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Thermoregulatory responses to ice slurry ingestion during low and moderate intensity exercises with restrictive heat loss

Sharifah B. Alhadad[a,b,c,1], Ivan C.C. Low[b,1], Jason K.W. Lee[b,d,e,*]

[a] NUS Graduate School for Integrative Sciences and Engineering, National University of Singapore, Singapore
[b] Department of Physiology, Yong Loo Lin School of Medicine, National University of Singapore, Singapore
[c] Saw Swee Hock School of Public Health, National University of Singapore, Singapore
[d] Global Asia Institute, National University of Singapore, Singapore
[e] N.1 Institute for Health, National University of Singapore, Singapore

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ABSTRACT

Objectives: We investigated the thermoregulatory responses to ice slurry ingestion during low- and moderate-intensity exercises with restrictive heat loss.
Design: Randomised, counterbalanced, cross-over design.
Methods: Following a familiarisation trial, ten physically active males exercised on a motorised treadmill at low-intensity (L; 40% VO_{2max}) or moderate-intensity (M; 70% VO_{2max}) for 75-min, in four randomised, counterbalanced trials. Throughout the exercise bout, participants donned a raincoat to restrict heat loss. Participants ingested 2 g kg^{-1} body mass of ambient water (L + AMB and M + AMB trials) or ice slurry (L + ICE and M + ICE trials) at 15-min intervals during exercise in environmental conditions of $T_{db,}$ 25.1 ± 0.6 °C and RH, 63 ± 5%. Heart rate (HR), gastrointestinal temperature (T_{gi}), mean weighted skin temperature (T_{sk}), estimated sweat loss, ratings of perceived exertion (RPE) and thermal sensation (RTS) were recorded.
Results: Compared to L + AMB, participants completed L + ICE trials with lower ΔT_{gi} (0.8 ± 0.3 °C vs 0.6 ± 0.2 °C; p = 0.03), mean RPE (10 ± 1 vs 9 ± 1; p = 0.03) and estimated sweat loss (0.91 ± 0.2 L vs 0.78 ± 0.27 L; p = 0.04). Contrastingly, T_{gi} (p = 0.22), T_{sk} (p = 0.37), HR (p = 0.31), RPE (p = 0.38) and sweat loss (p = 0.17) were similar between M + AMB and M + ICE trials. RTS was similar during both low-intensity (4.9 ± 0.5 vs 4.7 ± 0.3; p = 0.10) and moderate-intensity exercise (5.3 ± 0.47 vs 5.0 ± 0.4; p = 0.09).
Conclusions: Per-cooling using ice slurry ingestion marginally reduced thermal strain during low-intensity but not during moderate-intensity exercise. Ice slurry may be an effective and practical heat mitigation strategy during low-intensity exercise such as in occupational and military settings, but a greater volume should be considered to ensure its efficacy.

Practical implications

- Cooling with ice slurry ingestion can be useful in countering heat-related impairments in endurance performance.
- However, per-cooling with ice slurry ingestion is not as efficacious during moderate-intensity exercise.
- Instead, per-cooling with ice slurry is more effective during low-intensity exercise to reduce physiological strain due to the additional internal heat loss induced by ice slurry ingestion.
- As ice slurry lowers physiological strain, there is potential for ice slurry to improve performance and productivity measures during low-intensity exercises such as those found in occupational and military sectors.

1. Introduction

Global warming and climate change have resulted in an increase in mean global surface temperatures and an increased frequency, intensity and duration of extreme weather events, such as heat waves.[1] These increasingly hot and/or humid environments coupled with prolonged physical exertion in the heat can result in elevations in body core temperature (T_c).[2,3] Previous studies conducted in athletic settings showed that elevated T_c results in impairments to exercise performance (i.e. time trials) and exercise

* Corresponding author.
E-mail address: phsjlkw@nus.edu.sg (J.K.W. Lee).
[1] These authors contributed equally to this work.

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capacity (i.e. time to exhaustion).[4,5] Similarly, in occupational and military settings, increased thermal strain has been shown to cause an increase in heat-related illnesses[6] and reduce physical and mental work capacity.[7,8] To mitigate the debilitating effects of thermal strain, cooling strategies can be employed.

In athletic settings, ice slurry ingestion has been well-studied as an effective internal cooling strategy, In a hot environment, pre-cooling with ice slurry effectively reduces pre-exercise T_c by approximately 0.4 to 0.7 °C,[9–11] resulting in enhanced exercise performance and capacity. This is due to the internal heat sink induced by ice slurry ingestion, resulting in a greater heat storage capacity. More recently, pre-cooling with ice slurry ingestion in occupational contexts has been studied, with similar benefits observed in reducing pre-exercise T_c.[12,13] However, the effectiveness of pre-cooling with ice slurry may be limited as it is mostly done acutely before exertion, and its beneficial effects may be attenuated after 20–30 min.[12,14] Therefore, to extend the performance benefits of pre-cooling, the effects of per-cooling (ingestion during exercise) at an exercise intensity comparable to occupational settings would be of great interest.

Few studies have investigated the efficacy of per-cooling with ice slurry ingestion at low-intensity exercise. Hailes et al.[15] demonstrated that ice slurry ingestion during 40% maximal aerobic capacity (VO_{2max}) exercise resulted in lowered T_c and skin temperature (T_{sk}), but did not alter sweat rate at the end of the 3-h exercise bout. Contrastingly, the ingestion of ice slurry during moderate to high-intensity exercise appears to confer little, if any, protective effect against exertional heat strain.[16,17] This is demonstrated by the lack of changes in T_c or T_{sk} profiles when per-cooling with ice slurry, possibly due to decreases in skin evaporative potential associated with ingestion of colder beverages.[18,19]

Taken together, previous findings suggest that ice slurry ingestion induces a thermal debt at rest and lower intensities, but not during higher exercise intensities. It is thus compelling that the cooling efficacy of ice slurry ingestion may vary according to metabolic energy demand and exercise intensity. In addition, research on ice slurry has a largely athletic focus with participants donning exercise gear. However, in occupational settings, the usage of protective or encapsulating equipment may result in a restrictive heat loss environment. Therefore, the purpose of the present study was to investigate the thermoregulatory responses to ice slurry ingestion during low- and moderate-intensity exercise with restrictive heat loss.

2. Methods

Ten physically active males [mean ± SD: age 24 ± 1 years, height 1.73 ± 0.05 m, body mass 66.5 ± 4.9 kg, body fat 11 ± 4%, VO_{2max} 52 ± 6 mL kg^{-1} min^{-1}] volunteered to participate in this study. Ethical approval was obtained from the National University of Singapore Institutional Review Board (Reference number: B-16-115). Individuals provided their informed consent and underwent a mandatory health screening to be certified fit for participation by an independent physician prior to enrolment.

On the first visit, participants had their height measured to the nearest 0.01 m with a stadiometer (NAGATA BW-110H, Yong Kang, Tainan) and their body mass measured to the nearest 0.01 kg with an electronic precision balance scale (Mettler-Toledo GmBH Giessen, Germany). Skinfold measurements were taken at 4 sites (biceps, triceps, suprailiac and subscapular) using skinfold calipers (Model HSK-BI-3; Harpenden, Baty International, United Kingdom). Body density was calculated according to Durnin and Womersley,[20] while percent body fat was estimated using the equation of Siri.[21] Participants' VO_{2max} was measured using an incremental exercise protocol to volitional exhaustion on a motorised treadmill.

Each participant completed a familiarisation and four experimental trials – low-intensity with ambient drink (L + AMB), low-intensity with ice slurry (L + ICE), moderate-intensity with ambient drink (M + AMB) and moderate-intensity with ice slurry (M + ICE), in a randomised, counterbalanced order. For moderate-intensity trials, participants ran at a speed corresponding to 70% of their VO_{2max}. For low-intensity trials, participants walked at 6 km h^{-1}, with treadmill incline adjusted to a gradient corresponding to 40% VO_{2max}. Participants were reminded to have a standardised diet, at least 8 h of sleep, remain hydrated by consuming sufficient water, refrain from alcoholic and caffeinated beverages and to refrain from strenuous physical activity 24 h before each trial. Participants also completed trials at the same time of the day to avoid circadian differences.

T_{gi} was measured using an ingestible telemetric capsule (Vitalsense® temperature sensor) that transmits data to an ambulatory T_{gi} data-recording device (Mini Mitter Co., Inc., Bend, OR, USA). Participants were required to swallow the telemetric capsule ten hours before the commencement of the familiarisation trial. This allowed researchers to estimate the bowel transit time for each participant so as to more accurately advise on the time of ingestion of the capsule for subsequent trials. The telemetric capsule needs to sit deep in the rectum or gastrointestinal tract to allow for it to be used as an index of T_{gi}. If the telemetric capsule has not travelled deep enough into the gastrointestinal tract, such as in the transverse colon, the ingestion of cold fluid could directly influence the temperature recorded. The time of capsule ingestion was altered for each participant depending on each individual's bowel transit time and was kept consistent within each individual across the experimental trials.

On arrival, participants were asked to complete a 24 h dietary and physical activity questionnaire to ensure compliance to the requirements. A telemetric check was performed using the ambulatory T_{gi} data-recording device (Mini Mitter Co., Inc., Bend, OR, USA) to ensure that the capsule is residing within the participant and transmitting a signal. Participants provided a mid-stream urine sample, used for measurement of urine specific gravity (USG) using a hand-held refractometer (PAL-10S, Atago, Japan), before nude body mass was measured to the nearest 0.01 kg using an electronic precision balance scale (Mettler-Toledo GmBH, Giessen, Germany). Participants' euhydration status was assessed by USG (<1.025).[22] Subsequently, wireless iButtons® (Maxim Integrated Products, Inc., Sunnyvale, CA, USA) were attached to the skin of the mid belly of the biceps, chest, quadriceps and gastrocnemius on the right-hand side of the body using hypoallergenic polyacrylate adhesive tape (Fixomull®, Smith and Nephew Ltd., Auckland, New Zealand) for measurement of T_{sk}. Participants were fitted with Heart Rate (HR) monitors around the chest and T_{gi} data-recording device, carried in a pouch worn around the waist during exercise.

Participants exercised on a motorised treadmill (h/p/cosmos Mercury, Germany) at low or moderate-intensity for 75-min under the following environmental conditions - dry bulb temperature (T_{db}): 25.1 ± 0.6 °C and relative humidity (RH): 63 ± 5%. Participants wore athletic gear in the form of T-shirt and shorts, and also donned a raincoat (up to knee level, with the hood off) while exercising as a form of restrictive heat loss attire. During the exercise, participants ingested 2 g kg^{-1} body mass of sports drink (Pocari Sweat, Otsuka Pharmaceutical, Japan; carbohydrate percentage = 6.2%) in the form of either ice slurry (∼−2 °C) or ambient drink (∼26 °C) at 15-min intervals. Fluid amount and intake rate were chosen to increase drinkability of the ice slurry while exercising and to minimise discomfort associated with fast consumption of ice slurry (e.g. brain freeze, gastrointestinal discomfort, etc.). Ice slurry was prepared using a commercially available ice slurry machine (IPRO, SPM Drink Systems, Italy). During exercise, T_{gi}, HR and mean T_{sk} were continuously measured and reported as 5-min averages. Mean T_{sk} was calculated using Ramanathan's formula: $T_{sk} = 0.3(T_{chest} + T_{arm}) + 0.2 (T_{thigh} + T_{calf})$. Change in Tgi ($\Delta T_{gi}$) was calculated as ΔT_{gi} = End T_{gi} – Baseline T_{gi}. Ratings of perceived exertion (Borg's scale; RPE) and ratings of thermal sensation (8-point scale; RTS) were assessed every 15 min. After exercise, all devices were removed and the participant towelled dry prior to measurement of post-exercise nude body mass. Changes in nude body mass were used to estimate sweat loss using the formula: Sweat loss (L) = Pre-exercise body mass (kg) + fluid ingested (L) – urine excreted (L) – post-exercise body mass (kg). T_{db} and RH were continuously monitored using an environmental meter (Kestrel 4400 Heat Stress Tracker, Nielsen-Kellerman, USA) and recorded at 15-min intervals.

Statistical Package for Social Sciences (SPSS) version 26.0 (SPSS Inc., Chicago, IL, USA) was used for all statistical computations. Normality of data was assessed using Shapiro–Wilk test. One-way ANOVA was used to analyse controlled parameters of Tdb, RH and pre-trial USG. Paired t-test was performed to test for differences in mean Tgi, mean HR, mean Tsk, mean RPE, mean RTS, ΔTgi and estimated sweat loss in pre-planned comparisons (L + AMB vs L + ICE and M + AMB VS M + ICE). Significance level was set at $P < 0.05$. All values are expressed as mean ± SD.

3. Results

Participants started the trials euhydrated, with baseline USG lower than 1.025.[22] Mean baseline USG was similar between trials (L + ICE: 1.014 ± 0.008; L + AMB: 1.013 ± 0.007; M + ICE: 1.013 ± 0.007; M + AMB: 1.011 ± 0.008; p = 0.874). Mean T_{gi} and mean HR were similar when comparing L + ICE trials to L + AMB trials (T_{gi}: 37.6 ± 0.3 °C vs 37.7 ± 0.3 °C, p = 0.27; HR: 115 ± 10 bpm vs 118 ± 8 bpm, p = 0.12) and M + ICE trials to M + AMB trials (T_{gi}: 38.4 ± 0.3 °C vs 38.4 ± 0.3 °C, p = 0.22; HR: 158 ± 8 bpm vs 159 ± 8 bpm, p = 0.31; Fig. 1A and B). T_{sk} profiles were also similar during both low- and moderate-intensity trials (n = 8; L + ICE: 33.7 ± 0.6 °C vs L + AMB: 33.6 ± 0.5 °C, p = 0.49; M + ICE: 34.2 ± 0.4 °C vs M + AMB: 34.3 ± 0.5 °C, p = 0.37; Fig. 1C). Two participant's data were incomplete and not included due to the premature detachment of the wireless iButtons®.

Participants in L + ICE trials had lowered ΔT_{gi} (0.6 ± 0.2 °C vs 0.8 ± 0.3 °C, p = 0.03; Fig. 2A) and estimated sweat loss (0.78 ± 0.27 L vs 0.91 ± 0.19 L, p = 0.04; Fig. 2B) compared to L + AMB trials. However, no differences were observed during moderate-intensity exercise (ΔT_{gi}: 2.0 ± 0.4 °C vs 2.1 ± 0.5 °C, p = 0.41; Sweat loss: 1.66 ± 0.39 L vs 1.54 ± 0.47 L, p = 0.17; Fig. 2A and B).

Mean RPE was found to be lower in L + ICE compared to L + AMB (9 ± 1 vs 10 ± 1, p = 0.03), but no differences were observed in moderate-intensity trials (11 ± 1 vs 11 ± 1, p = 0.37; Fig. 3A). RTS was similar in both low- and moderate-intensity trials (L + ICE: 4.7 ± 0.3 vs L + AMB: 4.9 ± 0.5, p = 0.10; M + ICE: 5.0 ± 0.4, M + AMB: 5.3 ± 0.7, p = 0.09; Fig. 3B).

4. Discussion

The objective of our study was to investigate the thermoregulatory responses to ice slurry ingestion at varying exercise intensities while donning a raincoat. We observed that ice slurry ingestion was marginally more efficacious in lowering thermal strain during low-intensity compared to moderate-intensity exercise. At low-intensity, ice slurry ingestion resulted in a lowered ΔT_{gi}, a lowered estimated sweat loss and reductions in perceived exertion. Comparatively, physiological and perceptual parameters remained unchanged when ingesting ice slurry during moderate-intensity exercise. Our study thus demonstrates that the effectiveness of per-cooling with ice slurry varies according to exercise intensity, and its effectiveness is maintained even with the additional usage of a raincoat to restrict heat loss. Per-cooling with ice slurry may thus be a useful ergogenic aid during physical activity of lower intensities such as those found in occupational and military settings in restrictive heat loss environments.

Per-cooling with ice slurry may not be as efficacious in protecting against exertional heat strain during moderate-intensity exercise.[16,17] Indeed, results from this present study concur with previous findings in showing that ice slurry ingestion during moderate-intensity did not appear to alter T_c and T_{sk} profile.[17,19] However, estimated sweat loss was not reduced when ingesting ice slurry during moderate-intensity exercise. This contradicts observations by Morris et al.[19] which showed that ice slurry ingestion suppresses evaporative heat loss potential, thereby accounting for the lack of changes in T_{re} and T_{sk}. This contrasting observation may be due to the use of body mass measurements to estimate sweat loss, which may not be entirely indicative of the evaporative heat loss potential. Additionally, this study was conducted in humid environmental conditions, with 63 ± 5% RH, while the study conducted by Morris and colleagues was conducted at 24 ± 3% RH. The present study also utilised a raincoat to restrict heat loss. The difference in humidity coupled with the usage of a raincoat would decrease water vapour pressure gradient between the skin and the environment resulting in a lowered evaporative heat loss potential, regardless of differences in sweat rate induced by beverage temperature. As such, we postulate that ice slurry ingestion would not further lower estimated sweat loss, and no differences were thus observed in this present study.

While ice slurry may not be as efficacious at moderate-intensity, ice slurry appears to reduce thermal strain when ingested at low-intensity exercise. We postulate that this could be due to a lower absolute amount of metabolic heat production at the lower intensity. Internal heat storage is influenced by both metabolic heat gain and heat loss (largely via heat dissipation mechanisms).[23] The ingestion of ice slurry provides an additional avenue for internal heat loss. Therefore, as low-intensity exercise produces a lower amount of metabolic heat, ingestion of ice slurry can sufficiently ameliorate this heat gain via an increase in internal heat loss and, subsequent increased heat storage capacity. As such, although sweat loss is reduced, the loss of this heat dissipation mechanism is tolerable in terms of preventing excessive increases in heat storage. This is evidenced by the results of the present study in which there is a marginal but distinct reduction in ΔT_{gi} during low-intensity exercise despite a parallel decrease in estimated sweat loss. Therefore, our study demonstrates that, ice slurry ingestion during low-intensity exercise results in a lower overall gain in heat storage, resulting in a preservation of the beneficial net body cooling effect despite a reduced sudomotor response.

Although ΔT_{gi} was reduced during low-intensity exercise, end T_{gi} was not found to be similarly lowered. This contradicts findings by Hailes et al.,[15] which demonstrated that T_{re} at the end of a 3-h exercise bout at 40% VO_{2max} was lowered with ice slurry ingestion. The difference observed could be attributed to a shorter exercise bout of 75-min in this present study. The lowered T_{re} with ice slurry ingestion was only observed at the 3 h mark with no significant differences observed at earlier time points. We postulate that if exercise had been carried out for a longer period in this present study, the reduced ΔT_{gi} would have eventually caused a lowering of end T_{gi}. In addition, the total volume of ice slurry consumed was lower in the present study (10 g kg^{-1}; 2 g kg^{-1} every 15-min across 75-min of exercise) as compared to Hailes et al.[15] (~36 g kg^{-1} or 18 g kg^{-1}; 2 g kg^{-1} or 1 g kg^{-1} every 10-min across 3 h). We postulate that the dose of ice slurry provided during exercise may play a key role in reducing thermal strain, and a larger dose given at shorter time intervals may further accentuate the efficacy of per-cooling with ice slurry ingestion.

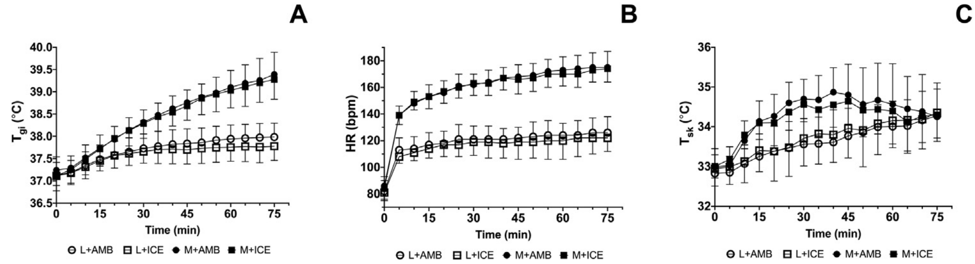

Fig. 1. Mean gastrointestinal temperature profile (T_{gi}; A), heart rate profile (HR; B) and skin temperature profile (T_{sk}; C) across the 75-min exercise at varying exercise intensities for all trial conditions. L + AMB – low-intensity with ambient drink, L + ICE – low-intensity with ice slurry, M + AMB – moderate-intensity with ambient drink, M + ICE – moderate-intensity with ice slurry. Physiological variables were measured continuously and averaged at 5-min intervals. Data are represented as mean ± SD.

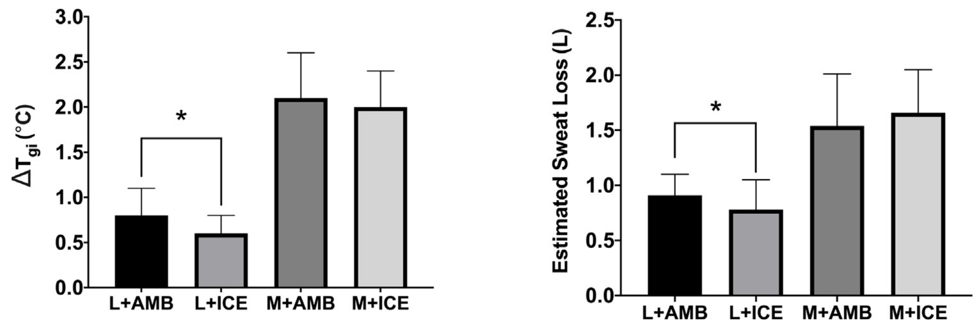

Fig. 2. Change in T_{gi} (ΔT_{gi}) (A) and estimated sweat loss (B) calculated for all trial conditions. L + AMB – low-intensity with ambient drink, L + ICE – low-intensity with ice slurry, M + AMB – moderate-intensity with ambient drink, M + ICE – moderate-intensity with ice slurry. * denotes significant difference ($p \leq 0.05$) between trial conditions. Data are represented as mean ± SD.

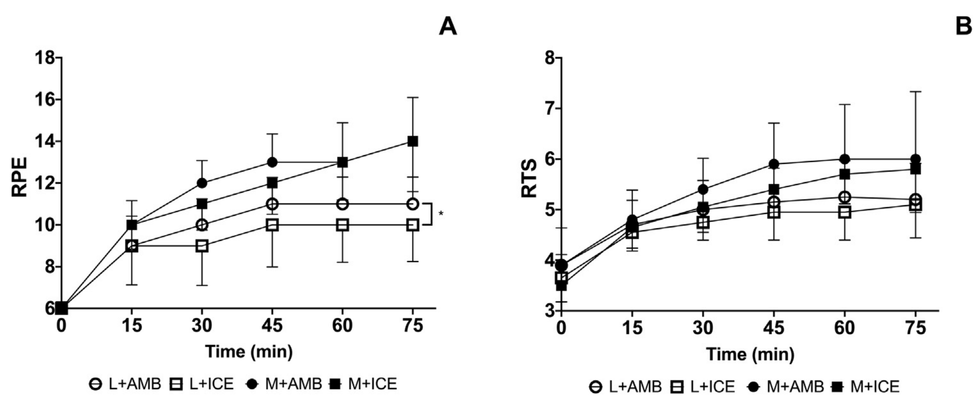

Fig. 3. Mean ratings of perceived exertion profile (RPE; A) and ratings of thermal sensation profile (RTS; B) across the 75-min exercise at varying exercise intensities for all trial conditions. L + AMB – low-intensity with ambient drink, L + ICE – low-intensity with ice slurry, M + AMB – moderate-intensity with ambient drink, M + ICE – moderate-intensity with ice slurry. Recordings were taken at 15-min intervals. * denotes significant difference ($p \leq 0.05$) between trial conditions. Data are represented as mean ± SD.

The present study was carried out at dry bulb temperature of 25.1 °C and relative humidity of 63%. Jay and Morris[23] have postulated that ingestion of ice slurry in a hotter and more humid environmental setting might accentuate the net cooling effect as evaporative potential would be limited. Whilst internal heat loss via ice slurry ingestion may be dampened due to a reduction in evaporative heat loss,[18] the reduction in sweating may not compromise actual evaporation in uncompensable environments. The attainment of the maximum evaporative potential in these settings would cause excess sweat generated to drip off the skin surface. In this present study, the humid environmental conditions are coupled with a raincoat that further restricts heat loss. Together, an uncompensable microenvironment is created and heat dissipation via the sudomotor response is limited. As such, the beneficial effect from the internal heat loss generated by ice slurry ingestion may be retained, especially in occupational and military settings with restrictive heat loss attires.

We also observed a reduction in subjective ratings of perceived exertion in low-intensity trials with ice slurry ingestion. While the reductions in perceived exertion may be minimal, such perceptual improvements may still be beneficial in enhancing performance in a hot environment.[10,24,25] This is where a reduced thermal strain may lead to an improvement in thermal comfort that may enhance motivation for an individual to continue to carry out the exercise.[24]

Our findings have potential implications in certain occupational and military settings of comparable low physical intensity. From this study, ice slurry appears to be more efficacious when ingested during low-intensity exercise to reduce thermal strain. This is of particular importance due to the increasing need for effective and practical heat mitigation strategies in such sectors. The usage of impermeable personal protective equipment (PPE) creates a restrictive state which may further increase thermal load.[26] As workers and military personnel have to adapt and perform in these unfavourable hot and humid environments, per-cooling with ice slurry could be implemented to counteract the adverse effects of heat stress and augment human performance and health. Indeed, this study adds to more recent research that hopes to extend the effects of ice slurry in occupational contexts. Considerations could also be given to increasing the volume of ice slurry,[27] provision of ice slurry at increased time-points during the workday (before and during work,[28] and/or during rest portions) and to combine different cooling modalities to extend the benefits of cooling in occupational contexts.[29]

However, there are several limitations. The study adopted the usage of raincoats in an attempt to create microenvironments of greater thermodynamic similarity to those found in restricted heat loss contexts such as when donning PPE or other encapsulating equipment. In addition, the study did not assess the effect of ice slurry on performance. As such, any potential enhancement of performance is estimated based on observations of a lowered physiological and perceptual strain that may drive increased performance measures. This study was also carried out in a controlled laboratory setting. Future studies should be focused on determining the efficacy of per-cooling with ice slurry ingestion in actual field settings to ascertain its practical application in military and occupational settings.

5. Conclusion

This study demonstrates that ice slurry is efficacious when ingested during low but not moderate-intensity exercise while wearing a raincoat. The lower amount of heat produced at lower exercise intensities can be sufficiently ameliorated by internal heat loss via ice slurry ingestion, despite the concomitant reduction in estimated sweat loss. Ice slurry is also more efficacious in hot and humid settings with restrictive attire, as a lowered sweat loss may not affect evaporative heat loss potential. This study is the first to demonstrate that the effectiveness of per-cooling with ice slurry may vary based on exercise intensities due to differences in human heat balance and modulation of thermoregulatory responses. Percooling with ice slurry ingestion may thus serve as an effective ergogenic aid for certain occupational and military settings of comparable low intensity.

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