Ice slurry ingestion does not enhance self-paced intermittent exercise in the heat

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This study aimed to determine if ice slurry ingestion improved self-paced intermittent exercise in the heat. After a familiarisation session, 12 moderately trained males (30.4 ± 3.4 year, 1.8 ± 0.1 cm, 73.5 ± 14.3 kg, VO2max 58.5 ± 8.1 mL/kg/min) completed two separate 31 min self-paced intermittent protocols on a non-motorised treadmill in 30.9 ± 0.9 °C, 41.1 ± 4.0% RH. Thirty minutes prior to exercise, participants consumed either 7.5 g/kg ice slurry (0.1 ± 0.1 °C) (ICE) or 7.5 g/kg water (23.4 ± 0.9 °C) (CONTROL). Despite reductions in Tc (ΔTc: −0.51 ± 0.3 °C, P < 0.05) and thermal sensation prior to exercise, ICE did not enhance self-paced intermittent exercise compared to CONTROL. The average speed during the walk (CONTROL: 5.90 ± 1.0 km, ICE: 5.90 ± 1.0 km), jog (CONTROL: 8.89 ± 1.7 km, ICE: 9.11 ± 1.5 km), run (CONTROL: 12.15 ± 1.7 km, ICE: 12.54 ± 1.5 km) and sprint (CONTROL: 17.32 ± 1.3 km, ICE: 17.18 ± 1.4 km) was similar between conditions (P > 0.05). Mean Tsk, Tb, blood lactate, heart rate and RPE were similar between conditions (P > 0.05). The findings suggest that lowering Tc prior to self-paced intermittent exercise does not translate into an improved performance.

It is well established that athletic performance in high ambient temperatures is impaired due to a reduced capacity for heat dissipation (Galloway & Maughan, 1997). The main limiting factor during exercise in the heat is thought to be the attainment of a high critical core temperature (Tc), which has been hypothesised to reduce skeletal muscle recruitment to protect the body against heat related illnesses (Gonzalez-Alonso et al., 1999; Tucker et al., 2004). To alleviate the impact of an elevated Tc during exercise in hot conditions, a number of different strategies to lower Tc prior to exercise have been investigated. More recently, internal pre-cooling using cold water or ice slurry ingestion has been examined with positive results on exercise performance (Lee et al., 2008; Burdon et al., 2010; Siegel et al., 2010, 2012; Stanley et al., 2010). In comparison to cold water immersion, consuming a 7.5 g/kg ice slurry beverage has led to similar reductions in Tc (−0.5 °C; Siegel et al., 2012) improved time to exhaustion (Siegel et al., 2010) and has proven effective in the field during a 10 km race (Yeo et al., 2012).

In addition to increasing the body’s heat storage capacity, it has been suggested that the process of ingesting an ice slurry beverage can lower brain temperature due to the close proximity of the mouth to the brain and the oesophagus to the carotid arteries (Siegel & Laursen, 2012) although this still awaits confirmation. There is further evidence of thermoreceptors located in the stomach/gastrointestinal region (Villanova et al., 1997; Morris et al., 2014) and ice slurry ingestion can directly affect these internal afferent signals much the same as the thermoreceptors located more peripherally to enhance exercise performance (Schlader et al., 2011; Faulkner et al., 2015; Lloyd et al., 2015). This internal pre-cooling strategy has multiple roles as it lowers Tc, hydrates and delivers substrates as it is often combined with carbohydrate (CHO) to enhance palatability. The thermodynamic properties of ice slurry beverages mean it provides greater heat storage capacity than water due to the added heat sink the enthalpy change in fusion creates when changing state from solid to liquid (Stanley et al., 2010).

Impaired performance during intermittent sports, such as football and field hockey, has also been reported during heat exposure (Morris et al., 2000; Drust et al., 2005; Mohr et al., 2010), which is typically characterised by less total distance covered, fewer high-intensity sprints, lower power output or slower sprint times. With the exception of ice slurry
ingestion, a number of studies have looked at different pre-cooling strategies to enhance intermittent exercise performance but the findings have been equivocal (Drust et al., 2000; Duffield & Marino, 2007; Minnett et al., 2011). This may be a result of the pre-cooling technique used or the method of assessing intermittent exercise performance. High-intensity activity has been measured using the speed to cover pre-defined distances (Duffield & Marino, 2007; Minnett et al., 2011), sprint ability on cycle ergometers and monitoring changes in power output (Duffield et al., 2003), as well as intermittent exercise until exhaustion at pre-defined speeds which correspond to a fixed percentage of starting $VO_{2\text{max}}$ (Jackson & Gerrett 2015). While self-paced intermittent protocols are difficult to conduct in a controlled laboratory setting, the reliability of using non-motorised treadmills to assess self-paced intermittent exercise has recently been confirmed (Tofari et al., 2015). Drust et al. (2000) investigated the influence of a 60-min cold shower prior to self-paced intermittent exercise on a non-motorised treadmill but reported no performance benefit despite a reduction in $T_c$ and $T_k$. The pre-cooling techniques used by studies investigating intermittent exercise have all used external cooling techniques (Drust et al., 2000; Duffield & Marino, 2007; Minnett et al., 2011) that aim to lower core temperature indirectly through the lowering of peripheral temperatures. Such studies are unable to determine whether the improvements in performance are related to lowering $T_c$ or changes in peripheral temperatures. Although the evidence is still unclear it has been reported that external cooling can reduce muscle blood flow, lower muscle temperature and impact enzymatic activity that could all impair anaerobic elements of an intermittent sporting activity (Bergh & Ekblom, 1979; Lloyd et al., 2015). Ice slurry ingestion provides direct internal cooling that bypasses the periphery (e.g., skin and muscles), so the sole impact of lowering $T_c$ to enhance self-paced intermittent exercise performance can be determined.

Therefore, the aim of this study was to determine if ice slurry ingestion improved self-paced intermittent exercise in the heat. It was hypothesised that consuming an ice slurry beverage would enhance intermittent exercise performance as observed by an increase in speed, especially during high-intensity exercise and therefore greater distance covered compared to a control beverage.

**Methods**

**Participants**

Twelve moderately to well-trained males (age 30.4 ± 3.4 year, height 1.8 ± 0.1 cm, weight 73.5 ± 14.3 kg, $VO_{2\text{max}}$ 58.5 ± 8.1 mL/kg/min; mean ± SD) volunteered to participate in this study. All participants trained regularly (minimum of five times per week) and were familiar with intermittent exercise (minimum exposure of intermittent exercise including, but not limited to, the following at least once per week: intermittent sports such as football and hockey, or interval training).

**Study overview**

Participants completed a health screen questionnaire and provided verbal and written consent and the institutional ethics committee granted human ethical clearance. A repeated measures design was used with each participant completing all interventions in a balanced order.

Prior to the main experimental trials participants completed a graded exercise test to determine $VO_{2\text{max}}$ and a separate familiarisation session of the self-paced intermittent exercise protocol. On two separate occasions participants completed an experimental trial in a climate-controlled room (30.9 ± 0.9 °C, 41.1 ± 4.0% RH). During the experimental trials, participants completed a 30-min pre-exercise period where they were required to consume either 7.5 g/kg of ice slurry (ICE) or 7.5 g/kg of water (23.4 ± 0.9 °C) (CONTROL). Both ICE and CONTROL beverages contained a CHO solution to enhance palatability and were matched (0.23%) for fair comparison between trials. They were then required to complete a self-paced intermittent exercise test on a non-motorised treadmill. All trials were completed at the same time of day, in a balanced order, with at least 5 days separating trials. Participants were asked to refrain from caffeine and alcohol ingestion and any strenuous exercise 24 h preceding the trials. They were asked to replicate their diet prior to each visit.

**Graded exercise test and familiarisation session**

On arrival to the Human Performance Laboratory participants had their height and weight (Seca, Birmingham, UK) recorded. Participants completed a 5-min self-selected warm-up prior to completing the graded exercise test for the determination of $VO_{2\text{max}}$ on a motorised treadmill (h/p/cosmos mercury 4.0 h/p/cosmos sports & Medical gmbh, Nußdorf-Traunstein, Germany). Starting treadmill speed was determined from the self-selected warm-up and corresponded to a heart rate value of approximately 130 b/min. The exercise intensity increased every minute by increasing speed by 1 km/h every minute until a comfortable speed was reached and thereafter gradient was increased by 0.5% until volitional fatigue (Hamlin et al., 2012). Respiratory gases were continuously monitored throughout using an online gas analysis system (Oxycon Pro, Jaeger, Wuerzberg, Germany) with 10-s averages being recorded. Heart rate was continuously monitored by telemetry using a HR monitor (Polar FT-1, Kempele, Finland) and RPE was recorded during the last 15 s of each stage using the 6- to 20-point Borg Scale (Borg, 1982). A finger prick blood lactate sample (Lactate Pro; Arkrey, Shiga, Japan) was taken approximately 3 min post-test. The variables were used for the determination of $VO_{2\text{max}}$ using the following criteria; a plateau in $VO_{2\text{peak}}$ HR ≥85% age predicted heart rate max, RER >1.15, RPE ≥19, voluntary exhaustion, post blood lactate ≥8.0 mmol/L. This was in accordance with the criteria recommended by BATES (1997). If all criteria were not met then a $VO_{2\text{peak}}$ value was recorded as the mean value from the final 30 s.

After a 5-min rest period participants were asked to familiarise themselves with the non-motorised treadmill (Woodway Curve 3.0™; Woodway, Inc., Waukesha, Wisconsin, USA)
for at least 5 min. Participants were asked to walk, jog, run and sprint on the treadmill to practice accelerating and decelerating and familiarise themselves with the treadmill. With at least 24 h separating the VO$_{2\text{max}}$ test participants returned to the laboratory to familiarise themselves with the intermittent protocol on the non-motorised treadmill in a thermoneutral room (~19 °C, 45% RH). The protocol included a 2-min warm-up at a self-selected speed followed by a 31-min intermittent protocol. The intermittent protocol was based on a previous protocol (Drust et al., 2000) which required participants to complete two 15.5 min bouts of the following, separated by a 71 s recovery period; 10 × 10 s sprints, 3 × 51 s run, 6 × 50 s jog, 6 × 30 s walk and 2 × 30 s rest period. The high-intensity bouts (run and sprint) were always followed by a low-intensity bout (rest, walk or jog). Three seconds were added to each exercise bout to account for time taken to accelerate or de-accelerate. Participants were informed that the performance indicators were the total distance covered and their average speed during each bout. They were instructed that ‘sprints’ should be completed at 100% effort, ‘runs’ at 75% effort, ‘jogs’ at 45% effort and ‘walks’ at 10% effort. A screen was placed at eye level and displayed the exercise instruction (e.g., WALK, JOG, RUN, SPRINT), the total exercise time and a time indicator of when the next exercise instruction would appear. Information regarding speed and distance covered was concealed from view.

**Experimental protocol**

Prior to arrival participants were instructed to swallow a telemetric pill (Cortemp®; HQ Inc., Palmetto, Florida, US) 4–8 h prior to testing after a discussion regarding typical bowel movements. On arrival to the laboratory a urine sample was collected prior to measurement of seminude body weight. Four wireless skin temperature sensors were attached and a heart rate monitor worn, after which, a resting fingertip blood lactate sample was taken along with a whole body thermal sensation (modified ASHRAE scale, ASHRAE, 1997). Participant then sat for 30 min in climatic controlled room (30.2 ± 0.9 °C, 39.8 ± 3.6% RH) and ingested either 7.5 g/kg of ice slurry (ICE: 0.14 ± 0.1 °C) or 7.5 g/kg of water (CONTROL: 23.4 ± 0.9 °C). Both beverages had 0.23% of a CHO (Robinson cordial, UK) to enhance palatability and the same flavour (except one participant who was allergic to orange so they were provided with an alternative flavour of the same brand) was used throughout the study. To reduce incidences of sphenopalatine ganglioneuralgia (brain freeze) and ensure standardised ingestion rate participants were given three bolus of 2.5 g/kg of either drink every 10 min. Participants were informed about the beverage with a description including consistency, quantity, temperature, flavour and timing consumption but they were not given a sample to try for familiarisation before the main trial. At 5-min intervals during the pre-exercise period $T_c$, HR and thermal sensation were recorded.

Within 5 min of consuming the final beverage participants began the intermittent exercise protocol (as outlined above) in 30.2 ± 1.2 °C, 42.5 ± 3.9% RH and a fan set at 1.3 m/s was placed 75 cm in front of the participant directed towards the torso. At 5-min intervals $T_c$, HR, RPE and thermal sensation were recorded. During the 71-s recovery period and at the end of the test a blood lactate sample from the fingertip was taken. At the end of the exercise, protocol participants towel dried themselves and were weighed semi nude again for body mass before the collection of another urine sample.

**Measurements**

**Exercise performance data**

The speed and distance covered were recorded continuously (sampling every 1 s) during the 31-min intermittent protocol on a non-motorised treadmill (Woodway Curve). The average speed and total distance covered during each exercise profile (walk, jog, run, sprint) was calculated for the entire protocol. The data were also separated into the first and last 15.5 min period.

**Core, skin and body temperature**

$T_c$ was monitored continuously during trials and averaged every 5 min during the pre-exercise and exercise period. If $T_c$ exceeded 39.5 °C the test was terminated and rapid cooling was provided to return $T_c$ to safe values. $T_{sk}$ was measured at four sites (chest, arm, thigh and calf) using iButtons® (Maxim Integrated Products, Inc., Sunnyvale, California, USA). $T_{sk}$ was continuously recorded at a sample rate of 1 per second. Data were then averaged over a 5-min period. Mean $T_{sk}$ was calculated using Ramannathan’s (1964) formula:

$$\text{mean}T_{sk} = 0.3(T_{chest} + T_{arm}) + 0.2(T_{thigh} + T_{calf})$$

Mean body temperature ($\bar{T}_b$) was calculated using the formula of Colin et al. (1971):

$$\bar{T}_b = (0.79 \times T_c) + (0.21 \times T_{sk})$$

**Thermal sensation, RPE, heart rate and blood lactate**

Heart rate was recorded using a wireless HR monitor (Polar FT-1) and 5-min averages were taken during rest and exercise. Thermal sensation was rated using a scale ranging from +10 (extremely hot) to −10 (extremely cold) with 0 indicating thermal neutrality (ASHRAE, 1997) and was recorded at 5-min intervals during rest and exercise. Participants were instructed to report the number (corresponding to the thermal sensation description) that best represents their whole body thermal status at that moment in time and were not permitted to recall their previous sensation. RPE was recorded using the 6- to 20-point Borg Scale (Borg, 1982) at 5-min intervals during exercise only. Participants were instructed to report the number (corresponding to the exertion description) that best represented how hard they felt they worked for the preceding 5-min period. Capillary blood samples (5 µL) were taken from the fingertip and analysed using an automated blood lactate analyser (Lactate Pro; Arkrey).
Urine osmolality and sweat rate

Urine samples were assessed for urine osmolality using a freezing point depression osmometer (Model 3300; Advanced Instruments, Inc., Norwood, Massachusetts, USA). Changes in seminude body mass were used to estimate gross sweat loss (L/h) adjusted for fluid intake.

Statistical analysis

Performance data (speed and distance) were analysed using three way repeated measures ANOVA (condition × time × exercise profile). \(T_c, T_s\), thermal sensation, RPE, blood lactate and HR data were analysed using two-way repeated measures ANOVA (condition × time). Where significant effects were identified, post hoc pairwise comparisons with a Bonferroni correction were conducted. Where an interaction effect was observed a paired samples \(t\)-test was conducted with Bonferroni correction applied. A student-paired \(t\)-test was performed on total distance covered, sweat rate and urine osmolality. All data were checked for normal distribution and the violation of sphericity prior to analysis and Greenhouse–Geisser epsilon correction was used to adjust the degrees of freedom, where sphericity was violated. Effect sizes (ES) (Cohen’s \(d\)) was calculated with the following criteria: an ES of <0.2 is classified as ‘trivial’, 0.2–0.4 as ‘small’, 0.5–0.7 as ‘moderate’ and >0.8 as a ‘large’ effect. The accepted level of significance for all analysis was \(P < 0.05\). All data are presented as mean ± SD.

Results

Environmental condition and hydration status

Ambient temperature and humidity were not different between conditions during rest (CONTROL: 30.1 ± 0.5 °C, 40.6 ± 3.4% RH, ICE: 29.8 ± 0.5 °C, 39.2 ± 3.9% RH, \(P > 0.05\)) or exercise (CONTROL: 30.2 ± 0.4 °C, 43.1 ± 3.7% RH, ICE: 30.2 ± 0.5 °C, 41.8 ± 4.1% RH, \(P > 0.05\)).

Hydration statuses, as measured using urine osmolality, were similar between conditions prior to the trial (CONTROL: 348.8 ± 301.7 mOsm/kg, ICE: 465.9 ± 343.4 mOsm/kg, \(P > 0.05\)) and after the trial (CONTROL: 352.7 ± 262.8 mOsm/kg, ICE: 424.1 ± 303.7 mOsm/kg, \(P > 0.05\)).

Performance data

Distance covered and average speed for each exercise profile during the first half, second half and total protocol are presented in Table 1. The average speed during the entire protocol for the walk (CONTROL: 5.90 ± 1.0 km/h, ICE: 5.90 ± 1.0 km/hr), jog (CONTROL: 8.89 ± 1.7 km/h, ICE: 9.11 ± 1.5 km/h), run (CONTROL: 12.15 ± 1.7 km/h, ICE: 12.54 ± 1.5 km/h) and sprint (CONTROL: 17.32 ± 1.3 km/h, ICE: 17.18 ± 1.4 km/h) were similar between conditions (all \(P > 0.05\), ES <0.2). There were also no differences between first and second half in either condition (\(P = 0.397\), ES = 0.02). As a result, there were also no differences in the distance covered between the two conditions in either the first half, second half or total protocol for all activity profiles (\(P = 0.653\), ES = 0.02).

Core temperature

Figure 1a illustrates \(T_c\) responses during the trial in both conditions. Two-way repeated measures ANOVA revealed an overall effect of condition, time and an interaction between condition and time (\(P < 0.05\)). There was no difference in initial resting \(T_c\) between the two conditions (ICE: 37.3 ± 0.4 °C, CONTROL: 37.3 ± 0.3 °C, \(P > 0.05\)). After the 30-min ingestion period there was a greater reduction in \(T_c\) after ingesting the ice slurry beverage compared to the control beverage (\(ΔT_c\): –0.51 ± 0.3 °C, –0.11 ± 0.2 °C, \(P < 0.05\), respectively). A trivial effect size was observed in the control condition (ES = 0.3) and a large effect size observed in the ICE condition (ES = 1.2). \(T_c\) was lower during ICE compared to CONTROL from 15 min into the rest period until the end of the exercise test, but post hoc comparison revealed differences during rest only (see Fig. 1a). A large effect size was observed at all time points during exercise when comparing ICE to the CONTROL (ES = 0.9–1.98).

Mean skin temperature

Mean \(T_s\) is illustrated in Fig. 1b. Mean \(T_s\) was similar between both conditions and two-way repeated measures ANOVA revealed no effect of condition but an effect of time. Mean \(T_s\) increased throughout the protocol and was higher at the end of the rest period compared to baseline (34.5 ± 0.4 °C and 33.9 ± 0.5 °C, respectively, \(P < 0.05\), ES = 1.3) and was higher at the end of exercise compared to the end of the rest period (35.6 ± 0.8 °C and 34.5 ± 0.4 °C, respectively, \(P < 0.05\), ES = 1.7). There was no interaction effect between condition and time (\(P > 0.05\)).

Body temperature

\(T_b\) is illustrated in Fig. 1c and two-way repeated measures ANOVA revealed an effect of condition, time and an interaction between condition and time. Baseline \(T_b\) was not different between conditions (CONTROL: 36.7 ± 0.2 °C, ICE: 36.6 ± 0.4 °C, \(P > 0.05\)). There was a trend for \(T_b\) to be lower during ICE compared to CONTROL throughout rest.
and exercise but post hoc comparison revealed that $T_r$ was only different at the start of exercise (CONTROL: 36.7 ± 0.2 °C, ICE: 36.3 ± 0.5 °C, $P < 0.05$). A large effect size was observed between ICE and CONTROL conditions from 15 min into rest until 25 min of exercise (ES = 1.0–1.7). A moderate effect size was observed at rest (5 and 10 min) and the final 5 min of exercise (ES = 0.45–0.7).

Blood lactate, heart rate and RPE

Figure 2 indicates blood lactate values pre, mid and post-exercise in both conditions. Blood lactate was not different between conditions at any time point during the test ($P > 0.05$, ES > 0.2). Blood lactate increased during exercise in both conditions and was higher mid and post-exercise compared to rest (both $P < 0.05$, ES = 2.8 and 3.3, respectively) but post-exercise values were similar from mid trial to post trial ($P < 0.05$, ES < 0.2).

Figure 3 illustrates heart rate during both conditions and analysis revealed no effect of condition but an effect of time. Heart rate (5 min averages) increased at the onset of exercise and remained stable over the 30-min exercise bout. As a result, heart rate was higher during exercise compared to rest ($159 \pm 14.3 \text{ beats/min vs } 66.4 \pm 8.4 \text{ beats/min, } P < 0.05$, ES = 7.9).

RPE continuously increased during exercise but was not different between conditions ($P > 0.05$). RPE increased every 5 min during exercise from an initial score of 12 ± 2.0 to 17 ± 2 at the end of exercise ($P < 0.05$, ES = 2.5) (Fig. 4).

Thermal sensation

Thermal sensation is illustrated in Fig. 5. Statistical analysis revealed an effect of condition, time and an interaction between condition and time ($P < 0.05$). Thermal sensation was similar at the start of the rest period (CONTROL: 2.5 ± 1.5, ICE: 2.8 ± 1.3, $P > 0.05$, ES < 0.2) and began to decline immediately during ICE, while it remained relatively stable during CONTROL. During rest, thermal sensation was lower during the ice slurry condition compared to control at −20, −15, −10, −5 and 0 min ($P < 0.05$). During exercise, there was a trend for thermal sensation to be lower during ICE compared to CONTROL until 15 min into exercise, after which it was similar between conditions ($P > 0.05$). Thermal sensation was only different during exercise between the two conditions at 10 min (CONTROL: 6.1 ± 0.9, ICE: 5.0 ± 1.2, $P < 0.05$). The effect size after 5 min of rest was moderate (ES = 0.77) and was then large thereafter (ES = 0.83–1.4) until 15 min into exercise after which the effect size was small to trivial (ES = 0–0.3).

Sweat rate

Sweat rate was not different between CONTROL and ICE (8.4 ± 1.6 g/min and 8.5 ± 1.8 g/min, respectively, $P > 0.05$, ES < 0.2).

Discussion

This study aimed to determine whether ice slurry ingestion enhances self-paced intermittent exercise in the heat. Despite $T_r$ being lower prior to exercise neither low (walking and jogging) nor high (running and sprinting) intensity activity was enhanced. In addition, thermal sensation was lower prior to and during the first 10 min of exercise but neither $T_r$ or thermal sensation altered self-paced intermittent exercise in the heat at any time point during the 31-

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Table 1. Mean (±SD) distance (km) covered during the first half, second half and entire (total) self-paced intermittent protocol. Distance covered is also presented for each activity profile; walk, jog, run and sprint. Where appropriate mean (±SD) speed (m/s) is presented under the data, inside parentheses. There were no differences in the distance covered or speed during the control or ice condition ($P > 0.05$)

|                  | Total distance (km) | First half distance (km) | Second half distance (km) | Entire distance (km) |
|------------------|---------------------|--------------------------|--------------------------|----------------------|
|                  |                     | Walk (km)                | Jog (km)                 | Run (km)             | Sprint (km)         |
|                  |                     | (SD)                     | (SD)                     | (SD)                 | (SD)                |
| Control          | 2.3 ± 0.2           | 0.33 ± 0.1               | 0.78 ± 0.1               | 0.53 ± 0.1           | 0.63 ± 0.1          |
|                  |                     | (5.91 ± 1.0)             | (8.86 ± 1.5)             | (11.84 ± 1.5)        | (17.48 ± 1.4)       |
| Ice              | 2.3 ± 0.2           | 0.33 ± 0.1               | 0.82 ± 0.1               | 0.54 ± 0.1           | 0.62 ± 0.1          |
|                  |                     | (6.00 ± 0.9)             | (9.26 ± 1.2)             | (12.05 ± 1.4)        | (17.18 ± 1.4)       |
| Control          | 2.29 ± 0.3          | 0.32 ± 0.1               | 0.79 ± 0.2               | 0.56 ± 0.1           | 0.62 ± 0.1          |
|                  |                     | (5.90 ± 1.0)             | (8.92 ± 1.9)             | (12.46 ± 2.0)        | (17.17 ± 1.3)       |
| Ice              | 2.32 ± 0.3          | 0.32 ± 0.1               | 0.79 ± 0.2               | 0.59 ± 0.1           | 0.62 ± 0.1          |
|                  |                     | (5.80 ± 1.1)             | (8.96 ± 1.9)             | (13.02 ± 1.7)        | (17.18 ± 1.5)       |
| Total            | 4.56 ± 0.5          | 0.65 ± 0.1               | 1.57 ± 0.3               | 1.09 ± 0.2           | 1.25 ± 0.1          |
|                  |                     | (5.90 ± 1.0)             | (8.89 ± 1.7)             | (12.15 ± 1.7)        | (17.32 ± 1.3)       |
| Ice              | 4.63 ± 0.5          | 0.65 ± 0.1               | 1.61 ± 0.3               | 1.13 ± 0.1           | 1.24 ± 0.1          |
|                  |                     | (5.90 ± 1.0)             | (9.11 ± 1.5)             | (12.54 ± 1.5)        | (17.18 ± 1.4)       |
min protocol. Mean $T_{sc}$, blood lactate, heart rate and RPE were similar between the two conditions.

### Core and skin temperature

This study supports previous research demonstrating the effective use of ice slurry ingestion in lowering $T_c$ (Siegel et al., 2010, 2012; Stevens et al., 2013). $T_c$ was $-0.51 \pm 0.3 \, ^\circ C$ ($P < 0.05$) lower after ingestion prior to exercise, which is comparable to other studies utilising this technique and 7.5 g/kg quantity (measured using rectal thermometer: $-0.66 \pm 0.14 \, ^\circ C$; Siegel et al., 2010; $-0.43 \pm 0.14 \, ^\circ C$; Siegel et al., 2012). According to Siegel et al. (2010), the combined thermodynamic properties of an ice slurry mixture and the change in physical states from solid to liquid (in comparison to a purely solid or liquid state) results in a greater heat sink ultimately permitting greater heat storage. This is partially evident from the decrease in $T_c$ observed between the two conditions (ICE: $-0.51 \pm 0.3 \, ^\circ C$, CONTROL: $-0.11 \pm 0.2 \, ^\circ C$, $P < 0.05$). While a greater heat storage capacity has been the reported mechanism associated with enhanced endurance performance.
Fig. 2. Mean (±SD) blood lactate at rest, during (half way) and at the end of the 31 min self-paced intermittent protocol during the control and ice slurry ingestion. There were no significant differences between conditions but during and post values were higher than rest (*P < 0.05).

Fig. 3. Mean (±SD) heart rate during the control and ice slurry condition. Dashed line (---) indicates the start of exercise. There were no differences in heart rate between conditions (P > 0.05).

Fig. 4. Mean (±SD) RPE during exercise in the control and ice slurry condition. There were no differences in RPE between conditions (P > 0.05).
through delaying the attainment in reaching a critical limiting temperature (Gonzalez-Alonso et al., 1999; Marino, 2002) the purported benefits of lowering \( T_c \) prior to self-paced intermittent exercise in the heat did not enhance performance in this study despite a number of studies reporting impaired intermittent performance as a result of an elevated \( T_c \) (Morris et al., 1998; Morris et al., 2000; Drust et al., 2005). A recent meta-analysis reported small effect size (weighted mean estimate; \( d = 0.47 \)) of lowering \( T_c \) prior to intermittent exercise (Tyler et al., 2015). \( T_c \) was lowered in this study, yet no performance improvements occurred, which raises the question over the importance of lowering \( T_c \) alone.

It has been suggested that \( T_c \) in excess of 38.5 °C would impair intermittent exercise performance (Sawka et al., 2001; Almudehki et al., 2012) and in this study \( T_c \) was 38.9 ± 0.3 °C (CONTROL) and 38.6 ± 0.3 °C (ICE) at the end of exercise. Impaired intermittent exercise performance in the heat, characterised by changes in total distance covered, slower sprint times and reduced power output have been reported in some studies (Morris et al., 2000; Drust et al., 2005) but not all (Backx et al., 2000; Girard et al., 2014). Inconsistent findings regarding the effects of heat stress on intermittent exercise performance can be associated with varying protocols and environmental conditions, but there is also large disparity between fundamental thermal physiological measures. Many studies on intermittent exercise have failed to measure or report mean \( T_{sk} \) (Morris et al., 1998, 2000 Ball et al., 1999; Drust et al., 2005; Duffield et al., 2009) or have only measured \( T_{sk} \) at one or two locations (Drust et al., 2000; Almudehki et al., 2012). As such, the decline in performance has been associated with elevations in \( T_c \) (Morris et al., 1998, 2000; Drust et al., 2005) resulting in pre-cooling studies focusing upon strategies to lower it. Interestingly, studies that have shown enhanced intermittent exercise performance following a pre-cooling strategy have typically been those that have reported both a decline in \( T_c \) and \( T_{sk} \) (Duffield & Marino, 2007; Minnett et al., 2011). Minnett et al. (2011) highlighted a dose dependent response of pre-cooling; the larger the surface exposed to cooling, the greater the work capacity achieved during self-paced intermittent exercise in the heat. Exposing more skin to a cooling mechanism results in larger reductions in both \( T_{sk} \) and \( T_c \). Duffield and Marino (2007) also showed that by lowering both \( T_c \) and \( T_{sk} \) (using whole body cold water immersion) resulted in greater distances covered during hard submaximal bouts compared to ice vest (lower surface area coverage) and a control condition (no cooling).

**Sensory feedback**

Sensory feedback from group III and group IV muscle afferents and thermoreceptors located in the core and skin are known to be important regulators in exercise performance (Schlader et al., 2011; Laurin et al. 2015; Lloyd et al., 2015). Recently, there has been an increase in the number of studies highlighting the role of \( T_{sk} \) in regulating exercise performance due to its role in afferent (sensory) feedback (Cheung & Sleivert, 2004; Faulkner et al., 2015). Schlader et al. (2011) demonstrated that by non-thermally cooling or warming the face using menthol or capsaicin altered thermal perceptions without any changes to \( T_{sk} \). These perceptual responses were similar to those seen with cooling and heating using forced convection. As a result of the altered thermal perception (with or without changes in \( T_{sk} \)) participants demonstrated a thermoregulatory behaviour as observed with changes in self-selected exercise intensity. A change in \( T_{sk} \) stimulates peripheral thermoreceptors providing feedback about the thermal state of the body that has been shown to be an
important regulatory function during self-paced exercise even in the absence of a change in $T_c$ (Schlader et al., 2011). Consistent with previous studies utilising ice slurry consumption (Siegel et al., 2010, 2012) is the minimal influence this technique had upon $T-sk$ in this study. Mean $T-sk$ was similar between both conditions whereby it increased during the first 10 min, remained relatively stable during rest and increased during exercise (Fig. 1b). Core temperature as a single limiting factor to exercise performance in the heat has raised further doubts in a recent study by Faulkner et al. (2015) who demonstrated that exercise performance (cycling time trial) can be improved with reductions in mean $T-sk$ and thermal sensation independent of changes in $T_c$. In this study, thermal sensation was significantly lower during the rest period, which was likely due to differences in $T_c$, as $T-sk$ was similar between conditions. During exercise, it began to converge and was similar after 15 min even though $T_c$ was different, suggesting thermoreceptors located elsewhere started to influence thermal sensation. The similar $T-sk$ between conditions and the absence of a lowered thermal sensation towards the end of exercise may explain why performance was similar between conditions. Although no data exist for intermittent exercise the importance of lowering $T-sk$ may be just as important as lowering $T_c$. The findings from this study and the disparity of information from the literature suggest that we must determine the role of $T_c$, and $T-sk$ (concomitantly and independently) on self-paced intermittent exercise in the heat, after which appropriate and effective cooling strategies may be developed.

Cardiovascular response

Pre-cooling strategies that lower $T_c$ and/or $T-sk$ are often accompanied by a reduced cardiovascular strain due to the reduced need for autonomic heat dissipation (Wilson et al. 2002). As $T_c$ was lower during the ICE condition but $T-sk$ was similar, a lowered cardiovascular strain might have been experienced however there is no indication of this from the heart rate data collected (Fig. 3). This may be due to the similarity in the $T-sk$ response between conditions. Although not measured, it is speculated that the $T-sk$ response resulted in similar skin blood flow and evaporation rates between the two conditions. The former supported by the similar heart rates observed during the entire protocol (Fig. 3). The latter supported by the similar estimated sweat loss from pre- and post-weight measurements between the two conditions (CONTROL: 8.4 ± 1.6 g/min, ICE: 8.5 ± 1.8 g/min, $P > 0.05$). To achieve a reduced cardiovascular strain that might enhance intermittent exercise performance in the heat a cooling strategy should serve to lower $T-sk$ in addition to $T_c$.

Practical application

Ice slurry ingestion has been reported to lower $T_c$ before and during exercise but by the end of exercise $T_c$ is typically higher than the control condition due to prolonged run time to exhaustion (Siegel et al., 2010, 2012). In this study, $T_c$ was lower ($P < 0.05$) only during the ingestion period and although not statistically different there was a large effect size observed throughout exercise ($d > 0.9$). Our data suggest that although ice slurry ingestion, as a pre-cooling strategy, is effective in enhancing self-paced endurance exercise it may not provide sufficient cooling power to enhance self-paced intermittent exercise. This may be related to the larger amounts of heat produced from the breakdown of ATP, which occurs at a faster rate during high-intensity activity compared to submaximal exercise. However, it was interesting to note that participants ran at similar exercise intensity as observed by the same speeds, heart rates, blood lactate values and RPE scores, yet had a lower $T_c$ of approximately $0.5 ± 0.6 °C$ throughout the 31 min. Despite no significant difference, a large effect size was observed for the lowered $T_c$ response during exercise ($0.5 ± 0.6 °C$). An average difference of $0.5 ± 0.6 °C$ is of physiological importance and whilst other studies report an elevated $T_c$ at the end of exercise $T_c$ remained lower than the control condition ($P > 0.05$). One half of a field hockey or football match last 35 and 45 min, respectively. So in this instance, we speculate that rather than enhancing performance, ice slurry ingestion may allow athletes to compete at a similar exercise intensity, but experience less thermal strain by working within safer $T_c$ values. Undoubtedly though, this theory warrants further investigation utilising additional, more robust thermal physiological measures of whole body heat content (not just limited to $T_c$ and $T-sk$ measures) rather than gastrointestinal temperature alone.

Limitations

A limitation of this study resides in the measure of $T_c$ using a telemetric pill. The study was designed to minimise the impact of cumbersome wires interfering with exercise performance so the use of wireless technology was opted for (i.e., telemetric pill and iButtons). The impact of which reduces the certainty of the data collected, especially given the proximity of the beverage in the stomach to the telemetric pill in the intestines. Studies have confirmed the validity of such devices and it is known to respond less rapidly than oesophageal but more rapidly than rectal thermometer (Byrne & Lim, 2007). However, the impact of ice slurry ingestion on the measures of $T_c$ using oesophageal, intestinal and rectal thermometers has
not been determined and certainly warrants investigating. In addition, the role of pre-cooling during exercise could underestimate total heat content when based on a two-compartment model because of the errors associated with its measurement based on $T_c$ and $T_{sk}$ alone and the potential contribution of heat storage from active and inactive muscle mass that is not accounted for (Jay et al., 2007). The influence of ice slurry ingestion on heat storage warrants further investigation.

**Perspectives**

This study demonstrated a popular pre-cooling technique shown to enhance endurance performance does not have the same benefits for self-paced intermittent exercise in the heat. Despite lowering $T_c$ and reducing thermal sensation in comparison to a control beverage, the speed or distance covered was similar between the two conditions. There was a trend for $T_c$ to be lower throughout exercise despite a similar exercise intensity (similar speeds, heart rate, blood lactate and RPE) therefore it does allow athletes to compete within a safer $T_c$ range. Further research is required to investigate the role of lowering both $T_c$ and $T_{sk}$ on self-paced intermittent exercise performance so that appropriate pre-cooling techniques can be designed.

**Key words:** Pre-cooling, thermoregulation, performance, team sports, intermittent exercise, self-pacing.

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**Conflict of interest**

The authors declare that there are no conflicts of interest.

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