from prolonged PCM
32 treatment (Δ : $4.2 \pm 1.9^\circ\text{C}$ 1 cm; $2.2 \pm 2.2^\circ\text{C}$ 3 cm; treatment \times time $P = 0.0001$). During the first
33 hour of recovery from both treatments, intramuscular temperature was higher from CWI at 1 cm
34 ($P = 0.013$) but not 3 cm. Core temperature decreased 0.25 ± 0.32 from CWI ($P = 0.001$) and
35 $0.28 \pm 0.27^\circ\text{C}$ from PCM ($P = 0.0001$) while heart rate variability increased during both treatments
36 ($P = 0.001$), with no differences between treatments.

37 **Conclusions:** The magnitude of temperature reduction from CWI was comparable to PCM but
38 intramuscular temperature was decreased for longer during PCM. Utilizing PCM cooling packs
39 offers an alternative for delivering prolonged cooling whenever application of CWI is
40 impractical while also exerting a central effect on core temperature and heart rate.

41 **Keywords:** cryotherapy; recovery; thermoregulation; cooling

42 **Introduction**

43 Cold water immersion (CWI) is a popular intervention utilized to facilitate recovery and
44 improve function in the days following strenuous exercise. Two comprehensive reviews on CWI
45 indicate some effectiveness at reducing soreness but inconclusive effects on other measures of
46 recovery.^{1,2} Since typical CWI protocols involve a single post-exercise treatment for 10-15 min
47 in water temperatures between 10-15°C,^{1,2} limited effectiveness might be a result of inadequate
48 treatment temperature, duration, or a combination of the two. Low immersion temperatures may
49 decrease tissue temperatures at a rate that may lead to excessive thermal stress and, if prolonged,
50 are not well tolerated³ and are limited by individual thermal discomfort and risk of cold-related
51 injury.⁴ Further, in practice, repeat treatments are impractical and present logistical challenges,
52 but may be necessary if the goal is to decrease muscle⁵ and core⁶ temperature.

53 A longer duration of targeted post-exercise cooling can be provided using temperature
54 controlled phase change material (PCM), whereby PCM packs are placed over specific muscle
55 groups and worn inside of garments to hold them in place. From a practical perspective, this
56 cryotherapy modality offers an attractive alternative to CWI as individuals can resume activities
57 of daily living while simultaneously receiving cryotherapy treatment that maintains a constant
58 temperature for an extended duration. A 6 h PCM application reduced pain and strength loss on
59 the days after eccentric quadriceps exercise in recreational athletes.⁷ A 3 h PCM application after
60 a professional soccer match also reduced pain and strength loss on subsequent days.⁸ In these
61 studies,^{7,8} participant thermal comfort was maintained while PCM packs were worn inside
62 compression shorts and maintained a constant temperature of 15°C for at least 3 h before
63 melting.

64 CWI has been shown to reduce muscle temperature,⁹⁻¹² core temperature,^{6,13,14} and
65 increase heart rate variability (HRV).¹⁵⁻¹⁷ CWI is purported to enhance recovery following
66 exercise primarily due to its ability to reduce tissue temperature and blood flow. Since the
67 mechanism through which CWI is thought to be effective is through its anti-inflammatory
68 effects,¹⁸ prolonging the duration of physiological cooling in order to attenuate metabolic
69 processes in tissues, slow the up-regulation of cytokines and myokines, and reduce the
70 circulatory exposure of the tissue to inflammatory cells following exercise seems intuitive. As
71 such, if the temperature of treatment remains physiologically favorable, then duration of
72 exposure can be extended. It is unknown to what extent prolonged PCM cooling might exert
73 effects similar to those from CWI. For this reason, it is important to understand the physiological
74 temperature effects that occur during prolonged PCM cooling and to compare them with a CWI
75 treatment of matched temperature. Therefore, the purpose of this study was to compare the
76 physiological effects (muscle, core, skin temperature and HRV) of CWI versus PCM cooling. It
77 was hypothesized that both CWI and PCM would decrease intramuscular temperature but with a
78 prolonged effect from PCM due to its ability to deliver a longer cooling duration.

79
80 **Methods**

81 *Participants*

82 Eleven active males (mean \pm SD; age, 27 \pm 6 years; height, 183.6 \pm 8.5 cm; body mass,
83 81.5 \pm 12.4 kg) volunteered to participate in this study. All participants were free from lower leg
84 injury for at least 1 month before the study and had no known vascular disease in the lower
85 limbs, compromised circulation, allergy or hypersensitivity to cold. Participants were instructed
86 to refrain from strenuous exercise for 72 h prior to, and for the duration of the study period. The

87 institutional ethics committee approved all procedures and participants gave written informed
88 consent.

89 *Experimental Design*

90 In this repeated measures, crossover design study participants visited the laboratory on 3
91 consecutive days. First for a familiarization session before data collection commenced followed
92 by two separate treatment sessions, all separated by 24 h. Participants were randomized to
93 receive one treatment on day 1 and the other treatment on day 2. Vastus lateralis muscle
94 temperature at 1 and 3 cm, skin temperature, core temperature, heart rate (HR), blood pressure
95 (BP) and thermal comfort were recorded continuously throughout baseline, treatment (15 min
96 CWI vs 3 h PCM) and recovery (2 h CWI vs 1 h PCM) during both treatments (Figure 1). Data
97 collection during CWI treatment and recovery consisted of a shorter overall collection period
98 compared to the PCM trial. Since both treatments were matched for temperature, it was
99 impractical for participants to remain instrumented for the additional 1 h of recovery following
100 CWI treatment, in order to match the duration of PCM treatment and recovery. During CWI
101 treatment (iCool Sport, Australia), participants sat immersed to the umbilicus in an inflatable,
102 temperature controlled ($15 \pm 1^\circ\text{C}$) cold-water bath for 15 min and recovery of all variables was
103 monitored for 2 h (2 h 15 min total time). During PCM treatment (Glacier Tek; USDA
104 BioPreferred PureTemp, Plymouth, MN), two PCM blocks (864 cm² area; 32.4 cm \times 2 cm \times
105 13.3 cm) frozen at 15°C were worn over the quadriceps muscles directly on the skin inside
106 compression shorts (worn up to the knee) for 3 h of treatment, and recovery of all variables was
107 monitored for 1 h (4 h total time). The PCM packs can maintain a constant temperature of 15°C
108 for at least 3 h in a thermoneutral environment (as verified by the manufacturer and an
109 independent quality assurance association, RAL; Quality and Testing Regulations for Phase
110 Change Materials), until the substance is fully melted.

111 During data collection, participants remained in a semi-reclined seated position with legs
112 outstretched on a bed except during the CWI treatment. Upon completion of each treatment, the
113 dry shorts remained on the participant, while rolled up so that the skin remained exposed, for the
114 duration of the recovery period. All testing was performed in a temperature-controlled laboratory
115 ($24.9 \pm 3.4^\circ\text{C}$).

116 *Intramuscular Temperature*

117 To account for subcutaneous fat, skinfold at the exact site of thermocouple insertion on
118 the quadriceps was measured using Skinfold Calipers (Harpenden, Baly International, West
119 Sussex, UK) by the same individual. The vastus lateralis was then marked approximately 6 cm
120 lateral to the mid-point between the superior pole of the patella and the anterior-superior iliac
121 crest using a sterile pen. Additional markings were placed 1 cm inferior and superior to this
122 point, one for each insertion depth. The area was cleaned with a povidone-iodine surgical scrub
123 solution. Insertion depth was based upon halving the skinfold measure and adding this to the
124 required depth (1 or 3 cm).

125 A 45 and 32 mm sterile intravenous 20 gauge needle catheter was used for the 3 and 1 cm
126 insertion, respectively. Insertion depth was verified by subtracting the total insertion depth (1 cm
127 or 3cm plus half the skinfold) from the corresponding length of the needle. The difference
128 (length of needle minus calculated insertion depth) was verified with a sterile ruler. Once at the
129 correct insertion depth, the needle was removed and the flexible catheter remained inserted. A
130 sterile flexible intramuscular Thermocouple Probe (Type T, IT-21; Physitemp Instruments,

131 Clifton, NJ) was threaded through the barrel of the catheter. The catheter was removed from the
132 muscle while the thermocouple remained inserted. The thermocouple insertion site was secured
133 in place with sterile tegaderm by bending the thermocouple flush with the skin. The procedure
134 was then repeated for the 1 cm deep thermocouple. Once fully instrumented, the thermocouples
135 were connected to a digital monitor (Bailey Instruments BAT-12, Physitemp Instruments, Inc)
136 for continuous recording. Thermocouples remained inserted throughout the duration of treatment
137 and recovery. At the conclusion of data collection, thermocouples were removed and ‘actual’
138 insertion depth was verified by measuring the inserted portion of the thermocouple against a
139 sterile ruler. The left leg of each subject was instrumented with thermocouples for CWI, while
140 the right leg of each subject was instrumented for PCM treatment.

141 *Body Temperature and Cardiovascular Measures*

142 Participants were provided with an activated ingestible core temperature sensor
143 (VitalSense, Respironic Inc, Murrysville, PA, USA) during familiarization. Participants were
144 instructed to ingest the capsule with water ~8 h prior to initial testing. Participants were given a
145 second core temperature sensor following completion of testing on day 1 to ingest at the same
146 time of day as done prior to the first visit.

147 On arrival to the lab for the treatments, participants were fitted with a wireless
148 ambulatory chest strap heart rate monitor equipped with a Sensor Electronics Module (SEM;
149 EQ02 LifeMonitor, Hidalgo Ltd, Cambridge, UK) that continuously recorded heart rate, core,
150 and skin temperature and with an automated blood pressure cuff on their right arm (M10-IT;
151 Omron Healthcare). A telemetric dermal patch temperature sensor (VitalSense, Respironic Inc,
152 Murrysville, PA, USA) was applied to the quadriceps of the leg that was not being instrumented
153 with intramuscular thermocouples to measure skin temperature.

154 Heart rate data were analyzed using Vivosense (Vivonoetics, San Diego, USA).
155 Automatic artifact-marking algorithm was applied to the raw electrocardiogram (sensitivity level:
156 medium noise filtering; minimal and maximal allowable heart rate limits: 30 and 220 beats per
157 minutes respectively). R-wave markings were generated for HRV calculations. The square root
158 of the mean squared differences of successive intervals (RMSSD) is reported. Research suggests
159 that RMSSD provides the most reliable and practically applicable measure for day-to-day
160 monitoring.²⁰ Five min rolling averages were calculated for RMSSD, with the baseline measure
161 taken prior to insertion of the intramuscular thermocouples.

162 Ratings of thermal comfort were recorded every 15 min. During CWI, thermal comfort
163 was asked at the first and last minute of immersion. Participants were asked to rate their thermal
164 comfort on a nine-point standard scale.²¹

165 *Data Analysis*

166 Prior to employing ANOVAs, normality of distribution of all data sets was verified using
167 the Shapiro-Wilk test. Mauchly’s test of sphericity was used to test assumptions of sphericity
168 and, where necessary, Greenhouse-Geisser corrections were applied. Statistical analyses were
169 performed using SPSS (v21 IBM, Armonk, NY). The comparison of treatments over time was
170 assessed using a 2×10 , treatment by time, repeated measures analyses of variance (ANOVA).
171 The levels for the treatment factor were group (CWI or PCM) and time (baseline [0 min], and
172 every 15 min up to 2 h 15 min). For these analyses, the entire duration of CWI treatment (15
173 min) and recovery (2 h) was compared to the first 2 h 15 min of PCM treatment. Additionally,

174 recovery effect (return to baseline) from both treatments over time was assessed using a 2×5 ,
175 treatment by time repeated measures analyses of variance (ANOVA). The levels for the time
176 factor were baseline (0 hr), 15, 30, 45 min, 1 h, and 1 h 15 min for CWI and baseline (0 hr), 3 h,
177 3 h 15 min, 3 h 30 min, 3 h 45 min, and 4 h for PCM. For these analyses, the first 1 h duration of
178 recovery following each treatment was compared. Where there was a significant treatment
179 effect, or treatment by time interaction, differences between treatments at any particular time
180 interval were assessed using Bonferroni corrections for planned pairwise comparisons.

181 Within each treatment, the changes in dependent variables over time were assessed by a
182 one factor ANOVA with differences versus baseline assessed using Bonferroni corrections for
183 planned pairwise comparisons. Additionally, Pearson product-moment correlation coefficients
184 were used to assess the relationship between thigh skinfold thickness and intramuscular
185 temperature. A probability level < 0.05 was accepted to determine significance. All data are
186 reported as group means \pm SD.

187

188 **Results**

189 *Thermocouple Depth and Skinfold*

190 Skinfolds were 10.1 ± 5.2 mm for the right leg of all participants, and 9.7 ± 5.5 mm for
191 the left leg. Thermocouple depths, corrected for skinfolds were 3.0 ± 0.4 cm and 1.0 ± 0.3 cm for
192 PCM and 3.1 ± 0.3 cm and 1.1 ± 0.3 cm for CWI. Decreases in intramuscular temperature were
193 correlated with skinfold thickness with stronger effects at 1 cm (CWI $r = 0.912$, $P < 0.001$; PCM
194 $r = 0.853$, $P < 0.001$) versus at 3 cm (CWI $r = 0.727$, $P < 0.01$; PCM $r = 0.594$, $P = 0.05$).

195 *Intramuscular Temperature*

196 Intramuscular temperature declined progressively during both treatments (time effect $P =$
197 0.0001 , Table 1) and remained below baseline at the conclusion of the recovery period (all $P <$
198 0.01 ; Figure 2). CWI decreased intramuscular temperature more rapidly and was 14.0 and 16.1%
199 lower at end of treatment vs 15 min into PCM treatment at both 1 and 3cm respectively (mean
200 difference: $4.3 \pm 1.7^\circ\text{C}$ at 1 cm and $5.5 \pm 2.1^\circ\text{C}$ at 3 cm, both $P = 0.01$). Intramuscular
201 temperature remained 10.6% lower 15 min into recovery following the CWI treatment vs 30 min
202 into PCM treatment at 3 cm (difference: $3.4 \pm 1.6^\circ\text{C}$, $P = 0.01$) but no longer at 1 cm (2.1%;
203 difference: $0.6 \pm 1.8^\circ\text{C}$, $P = 0.99$). Intramuscular temperature at 3 cm was 7.5% higher
204 (difference: $2.4 \pm 2.3^\circ\text{C}$, $P = 0.045$; Figure 2) upon conclusion of CWI recovery (2 h 15 min total
205 time) compared with 2 h 15 min into PCM treatment, while intramuscular temperature at 1 cm
206 was on average 12.5% higher between CWI vs PCM treatment from 1 h ($P = 0.003$) to 2 h 15
207 min ($P < 0.001$; Figure 2). Over time, intramuscular temperature was lower from PCM treatment
208 (treatment \times time $P = 0.0001$ at 3 and 1 cm; Figure 2). When comparing intramuscular
209 temperature for the first 1 h of recovery from both treatments, intramuscular temperature at 1 cm
210 was 4.1% higher from CWI averaging $28.6 \pm 1.4^\circ\text{C}$ than from PCM averaging $27.7 \pm 1.7^\circ\text{C}$
211 (treatment effect, $P = 0.013$; Figure 3), with no difference at 3 cm (2.2%; treatment effect $P =$
212 0.35 ; Figure 3).

213 *Core Temperature*

214 Core temperature declined during the PCM and CWI treatments (time effect, $P = 0.0001$,
215 Figure 4), with no difference between treatments (treatment \times time $P = 0.10$) (Figure 4). The
216 nadir of core temperature from PCM treatment occurred 45 min into the recovery period

217 (absolute time: 3 h 45 min; $0.28 \pm 0.27^{\circ}\text{C}$ below baseline) while the nadir of core temperature
218 from CWI treatment occurred 1 h 30 min into the recovery period (absolute time: 1 h 45 min;
219 $0.25 \pm 0.32^{\circ}\text{C}$ below baseline).

220 *Skin Temperature*

221 Skin temperature declined during both PCM and CWI treatments (time effect, $P =$
222 0.0001). CWI decreased skin temperature more rapidly (treatment \times time, $P = 0.0001$) than PCM.
223 Skin temperature immediately after CWI was $2.4 \pm 1.7^{\circ}\text{C}$ lower than 15 min into the PCM
224 treatment, however, at all subsequent time points, skin temperature was lower during the PCM
225 treatment ($P < 0.01$). During CWI treatment, skin temperature dropped from $31.3 \pm 1.1^{\circ}\text{C}$ at
226 baseline to $23.6 \pm 0.8^{\circ}\text{C}$ at 15 min and was $29.5 \pm 1.2^{\circ}\text{C}$ 2 h after CWI. During PCM treatment,
227 skin temperature averaged $24.1 \pm 0.3^{\circ}\text{C}$ over the 3 h during which subjects wore the PCM and
228 was $27.7 \pm 1.1^{\circ}\text{C}$ 1 h after removal of PCM.

229 *Perceived Thermal Comfort*

230 Thermal comfort was significantly different between treatments (treatment \times time $P =$
231 0.002) with greater thermal discomfort reported immediately post CWI (2.7 ± 0.8 vs. 4.5 ± 0.8
232 15 min into the PCM treatment, $P = 0.01$). This time point is also where thermal comfort reached
233 its nadir for both treatments. Upon conclusion of PCM treatment, thermal comfort was ($4.9 \pm$
234 1.0). Thermal comfort returned to baseline following 30 min of the recovery period post PCM
235 treatment.

236 *Cardiovascular Measures*

237 There were technical issues with heart rate signals for 2 participants during the entire
238 PCM treatment and for one participant after 2 h of the PCM treatment. Thus only 9 participants
239 were included in the treatment by time analysis of heart rate data and the time analysis only
240 included data up to 2 h. heart rate declined during both treatments (time effect $P = 0.0001$) with
241 no interaction effects ($P > 0.05$; Table 2). Overall there was an increase in RMSSD during
242 treatments (Time effect $P < 0.0001$) with no interaction effect ($P = 0.155$; Table 2). For the PCM
243 treatment there was a trend for an increase in RMSSD (Time effect $P = 0.069$) while for the CWI
244 treatment there was a clear increase in RMSSD (Time effect $P = 0.0001$). Blood pressure was
245 unaffected by either treatment ($P = 0.15-0.95$) and there were no differences between treatments
246 ($P = 0.62$ for systolic, $P = 0.84$ for diastolic).

247 **Discussion**

249 The main finding in this study was that 15 min of CWI was comparable to PCM packs
250 applied directly to the skin overlying the quadriceps for 3 hours in terms of the magnitude of
251 reduction in vastus lateralis intramuscular temperature. Ultimately PCM treatment provided a
252 sustained decrease in intramuscular temperature that was maintained for the 3 h of application
253 (Figure 2), and a more gradual recovery (Figure 3). However, the initial reduction in
254 intramuscular temperature was more rapid during the CWI treatment. In addition to the local
255 effects on muscle temperature, both treatments provided local and systemic effects by decreasing
256 core temperature, heart rate and increasing HRV. Importantly, the systemic effects were
257 observed despite there being no exercise intervention to induce cardiovascular stress prior to the
258 treatments. The combined local and systemic effects likely explain the accelerated recovery from
259 strenuous exercise that have recently been demonstrated with PCM cooling.^{7,8} This study

260 provides the first evidence that the application of this novel cooling modality, PCM, elicits
261 comparable physiological effects to those from CWI treatment.

262 In the present study, average vastus lateralis temperature at 1 cm for the total PCM trial
263 period (4 h) was 7% lower than the average temperature at 1 cm for the total CWI trial (2 h 15
264 min).. Thus, not only can PCM provide prolonged cooling, it can also provide a greater
265 magnitude of cooling to the peripheral musculature. This may have implications for use in
266 exercise recovery. Since the damage that occurs following strenuous exercise is bimodal,
267 involving both the initial mechanical and/or metabolic muscle injury and a secondary phase that
268 involves a disruption in intracellular homeostasis followed by an inflammatory response which
269 initiates 2-6 hrs post damaging exercise.²² A prolonged cooling intervention during this
270 timeframe has potential to blunt the inflammatory process that occurs following exercise, thereby
271 mitigating any additional damage caused by the inflammatory response,¹⁸ limiting further
272 hemorrhage and cell death.²² In support of this rationale, it has previously been demonstrated in
273 an animal model that local cooling at 8°C for 6 hrs after closed soft tissue injury limited
274 subsequent tissue damage.²³

275 An interesting aspect of the current results is that CWI can induce a rapid drop in muscle
276 temperature while PCM cooling provides a gradual prolonged decrease in muscle temperature
277 with a slower rise in muscle temperature at 1 cm during recovery (Figure 3). Therefore, if the
278 goal is to maximize the tolerable decline in muscle temperature for a sustained period of time,
279 athletes might opt to combine the treatments. In practice, once an athlete completed a CWI
280 treatment, quickly decreasing their intramuscular and core temperature, they could apply PCM
281 over muscle groups they wish to keep cool in order to maintain the reduction of temperature
282 while returning to normal post exercise activities (e.g. meal, relaxation, recreational activities).
283 This could allow the athlete to sustain the treatment effect from CWI for a longer period of time
284 in the immediate post-exercise period.

285 The systemic effects observed from PCM cooling in this study are surprising considering
286 PCM application was localized while CWI involved submerging the lower half of the body. The
287 longer treatment duration from PCM provided a progressive decline in core temperature so that
288 ultimately the effects on core temperature and HRV were comparable between treatments.
289 Previous studies have shown that the rate of core temperature reduction during post-exercise
290 CWI is dependent on temperature, duration, and the time from the end of exercise to
291 commencement of CWI treatment.⁶ However, few studies have examined the impact of CWI on
292 resting core temperature where there is no exercise-induced temperature elevation prior to CWI
293 treatment. Costello et al (2012) reported a $0.4 \pm 0.2^{\circ}\text{C}$ reduction in resting rectal temperature 60
294 min after a 4 min CWI at 8°C with subjects submerged to the sternum. Gregson et al (2011)
295 reported a $0.2 \pm 0.1^{\circ}\text{C}$ drop in core temperature following two 5 min, 8°C CWI treatments,
296 separated by 2 min with subjects submerged to the waist. Comparable reductions in core
297 temperature during treatment were evident in the present study and core temperature remained
298 depressed for the duration of recovery from both treatments.

299 In line with the reduction in core temperature, there was a decrease in heart rate and an
300 increase in HRV, from both treatments. Restoration of cardiovascular homeostasis is an
301 important component of overall recovery and interventions that increase HRV are thought to be
302 advantageous to exercise recovery.²⁴ Monitoring indices of HRV has been of increasing interest
303 among athletes.²⁵ Post-exercise CWI has been shown to accelerate recovery of HRV.^{15,16} The
304 present data indicate that CWI and PCM are capable of elevating HRV from a resting condition.

305 Since this study did not utilize an exercise intervention prior to the treatments, both the
306 magnitude and duration of the physiological effects cannot be extrapolated to what might occur
307 in a post-exercise condition. It remains imperative to mention the paradox between the use of
308 cryotherapy for acute reduction in inflammation to facilitate recovery and the potential negative
309 effects that may be caused by blunting the stress response.¹⁸ Since some degree of inflammation,
310 which plays a crucial role in the remodeling and adaptation of skeletal muscle, is required for the
311 resolution of muscle fiber damage resulting from an exercise insult. However, since the recovery
312 benefits of CWI have been extensively studied, and preliminarily studies utilizing PCM cooling
313 with durations between 3-6 h illustrate beneficial effects on recovery of strength, in addition to
314 soreness,^{7,8} the present results serve primarily to demonstrate the capacity of both CWI and PCM
315 cooling to have local and systemic effects. The shorter overall CWI data collection period
316 compared with PCM data collection complicated the comparisons between treatments. However,
317 it was not practical to have study participants remain instrumented for an additional 1 h 45 min
318 following CWI to match the PCM duration, especially since it was a crossover design. A post
319 CWI duration of 2 h was sufficient to demonstrate the magnitude and duration of effects on
320 recovery, especially since it has been demonstrated that intramuscular temperature does not
321 return to baseline for up to 4 h following CWI administered after exercise.²⁶ The 3 h PCM
322 duration was chosen to replicate the treatment time in field testing,⁸ and the 1 h recovery time
323 was deemed sufficient and practical for study participants who were sitting for more than 4
324 hours. Previous studies have demonstrated that the cooling effect in calf muscles is maintained
325 for 3-4 h following CWI in normothermic individuals^{27,28} due to inactivity. Therefore, it was not
326 feasible to keep study participants instrumented to monitor temperatures that likely would not
327 have returned to baseline.

328 This study utilized a cohort of male participants with thigh skinfolds averaging 9.9 ± 5.2
329 mm., Decreases in intramuscular temperature were correlated with skinfold thickness during
330 both treatments, due to the insulating effect of adiposity.^{29,30} It has previously been shown that
331 body composition influences the magnitude of change in skin, muscle, and core temperature
332 during and after CWI²⁶. It has also been suggested that muscle mass and its regional distribution,
333 body surface area to mass ratio, age and ethnicity influence thermal and physiological responses
334 to water immersion³¹ Therefore, the results of this study should be cautiously interpreted when
335 relating them to a more heterogeneous group. This study should be repeated in a female
336 population since women generally have greater subcutaneous body fat compared to men, and
337 because for a given change in body temperature, as occurs during and from exercise, females
338 require a greater cooling stimulus to maintain thermal comfort levels.³² The results from this
339 study may further differ in a female population due to the added variable of sex hormone-related
340 fluctuations in body temperature and some thermoregulatory processes during the menstrual
341 cycle.³³ Consequently, the results of this study should be extrapolated with a degree of caution to
342 the effect of CWI or PCM on intramuscular and core temperature in females, and following
343 exercise in both genders. Future research should examine PCM application in a more
344 heterogeneous group as well as following exercise.

345 *Practical Applications*

346 PCM cooling packs applied directly to the skin underneath garments to hold them in
347 place is an efficacious alternative to CWI, especially if the athlete is seeking a prolonged cooling
348 exposure. PCM cooling may be more practical than CWI, because individuals can continue with
349 their activities of daily living while simultaneously receiving a cryotherapy dose.

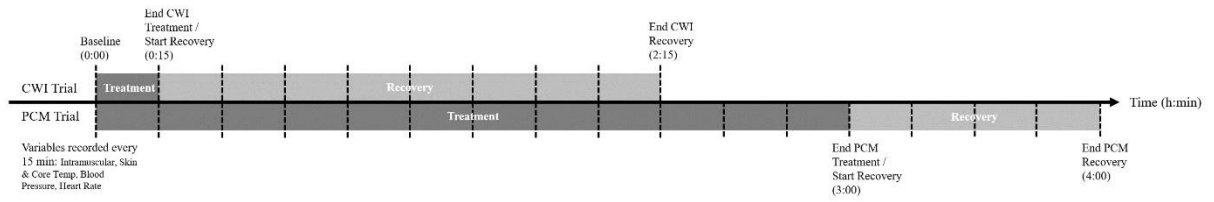
350 *Conclusions*

351 This is the first examination of the effect of PCM cooling on intramuscular temperature,
352 core temperature and cardiovascular function. The magnitude of temperature reduction with
353 prolonged PCM application was similar to the CWI treatment, but critically, the PCM provided a
354 sustained cooling effect that was better tolerated than CWI. These physiological effects may
355 explain the previously reported benefits of PCM cooling in reducing muscle damage in
356 recreational athletes⁷ and accelerating recovery in professional soccer players.⁸

357 **References**

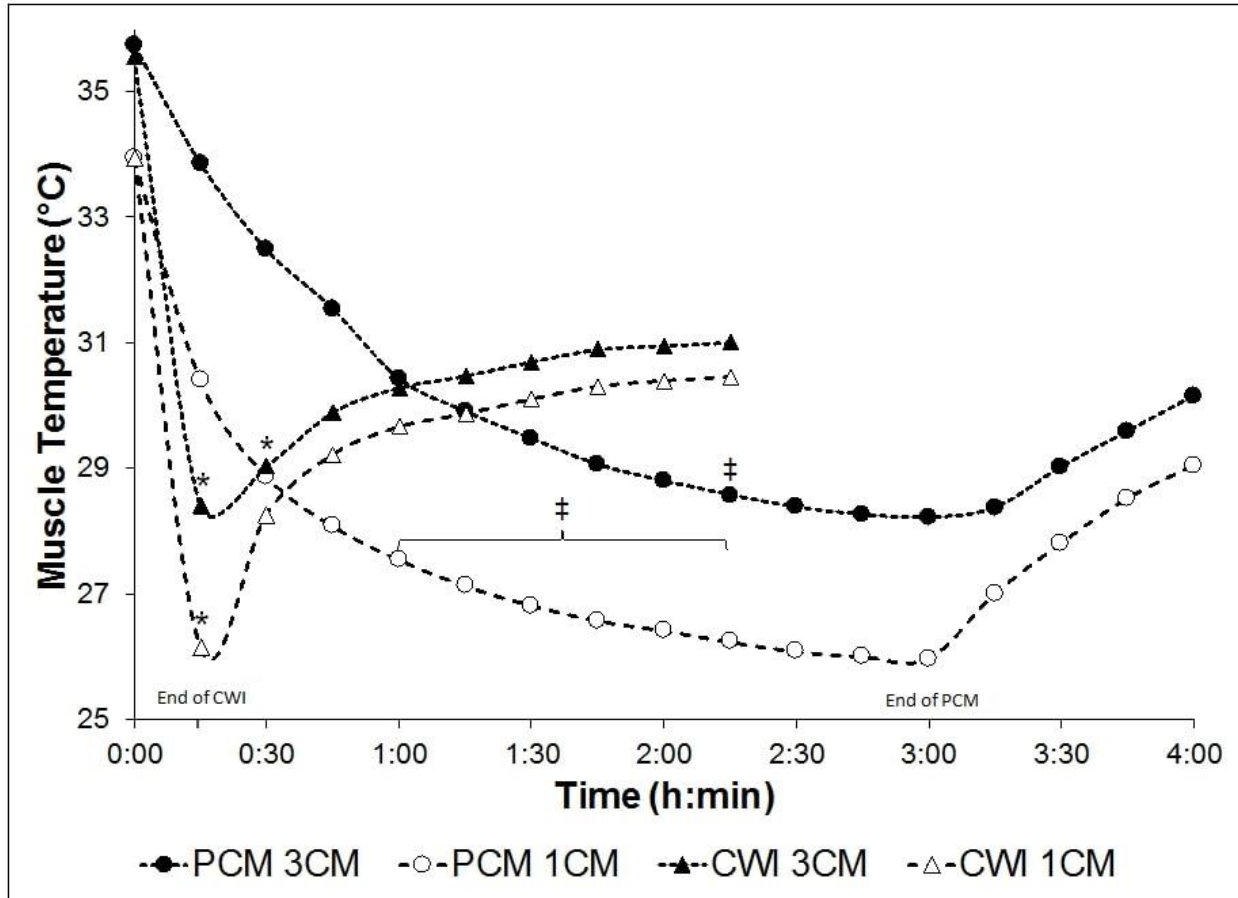
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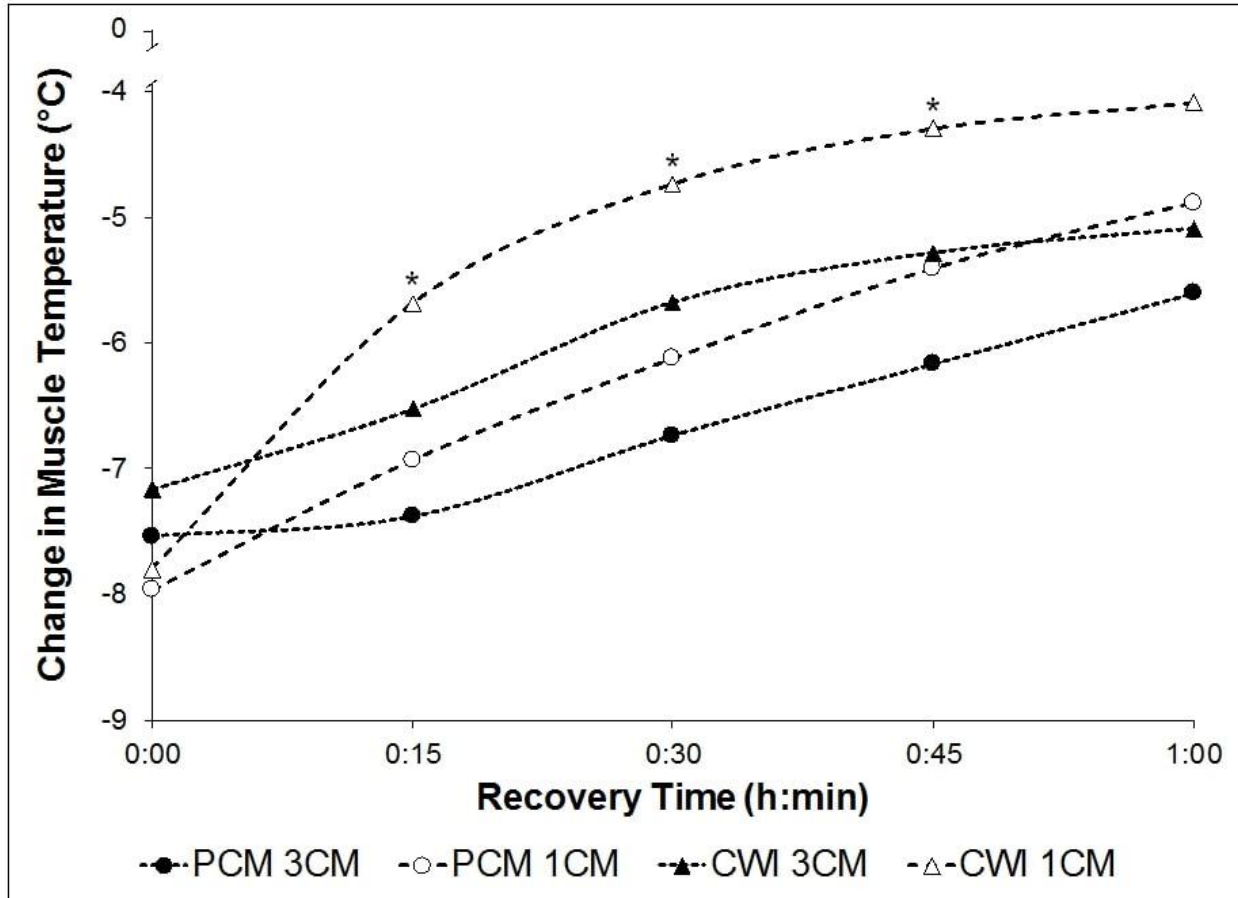


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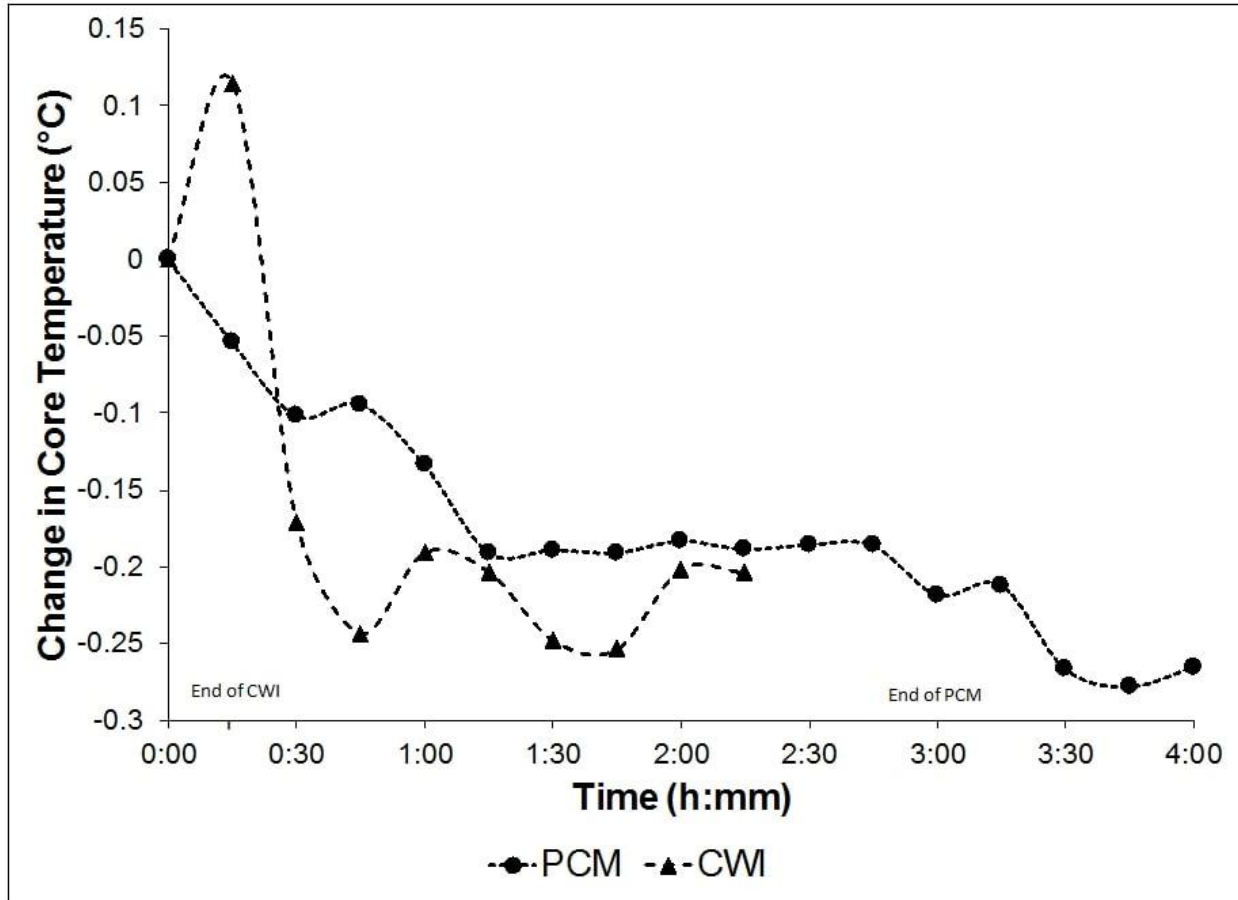
Figure 1: Experimental protocol of treatment and recovery during both conditions over time.



442
 443 **Figure 2:** Vastus lateralis intramuscular temperature. Intramuscular temperature declined
 444 progressively during the PCM treatment (time effect, $P < 0.0001$) and remained below baseline
 445 after 1:00 of recovery at both depths ($P < 0.01$). CWI treatment decreased intramuscular
 446 temperature from a baseline to immediately post treatment (time effect, $P < 0.0001$) and
 447 remained below baseline after 2 h of recovery at both depths ($P < 0.01$). Intramuscular
 448 temperature was lower with the PCM treatment (treatment x time, $P < 0.0001$ at 3 and 1 cm).
 449 Intramuscular temperature was lower with CWI vs PCM at 3 cm from 0:00 to 0:30 but only from
 450 0:00 to 0:15 at 1 cm (*, $P < 0.01$). Intramuscular temperature was lower at 2:15 for PCM vs CWI
 451 treatment at 3 cm and at from 1:00 to 2:15 at 1 cm (‡, $P < 0.05$).



452
 453 **Figure 3:** Change in vastus lateralis intramuscular temperature from baseline during recovery.
 454 Recovery time is displayed for the 1 hour immediately following conclusion of both treatments.
 455 Absolute time displayed for CWI is 0:15 through 1:15, and for PCM is 3:00 through 4:00.
 456 Intramuscular temperature was lower (treatment effect, $P = 0.013$) with PCM vs. CWI at 1 cm (*,
 457 $P < 0.05$).



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Figure 4: Mean core temperature of 11 subjects superimposed over the same duration of treatment and recovery after both PCM and CWI treatment. Core temperature declined during the PCM and CWI treatments (time effect, $P < 0.0001$) with no difference between treatments (treatment x time, $P = 0.10$).

464 **Table 1 A Comparison of Intramuscular Temperatures (1cm and 3cm) during**
 465 **Baseline, Treatment, and Recovery of the 2 Cryotherapy Treatments (CWI vs PCM),**
 466 **Mean \pm SD**

Temperature at Protocol Times	CWI 1cm	CWI 3cm	PCM 1cm	PCM 3cm
Baseline	34.0 \pm 1.1°C	35.6 \pm 0.6°C	33.9 \pm 1.5°C	35.8 \pm 0.5°C
End of Treatment	26.2 \pm 2.9°C	28.4 \pm 2.7°C	26.0 \pm 2.2°C	28.2 \pm 2.8°C
End of Recovery	30.5 \pm 1.0°C*&	31.0 \pm 1.0°C*	29.0 \pm 1.6°C*	30.1 \pm 2.1°C*
Average	29.4 \pm 1.1°C	30.2 \pm 1.2°C	27.4 \pm 2.1°C\$	29.8 \pm 2.4°C

467 Intramuscular temperature remained significantly below baseline at the end of recovery for all
 468 conditions (*P < 0.01). Intramuscular temperature during the first hour of recovery was higher
 469 from CWI vs PCM at 1cm (treatment effect, &P = 0.013) but not at 3cm (treatment effect P =
 470 0.35). Average intramuscular temperature at 1cm was significantly lower from PCM treatment
 471 than CWI (\$P<0.001) but there was no difference at 3cm (P=0.46).

472 **Table 2 Fifteen min rolling average HR and RMSSD data during 2 h of PCM**
 473 **application and 15 min of CWI followed by 1 h 45 min of recovery, Mean \pm SD**

Time	PCM HR	CWI HR	PCM RMSSD	CWI RMSSD
Baseline	68 \pm 7	68 \pm 8	60 \pm 22	62 \pm 30
0:15	62 \pm 9*	61 \pm 11	63 \pm 24	67 \pm 28
0:30	63 \pm 7	61 \pm 8*	61 \pm 24	79 \pm 25*
0:45	64 \pm 6	57 \pm 8*	65 \pm 22	74 \pm 26
1:00	61 \pm 7*	59 \pm 8*	65 \pm 26	70 \pm 31
1:15	62 \pm 9	57 \pm 8*	70 \pm 26	71 \pm 27
1:30	60 \pm 5*	59 \pm 11	75 \pm 25	75 \pm 31
1:45	59 \pm 7*	56 \pm 9*	70 \pm 25	79 \pm 32
2:00	61 \pm 9	57 \pm 8*	73 \pm 23	84 \pm 33*

474 HR was elevated immediately following CWI treatment (15 min) but was reduced over time
 475 during both treatments (time effect, $P < .0001$). There was a trend for an increase in RMSSD
 476 during PCM treatment (Time effect, $P = 0.069$) and a clear increase in RMSSD during and
 477 following CWI (Time effect, $P < .0001$). * = significant difference from baseline ($P < .05$)