

Exploring the Efficacy of a Safe Cryotherapy Alternative: Physiological Temperature Changes From Cold-Water Immersion Versus Prolonged Cooling of Phase-Change Material

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Purpose: To evaluate the effectiveness between cold-water immersion (CWI) and phase-change-material (PCM) cooling on intramuscular, core, and skin-temperature and cardiovascular responses. **Methods:** In a randomized, crossover design, 11 men completed 15 min of 15°C CWI to the umbilicus and 2-h recovery or 3 h of 15°C PCM covering the quadriceps and 1 h of recovery, separated by 24 h. Vastus lateralis intramuscular temperature at 1 and 3 cm, core and skin temperature, heart-rate variability, and thermal comfort were recorded at baseline and 15-min intervals throughout treatment and recovery. **Results:** Intramuscular temperature decreased ($P < .001$) during and after both treatments. A faster initial effect was observed from 15 min of CWI (Δ : 4.3°C [1.7°C] 1 cm; 5.5°C [2.1°C] 3 cm; $P = .01$). However, over time (2 h 15 min), greater effects were observed from prolonged PCM treatment (Δ : 4.2°C [1.9°C] 1 cm; 2.2°C [2.2°C] 3 cm; treatment \times time, $P = .0001$). During the first hour of recovery from both treatments, intramuscular temperature was higher from CWI at 1 cm ($P = .013$) but not 3 cm. Core temperature decreased 0.25° (0.32°) from CWI ($P = .001$) and 0.28°C (0.27°C) from PCM ($P = .0001$), whereas heart-rate variability increased during both treatments ($P = .001$), with no differences between treatments. **Conclusions:** The magnitude of temperature reduction from CWI was comparable with PCM, but intramuscular temperature was decreased for longer during PCM. PCM cooling packs offer an alternative for delivering prolonged cooling whenever application of CWI is impractical while also exerting a central effect on core temperature and heart rate.

Keywords: recovery, thermoregulation, cold therapy, hydrotherapy, ice bath

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

A longer duration of targeted postexercise cooling can be provided using temperature-controlled phase-change material (PCM), whereby PCM packs are placed over specific muscle groups and worn inside of garments to hold them in place. From a practical perspective, this cryotherapy modality offers an attractive alternative to CWI, as individuals can resume activities of daily living while simultaneously receiving cryotherapy treatment

that maintains a constant temperature for an extended duration. A 6-hour PCM application reduced pain and strength loss on the days after eccentric quadriceps exercise in recreational athletes.⁷ A 3-hour PCM application after a professional soccer match also reduced pain and strength loss on subsequent days.⁸ In these studies,^{7,8} participant thermal comfort was maintained while PCM packs were worn inside compression shorts and maintained a constant temperature of 15°C for at least 3 hours before melting.

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

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Methods

Participants

A total of 11 active males (mean [SD]: age 27 [6] y, height 183.6 [8.5] cm, body mass 81.5 [12.4] kg) volunteered to participate in this study. All participants were free from lower-leg injury for at least 1 month before the study and had no known vascular disease in the lower limbs, compromised circulation, and allergy or hypersensitivity to cold. Participants were instructed to refrain from strenuous exercise for 72 hours prior to and for the duration of the study period. The Northumbria University research ethics committee, in accordance with the Declaration of Helsinki, approved all procedures, and participants gave written informed consent.

Experimental Design

In this repeated-measures, cross-over design, study participants visited the laboratory on 3 consecutive days. First for a familiarization session before data collection commenced followed by 2 separate treatment sessions; all separated by 24 hours. Participants were randomized to receive 1 treatment on day 1 and the other treatment on day 2. Vastus lateralis muscle temperature at 1 and 3 cm, skin temperature, core temperature, heart rate (HR), blood pressure, and thermal comfort were recorded continuously throughout baseline, treatment (15-min CWI vs 3-h PCM), and recovery (2-h CWI vs 1-h PCM) during both treatments (Figure 1). Data collection during CWI treatment and recovery consisted of a shorter overall collection period compared with the PCM trial. As both treatments were matched for temperature, it was impractical for participants to remain instrumented for the additional 1 hour of recovery following CWI treatment in order to match the duration of PCM treatment and recovery. During CWI treatment (iCool Sport; Gold Coast, QLD, Australia), participants sat immersed to the umbilicus in an inflatable, temperature-controlled (15°C [1°C]) cold-water bath for 15 minutes, and recovery of all variables was monitored for 2 hours (2 h 15 min total time). During PCM treatment (Glacier Tek; USDA BioPreferred PureTemp, Plymouth, MN), 2 PCM blocks (864 cm² area; 32.4 cm × 2 cm × 13.3 cm) frozen at 15°C were worn over the quadriceps muscles directly on the skin inside compression shorts (worn up to the knee) for 3 hours of treatment, and recovery of all variables was monitored for 1 hour (4-h total time). The PCM packs can maintain a constant temperature of 15°C for at least 3 hours in a thermoneutral environment (as verified by the manufacturer and an independent quality association PCM, RAL, Stuttgart, Germany), until the substance is fully melted.

During data collection, participants remained in a semireclined seated position with legs outstretched on a bed except during the CWI treatment. On completion of each treatment, the dry shorts remained on the participant while rolled up to the inguinal region so that the skin remained exposed for the duration of the recovery period. All testing was performed in a temperature-controlled laboratory (24.9°C [3.4°C]).

Intramuscular Temperature

To account for subcutaneous fat, skinfold at the exact site of thermocouple insertion on the quadriceps was measured using skinfold calipers (Harpender; Baty International, West Sussex, United Kingdom) by the same individual. The vastus lateralis was then marked approximately 6-cm lateral to the midpoint between the superior pole of the patella and the anterior-superior iliac crest using a sterile pen. Additional markings were placed 1-cm inferior

and superior to this point, 1 for each insertion depth. The area was cleaned with a povidone-iodine surgical scrub solution. Insertion depth was based on halving the skinfold measure and adding this to the required depth (1 or 3 cm).

A 45- and 32-mm sterile intravenous 20 gauge needle catheter was used for the 3 and 1 cm insertion, respectively. Insertion depth was verified by subtracting the total insertion depth (1 or 3 cm plus half the skinfold) from the corresponding length of the needle. The difference (length of needle minus calculated insertion depth) was verified with a sterile ruler. Once at the correct insertion depth, the needle was removed, and the flexible catheter remained inserted. A sterile flexible intramuscular thermocouple probe (Type T, IT-21; Physitemp Instruments, Clifton, NJ) was threaded through the barrel of the catheter. The catheter was removed from the muscle while the thermocouple remained inserted. The thermocouple insertion site was secured in place with sterile tegaderm by bending the thermocouple flush with the skin. The procedure was then repeated for the 1-cm deep thermocouple. Once fully instrumented, the thermocouples were connected to a digital monitor (Bailey Instruments BAT-12; Physitemp Instruments) for continuous recording. Thermocouples remained inserted throughout the duration of treatment and recovery. At the conclusion of data collection, thermocouples were removed and “actual” insertion depth was verified by measuring the inserted portion of the thermocouple against a sterile ruler. The left leg of each subject was instrumented with thermocouples for CWI, whereas the right leg of each subject was instrumented for PCM treatment.

Body Temperature and Cardiovascular Measures

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

On arrival to the lab for the treatments, participants were fitted with a wireless ambulatory chest-strap HR monitor equipped with a sensor electronics module (EQ02 LifeMonitor; Hidalgo Ltd, Cambridge, United Kingdom) that continuously recorded HR, core, and skin temperature and with an automated blood pressure cuff on their right arm (M10-IT; Omron Healthcare, Hoofddorp, the Netherlands). A telemetric dermal patch temperature sensor (VitalSense; Respironics Inc) was applied to the quadriceps of the leg that was not being instrumented with intramuscular thermocouples to measure skin temperature.

Heart-rate data were analyzed using Vivosense (Vivonoetics, San Diego, CA). Automatic artifact-marking algorithm was applied to the raw electrocardiogram (sensitivity level: medium noise filtering; minimal and maximal allowable HR limits: 30 and 220 beats/min, respectively). R-wave markings were generated for HRV calculations. The root mean square of successive differences (RMSSD) between R-R intervals of normal heartbeats is reported. Research suggests that RMSSD provides the most reliable and practically applicable measure for day-to-day monitoring.¹⁹ Five-minute rolling averages were calculated for RMSSD, with the baseline measure taken prior to insertion of the intramuscular thermocouples.

Ratings of thermal comfort were recorded every 15 minutes. During CWI, thermal comfort was asked at the first and last minute of immersion. Participants were asked to rate their thermal comfort on a 9-point standard scale.²⁰

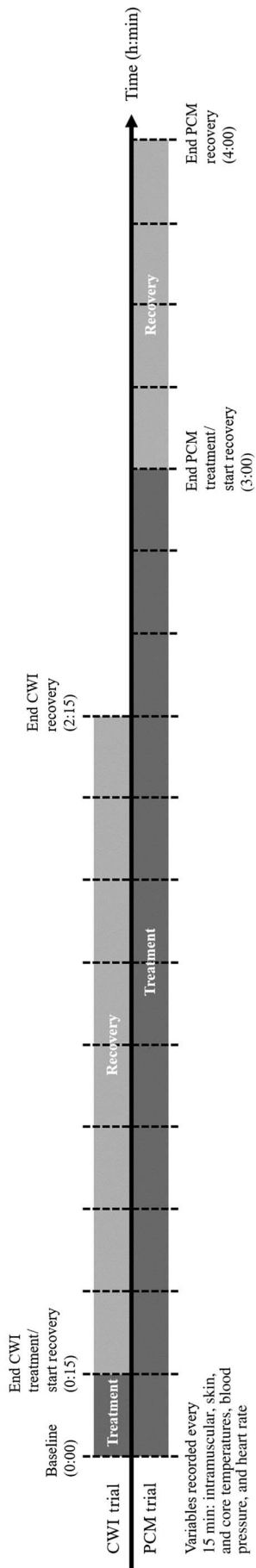


Figure 1 — Experimental protocol of treatment and recovery during both conditions over time. CWI indicates cold-water immersion; PCM, phase-change material.

Data Analysis

Prior to employing analyses of variance (ANOVAs), normality of distribution of all data sets was verified using the Shapiro–Wilk test. Mauchly test of sphericity was used to test assumptions of sphericity, and where necessary, Greenhouse–Geisser corrections were applied. Statistical analyses were performed using SPSS (version 21; IBM, Armonk, NY). The comparison of treatments over time was assessed using a 2×10 , treatment by time, repeated-measures ANOVA. The levels for the treatment factor were group (CWI or PCM) and time (baseline [0 min] and every 15 min up to 2 h 15 min). For these analyses, the entire duration of CWI treatment (15 min) and recovery (2 h) was compared with the first 2 hours 15 minutes of PCM treatment. In addition, recovery effect (return to baseline) from both treatments over time was assessed using a 2×5 , treatment by time repeated-measures ANOVA. The levels for the time factor were baseline (0 h), 15 minutes, 30 minutes, 45 minutes, 1 hour, and 1 hour 15 minutes for CWI and baseline (0 h), 3 hours, 3 hours 15 minutes, 3 hours 30 minutes, 3 hours 45 minutes, and 4 hours for PCM. For these analyses, the first 1-hour duration of recovery following each treatment was compared. Where there was a significant treatment effect or treatment by time interaction, differences between treatments at any particular time interval were assessed using Bonferroni corrections for planned pairwise comparisons.

Within each treatment, the changes in dependent variables over time were assessed by a 1-factor ANOVA with differences versus baseline assessed using Bonferroni corrections for planned pairwise comparisons. In addition, Pearson product–moment correlation coefficients were used to assess the relationship between thigh skinfold thickness and intramuscular temperature. A probability level $<.05$ was accepted to determine significance. All data are reported as group mean (SD).

Results

Thermocouple Depth and Skinfold

Skinfolds were 10.1 (5.2) mm for the right leg and 9.7 (5.5) mm for the left leg of all participants. Thermocouple depths, corrected for skinfolds, were 3.0 (0.4) cm and 1.0 (0.3) cm for PCM and 3.1 (0.3) cm and 1.1 (0.3) cm for CWI. Decreases in intramuscular temperature were correlated with skinfold thickness with stronger effects at 1 cm (CWI: $r = .912$, $P < .001$; PCM: $r = .853$, $P < .001$) versus at 3 cm (CWI: $r = .727$, $P < .01$; PCM: $r = .594$, $P = .05$).

Intramuscular Temperature

Intramuscular temperature declined progressively during both treatments (time effect, $P = .0001$, Table 1) and remained below

baseline at the conclusion of the recovery period (all $P_s < .01$; Figure 2). CWI decreased intramuscular temperature more rapidly and was 14.0% and 16.1% lower at end of treatment versus 15 minutes into PCM treatment at both 1 and 3 cm, respectively (mean difference: 4.3°C [1.7°C] at 1 cm and 5.5°C [2.1°C] at 3 cm, both $P_s = .01$). Intramuscular temperature remained 10.6% lower 15 minutes into recovery following the CWI treatment versus 30 minutes into PCM treatment at 3 cm (difference: 3.4°C [1.6°C], $P = .01$) but no longer at 1 cm (2.1%; difference: 0.6°C [1.8°C], $P = .99$). Intramuscular temperature at 3 cm was 7.5% higher (difference: 2.4°C [2.3°C], $P = .045$; Figure 2) on conclusion of CWI recovery (2 h 15 min total time) compared with 2 hours 15 minutes into PCM treatment, whereas intramuscular temperature at 1 cm was on average 12.5% higher between CWI versus PCM treatment from 1 hours ($P = .003$) to 2 hours 15 minutes ($P < .001$; Figure 2). Over time, intramuscular temperature was lower from PCM treatment (treatment \times time, $P = .0001$ at 3 and 1 cm; Figure 2). When comparing intramuscular temperature for the first 1 hour of recovery from both treatments, intramuscular temperature at 1 cm was 4.1% higher from CWI averaging 28.6°C (1.4°C) than from PCM averaging 27.7°C (1.7°C) (treatment effect, $P = .013$; Figure 3), with no difference at 3 cm (2.2%; treatment effect, $P = .35$; Figure 3).

Core Temperature

Core temperature declined during the PCM and CWI treatments (time effect; $P = .0001$) with no difference between treatments (treatment \times time; $P = .10$) (Figure 4). The nadir of core temperature from PCM treatment occurred 45 minutes into the recovery period (absolute time: 3 h 45 min; 0.28°C [0.27°C] below baseline), whereas the nadir of core temperature from CWI treatment occurred 1 hour 30 minutes in to the recovery period (absolute time: 1 h 45 min; 0.25°C [0.32°C] below baseline).

Skin Temperature

Skin temperature declined during both PCM and CWI treatments (time effect, $P = .0001$). CWI decreased skin temperature more rapidly (treatment \times time, $P = .0001$) than PCM. Skin temperature immediately after CWI was 2.4°C (1.7°C) lower than 15 minutes into the PCM treatment; however, at all subsequent time points, skin temperature was lower during the PCM treatment ($P < .01$). During CWI treatment, skin temperature dropped from 31.3°C (1.1°C) at baseline to 23.6°C (0.8°C) at 15 minutes and was 29.5°C (1.2°C) 2 hours after CWI. During PCM treatment, skin temperature averaged 24.1°C (0.3°C) over the 3 hours during which subjects wore the PCM and was 27.7°C (1.1°C) 1 hour after removal of PCM.

Table 1 Intramuscular Temperatures (1 and 3 cm) During Baseline, Treatment, and Recovery of the 2 Cryotherapy Treatments (CWI vs PCM), Mean (SD)

Time point	CWI 1 cm, °C	CWI 3 cm, °C	PCM 1 cm, °C	PCM 3 cm, °C
Baseline	34.0 (1.1)	35.6 (0.6)	33.9 (1.5)	35.8 (0.5)
End of treatment	26.2 (2.9)	28.4 (2.7)	26.0 (2.2)	28.2 (2.8)
End of recovery	30.5 (1.0)***	31.0 (1.0)*	29.0 (1.6)*	30.1 (2.1)*
Average	29.4 (1.1)	30.2 (1.2)	27.4 (2.1)***	29.8 (2.4)

Abbreviations: CWI, cold-water immersion; PCM, phase-change material. Note: Intramuscular temperature remained significantly below baseline at the end of recovery for all conditions ($*P < .01$). Intramuscular temperature during the first hour of recovery was higher from CWI versus PCM at 1 cm (treatment effect, $**P = .013$) but not at 3 cm (treatment effect, $P = .35$). Average intramuscular temperature at 1 cm was significantly lower from PCM treatment than CWI ($***P < .001$), but there was no difference at 3 cm ($P = .46$).

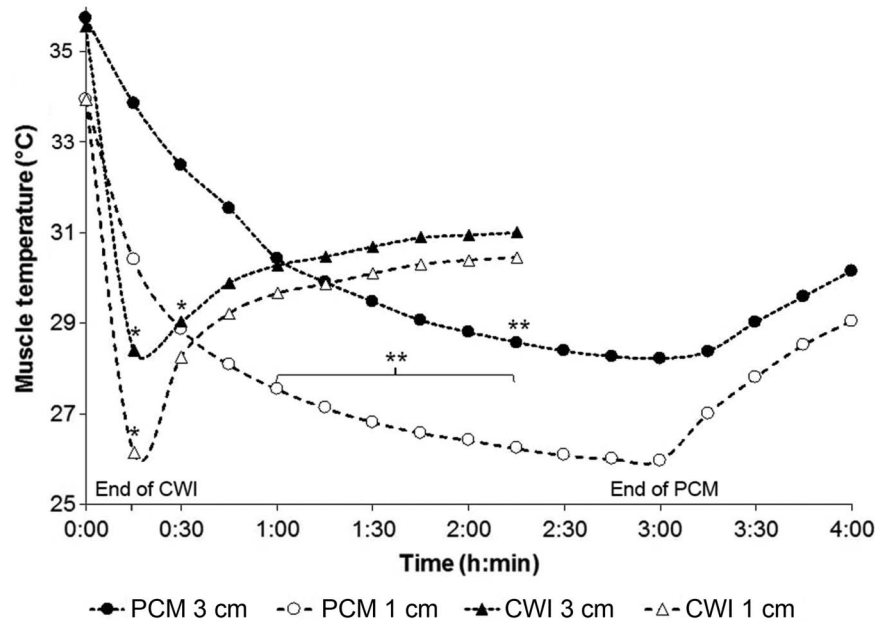


Figure 2 — Vastus lateralis intramuscular temperature. Intramuscular temperature declined progressively during the 3-hour PCM treatment (time effect, $P < .0001$) and remained below baseline after 1 hour of recovery at both depths ($P < .01$). Fifteen-minute CWI treatment decreased intramuscular temperature (time effect, $P < .0001$), which remained below baseline after 2 hours of recovery at both depths ($P < .01$). Over time, intramuscular temperature was lower with the PCM treatment at both depths (treatment \times time, $P < .0001$ at 3 and 1 cm). It was lower with CWI from baseline to 30 minutes absolute time at 3 cm and only through 15 minutes at 1 cm ($*P < .01$), and it was lower with PCM at 2 hours and 15 minutes absolute time at 3 cm and from 1 hour through 2 hours and 15 minutes at 1 cm ($**P < .05$). CWI indicates cold-water immersion; PCM, phase-change material.

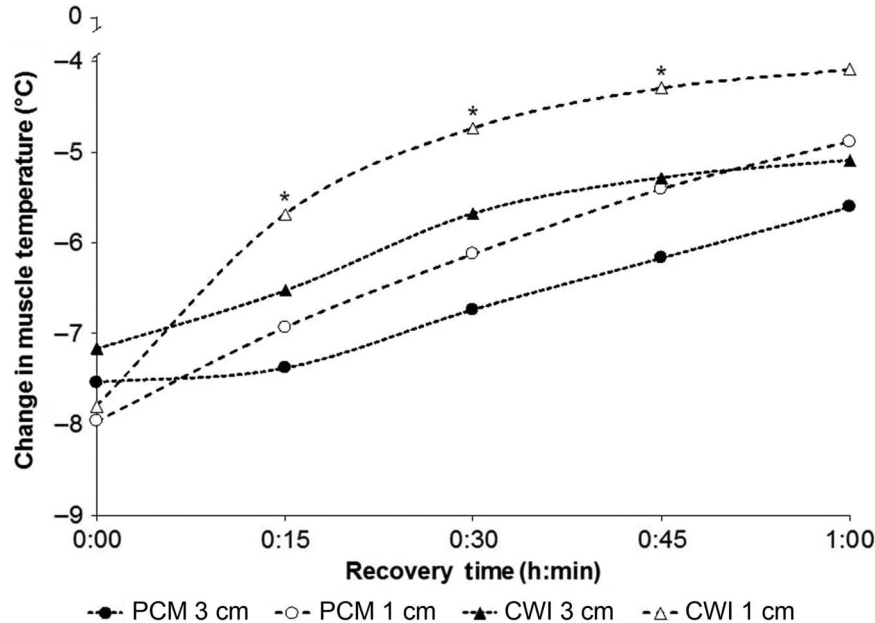


Figure 3 — Change in vastus lateralis intramuscular temperature from baseline during recovery. Recovery time is displayed for the 1 hour immediately after conclusion of both treatments. Absolute time displayed for CWI is 0:15 to 1:15 hours and for PCM is 3:00 to 4:00 hours. Intramuscular temperature was lower (treatment effect, $P = .013$) with PCM versus CWI at 1 cm. $*P < .05$. CWI indicates cold-water immersion; PCM, phase-change material.

Perceived Thermal Comfort

Thermal comfort was significantly different between treatments (treatment \times time, $P = .002$) with greater thermal discomfort reported immediately after CWI (2.7 [0.8] vs 4.5 [0.8] 15 min into the PCM

treatment, $P = .01$). This time point is also where thermal comfort reached its nadir for both treatments. On conclusion of PCM treatment, thermal comfort was 4.9 (1.0). Thermal comfort returned to baseline following 30 minutes of the recovery period after PCM treatment.

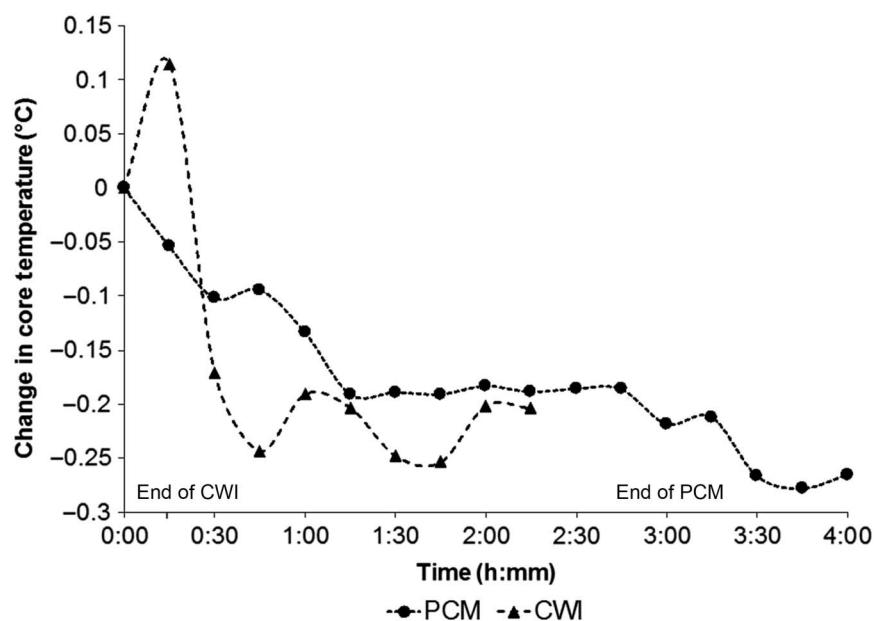


Figure 4 — Mean core temperature of 11 subjects superimposed over the same duration of treatment and recovery after both PCM and CWI treatment. Core temperature declined during the PCM and CWI treatments (time effect, $P < .0001$) with no difference between treatments (treatment \times time, $P = .10$). CWI indicates cold-water immersion; PCM, phase-change material.

Cardiovascular Measures

There were technical issues with HR signals for 2 participants during the entire PCM treatment and for 1 participant after 2 hours of the PCM treatment. Thus, only 9 participants were included in the treatment by time analysis of HR data, and the time analysis only included data up to 2 hours. HR declined during both treatments (time effect, $P = .0001$) with no interaction effects ($P > .05$; Table 2). Overall, there was an increase in RMSSD during treatments (time effect, $P < .0001$) with no interaction effect ($P = .155$; Table 2). For the PCM treatment, there was a trend for an increase in RMSSD (time effect, $P = .069$), whereas for the CWI treatment, there was a clear increase in RMSSD (time effect, $P = .0001$). Blood pressure was unaffected by either treatment ($P = .15$ – $.95$), and there were no differences between treatments ($P = .62$ for systolic and $P = .84$ for diastolic).

Discussion

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

Table 2 Fifteen-Minute Rolling Average HR and RMSSD Data During 2 Hours of PCM Application and 15 Minutes of CWI Followed by 1 Hour 45 Minutes of Recovery, Mean (SD)

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

Abbreviations: CWI, cold-water immersion; HR, heart rate; PCM, phase-change material; RMSSD, root mean square of successive differences between R-R intervals of normal heartbeats. Note: HR was elevated immediately after CWI treatment (15 min) but reduced over time during both treatments (time effect, $P < .0001$). There was a trend for an increase in RMSSD during PCM treatment (time effect, $P = .069$) and a clear increase in RMSSD during and after CWI (time effect, $P < .0001$).

*Significant difference from baseline ($P < .05$).

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

In the present study, average vastus lateralis temperature at 1 cm for the total PCM trial period (4 h) was 7% lower than the average temperature at 1 cm for the total CWI trial (2 h 15 min). Thus, not only can PCM provide prolonged cooling, but it can also provide a greater magnitude of cooling to the peripheral musculature. This may have implications for use in exercise

recovery. As the damage that occurs following strenuous exercise is bimodal, involving both the initial mechanical and/or metabolic muscle injury and a secondary phase that involves a disruption in intracellular homeostasis followed by an inflammatory response which initiates 2 to 6 hours postdamaging exercise.²¹ A prolonged cooling intervention during this time frame has potential to blunt the inflammatory process that occurs following exercise, thereby mitigating any additional damage caused by the inflammatory response¹⁸ and limiting further hemorrhage and cell death.²¹ In support of this rationale, it has previously been demonstrated in an animal model that local cooling at 8°C for 6 hours after closed soft-tissue injury limited subsequent tissue damage.²²

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

The systemic effects observed from PCM cooling in this study are surprising considering PCM application was localized, whereas CWI involved submerging the lower half of the body. The longer treatment duration from PCM provided a progressive decline in core temperature so that ultimately the effects on core temperature and HRV were comparable between treatments. Previous studies have shown that the rate of core temperature reduction during postexercise CWI is dependent on temperature, duration, and the time from the end of exercise to commencement of CWI treatment.⁶ However, few studies have examined the impact of CWI on resting core temperature where there is no exercise-induced temperature elevation prior to CWI treatment. Costello et al¹³ reported a 0.4°C (0.2°C) reduction in resting rectal temperature 60 minutes after a 4-minute CWI at 8°C with subjects submerged to the sternum. Gregson et al¹⁴ reported a 0.2°C (0.1°C) drop in core temperature following two 5 minutes, 8°C CWI treatments, separated by 2 minutes with subjects submerged to the waist. Comparable reductions in core temperature during treatment were evident in the present study, and core temperature remained depressed for the duration of recovery from both treatments.

In line with the reduction in core temperature, there was a decrease in HR and an increase in HRV, from both treatments. Restoration of cardiovascular homeostasis is an important component of overall recovery and interventions that increase HRV are thought to be advantageous to exercise recovery.²³ Monitoring indices of HRV has been of increasing interest among athletes.²⁴ Postexercise CWI has been shown to accelerate recovery of HRV.^{15,16} The present data indicate that CWI and PCM are capable of elevating HRV from a resting condition.

As this study did not utilize an exercise intervention prior to the treatments, both the magnitude and duration of the physiological effects cannot be extrapolated to what might occur in a postexercise condition. It remains imperative to mention the paradox between the use of cryotherapy for acute reduction in inflammation to facilitate recovery and the potential negative effects that

may be caused by blunting the stress response.¹⁸ As some degree of inflammation, which plays a crucial role in the remodeling and adaptation of skeletal muscle, is required for the resolution of muscle fiber damage resulting from an exercise insult. However, as the recovery benefits of CWI have been extensively studied and preliminarily studies utilizing PCM cooling with durations between 3 and 6 hours illustrate beneficial effects on recovery of strength, in addition to soreness,^{7,8} the present results serve primarily to demonstrate the capacity of both CWI and PCM cooling to have local and systemic effects. The shorter overall CWI data collection period compared with PCM data collection complicated the comparisons between treatments. However, it was not practical to have study participants remain instrumented for an additional 1 hour 45 minutes following CWI to match the PCM duration, especially as it was a cross-over design. A post-CWI duration of 2 hours was sufficient to demonstrate the magnitude and duration of effects on recovery, especially as it has been demonstrated that intramuscular temperature does not return to baseline for up to 4 hours following CWI administered after exercise.²⁵ The 3-hour PCM duration was chosen to replicate the treatment time in field testing,⁸ and the 1-hour recovery time was deemed sufficient and practical for study participants who were sitting for more than 4 hours. Previous studies have demonstrated that the cooling effect in calf muscles is maintained for 3 to 4 hours following CWI in normothermic individuals^{26,27} due to inactivity. Therefore, it was not feasible to keep study participants instrumented to monitor temperatures that likely would not have returned to baseline.

This study utilized a cohort of male participants with thigh skinfolds averaging 9.9 (5.2) mm. Decreases in intramuscular temperature were correlated with skinfold thickness during both treatments due to the insulating effect of adiposity.^{28,29} It has previously been shown that body composition influences the magnitude of change in skin, muscle, and core temperature during and after CWI.²⁵ It has also been suggested that muscle mass and its regional distribution, body surface area to mass ratio, age, and ethnicity influence thermal and physiological responses to water immersion.³⁰ Therefore, the results of this study should be cautiously interpreted when relating them to a more heterogeneous group. This study should be repeated in a female population because women generally have greater subcutaneous body fat compared with men, and because for a given change in body temperature, as occurs during and from exercise, females require a greater cooling stimulus to maintain thermal comfort levels.³¹ The results from this study may further differ in a female population due to the added variable of sex hormone-related fluctuations in body temperature and some thermoregulatory processes during the menstrual cycle.³² Consequently, the results of this study should be extrapolated with a degree of caution to the effect of CWI or PCM on intramuscular and core temperature in females and following exercise in both genders. Future research should examine PCM application in a more heterogeneous group and following exercise.

Practical Applications

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

Conclusions

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

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