Ice Slurry Ingestion Increases Core Temperature Capacity and Running Time in the Heat

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ABSTRACT

SIEGEL, R., J. MATÉ, M. B. BREARLEY, G. WATSON, K. NOSAKA, and P. B. LAURSEN. Ice Slurry Ingestion Increases Core Temperature Capacity and Running Time in the Heat. *Med. Sci. Sports Exerc.*, Vol. 42, No. 4, pp. 717–725, 2010. **Purpose**: To investigate the effect of ice slurry ingestion on thermoregulatory responses and submaximal running time in the heat. **Methods**: On two separate occasions, in a counterbalanced order, 10 males ingested 7.5 $g \cdot kg^{-1}$ of either ice slurry (−1°C) or cold water (4°C) before running to exhaustion at their first ventilatory threshold in a hot environment (34.0°C ± 0.2°C, 54.9% ± 5.9% relative humidity). Rectal and skin temperatures, HR, sweating rate, and ratings of thermal sensation and perceived exertion were measured. **Results**: Running time was longer (P = 0.001) after ice slurry (50.2 ± 8.5 min) versus cold water (40.7 ± 7.2 min) ingestion. Before running, rectal temperature dropped 0.66°C ± 0.14°C after ice slurry ingestion compared with 0.25°C ± 0.09°C (P = 0.001) with cold water and remained lower for the first 30 min of exercise. At exhaustion, however, rectal temperature was higher (P = 0.001) with ice slurry (39.36°C ± 0.41°C) versus cold water ingestion (39.05°C ± 0.37°C). During exercise, mean skin temperature was similar between conditions (P = 0.992), as was HR (P = 0.122) and sweat rate (P = 0.242). After ice slurry ingestion, subjects stored more heat during exercise (100.10 ± 25.00 vs 78.93 ± 20.52 $W \cdot m^{-2}$, P = 0.005), and mean ratings of thermal sensation (P = 0.001) and perceived exertion (P = 0.022) were lower. **Conclusions**: Compared with cold water, ice slurry ingestion lowered preexercise rectal temperature, increased submaximal endurance running time in the heat (+19% ± 6%), and allowed rectal temperature to become higher at exhaustion. As such, ice slurry ingestion may be an effective and practical precooling maneuver for athletes competing in hot environments.

Key Words: PRECOOLING, RECTAL TEMPERATURE, THERMOREGULATION, TIME TO EXHAUSTION

The rise in core body temperature (T_c) associated with exercise in hot environments is generally thought to be the principle contributing factor causing fatigue and the reduction in motor output observed during prolonged exercise in the heat (13,32). A fundamental concept in the thermoregulatory literature is that the termination of prolonged exercise in the heat seems to coincide with the attainment of a critically high T_c (15,29). For example, Gonzalez-Alonso et al. (15) showed that despite differences in starting T_c, subjects consistently fatigued at the same T_c. Such an occurrence may serve as a protective mechanism aimed at reducing motor output and heat production before the development of severe heat illness.

As thoroughly reviewed by Marino (24) and Quod et al. (33), precooling is a useful strategy for combating the detrimental effects that heat stress has on exercise performance. The main benefit of precooling is the lowering of T_c before exercise in the heat, thereby increasing heat storage capacity and in turn prolonging or even preventing attainment of critical core temperatures. This consequently improves endurance performance in hot conditions. Precooling maneuvers investigated to date have been achieved almost exclusively via external cooling procedures, such as cold water immersion or wearing ice jackets (34), with limited exploration into the potential benefits of internal cooling modalities. Lee et al. (22) investigated the effect of cold (4°C) and warm (37°C) water ingestion before, and during, exercise on cycling performance in hot, humid conditions. Compared with warm water, cold water ingestion reduced rectal temperature (T_{re}) by 0.5°C ± 0.1°C before exercise and significantly increased cycling time to exhaustion by 23% ± 6%. It is difficult to ascertain whether the lower mean T_{re} throughout the trial and subsequent improved exercise performance was due to the cooling effect of the cold water before or during exercise; however, it is probable that both factors contributed.

A more aggressive and practical internal precooling technique might arise from the ingestion of an ice slurry mixture. Ice slurries, commonly called slushies, are icy mixtures that are consumed as a drink. Changing the physical state of

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Submitted for publication May 2009.
Accepted for publication August 2009.

0195-9131/10/4204-0717/0
MEDICINE & SCIENCE IN SPORTS & EXERCISE®

DOI: 10.1249/MSS.0b013e3181bf257a

water (H_2O) from solid to liquid (phase change) requires a large transfer of heat energy into the system. Using this "enthalpy of fusion" of ice as an additional heat sink allows more heat to be transferred into the drink rather than being stored in the body. Hence, solid ice provides a greater cooling effect than liquid water alone. For example, Merrick et al. (26) showed that cooling treatments that undergo phase change (ice bag and wet ice) lower skin temperature (T_{sk}) and 1 cm of subadipose tissue temperature significantly more than treatments that do not undergo phase change (Flex-i-Cold frozen gel pack). Because ice slurry ingestion is an internal cooling modality, it is possible that a greater amount of internal heat might be transferred to the drink as it changes phase from solid ice to liquid water. This effect, in turn, may lower T_c significantly more than water of a similar temperature, potentially resulting in improvements to prolonged exercise performance in the heat. A lowering of internal temperatures with an ice slurry solution has been shown in swine. Vanden Hoek et al. (40) showed that a 50-mL·kg^{-1} intravenous bolus of saline ice slurry (−1°C to 0°C) reduced swine brain temperature by 5.3°C ± 0.7°C compared to 3.4°C ± 0.4°C with chilled saline (0°C–1°C). Although ice slurry cooling has been shown to reduce internal temperatures to a greater degree than chilled water in swine, limited research has focused on its effect on cooling and subsequent exercise performance in the heat in humans.

The purpose of the present investigation was to examine the effects of ice slurry versus cold water ingestion on thermoregulatory responses and prolonged submaximal exercise performance in the heat. We hypothesized that ice slurry (−1°C) ingestion would significantly reduce T_c and, in turn, improve run time to exhaustion in the heat compared with cold water (4°C) ingestion.

METHODS

Participants. Ten healthy males (age = 28 ± 6 yr, height = 178.9 ± 6.3 cm, body mass = 79.9 ± 11.2 kg, sum of nine skinfolds = 92.8 ± 41.4 mm, $\dot{V}O_{2max}$ = 56.4 ± 4.7 mL·kg^{-1}·min^{-1}) volunteered for this study. Subjects were considered moderately active, participating in recreational sport, had no previous history of heat illness, and were without injuries. Subjects provided written informed consent before study commencement. The study procedures were approved by the Edith Cowan University's Human Research Ethics Committee.

Preliminary measurements. On their first visit to the laboratory, subjects performed a progressive exercise test on a running treadmill (Trackmaster; JAS Fitness Systems, Newton, KS) at room temperature (24.6°C ± 1.9°C, 44.4% ± 8.2% RH) for the determination of maximal oxygen uptake ($\dot{V}O_{2max}$) and their first ventilatory threshold (V_{T1}). Before the test, the subject's body mass and height were measured to the nearest 10 g and 0.1 cm using a floor scale (Model ID1; Mettler Toledo, Columbus OH) and stadiometer (Seca, Brooklyn, NY), respectively. Skinfold thickness measurements were taken at nine sites (triceps, subscapular, biceps, mid axilla, iliac crest, supraspinale, abdominal, front thigh, and medial gastrocnemius) in duplicate using skinfold calipers (Model HSK-BI-3; Baty International, West Sussex, UK), and the mean value was used to calculate the sum of nine skinfolds. For the progressive exercise test, a diagnostic system (TrueOne 2400; ParvoMedics, Sandy, UT) was used to measure minute ventilation, carbon dioxide production, and oxygen uptake. The test began with subjects running at 8 km·h^{-1} for 4 min on a 0% gradient, with 2-km·h^{-1} increases in treadmill speed occurring every 4 min. Once speed reached 16 km·h^{-1}, gradient remained at 0 for the first 4 min and then increased by 2% every 4 min thereafter until volitional fatigue. HR was monitored continuously by telemetry using an HR monitor (Model S610i; Polar Electro Oy, Kempele, Finland), and RPE was taken every 4 min using the 6- to 20-point Borg Scale (4). $\dot{V}O_{2max}$ was recorded as the highest value obtained in a 30-s period (27). Attainment of $\dot{V}O_{2max}$ was indicated by a plateau in oxygen consumption. Secondary criteria used to confirm $\dot{V}O_{2max}$ attainment were an RER greater than 1.10 and peak HR within 10 beats·min^{-1} of age-predicted maximum (220 − age). When $\dot{V}O_{2max}$ was not achieved, the $\dot{V}O_{2peak}$ was recorded. V_{T1} was determined by the increase in the ventilatory equivalent for oxygen uptake ($\dot{V}_E$· $\dot{V}O_2$$^{-1}$) with no concomitant increase in the ventilatory equivalent for carbon dioxide production ($\dot{V}_E$· $\dot{V}CO_2$$^{-1}$) (23).

Experimental design. Throughout the study, subjects were asked to keep stable their normal lifestyle activities, including physical activity and nutritional habits. On the day before each trial, subjects were asked to eat at least 6 g carbohydrate per kilogram body weight and the same pretrial meal on the day of the experimental trials (providing at least 1 g carbohydrate per kilogram). They were also asked to consume at least 2 L of fluid on this day and 400 mL of fluid during the meal consumed just before the experimental trials. In the 24-h period before the trials, subjects were asked to avoid strenuous exercise, as well as the consumption of alcohol, caffeine, nonsteroidal anti-inflammatory drugs, or nutritional supplements. Before the experimental trials were completed, subjects performed a familiarization trial involving running to exhaustion at the subject's previously determined V_{T1} running speed in the same hot environment as the experimental trials. Within 5–14 d after this familiarization trial, subjects completed the first of two experimental trials on a treadmill, running to exhaustion at their V_{T1} running speed after ingesting either ice slurry (−1°C) or cold water (4°C). We chose a 4°C temperature for our control drink because this is the typical temperature of drinks found in conventional refrigeration units. Subjects completed their assigned conditions in a counterbalanced and random order, at the same time of day, separated by 5–20 d. For each trial, the subjects wore the same exercise clothing.

Experimental procedures. On arrival to the laboratory, urine and blood samples were collected before nude body mass was recorded. Approximately 5 mL of blood was drawn using standard venipuncture technique from an antecubital vein. A disposable rectal thermistor (Monatherm Thermistor, 400 Series; Mallinckrodt Medical, St. Louis, MO) was then self-inserted 120 mm past the anal sphincter. Four reusable skin thermistors were affixed using hypoallergenic polyacrylate adhesive tape (Fixomull; Smith and Nephew Ltd., Auckland, New Zealand) at the mid belly of the left gastrocnemius, quadriceps, biceps, and chest. An HR monitor was then fixed to the subjects' chest before a 15-min rest period to gather baseline resting data. After this rest period, during the next 30 min, subjects ingested either a 7.5-g$\cdot$kg^{-1} ice slurry (-1°C) with added syrup for flavor (Cottee's Foods, New South Wales, Australia) or 7.5 g$\cdot$kg^{-1} of cold water (4°C) with added syrup. Both solutions were made with the same flavoring for all subjects and consisted of 5% carbohydrate. Ice slurries were made using a slushy machine (Essential Slush Co., Queensland, Australia), and every 5 min, subjects were given 1.25 g$\cdot$kg^{-1} of either drink to ensure a standardized ingestion rate. To establish the possible influence of ice slurry or cold water ingestion on bronchial constriction during the experimental trials, subjects performed a pulmonary function test (MED Graphics CPX/D System; Medical Graphics Corporation, St. Paul, MN) to measure forced vital capacity (FVC) and forced expiratory volume in 1 s immediately before and after drink ingestion. Subjects then commenced running, approximately 5 min after completing drink ingestion. After exercise, subjects toweled dry and were weighed again for nude body mass before the collection of urine and blood samples.

Measurements. Throughout the experimental protocol, T_{re} and T_{sk} were recorded continuously at a sampling rate of 1 Hz via a data logger (Grant Instruments, Shepreth Cambridgeshire, UK). From these data, 5-min averages were calculated. Mean T_{sk} was calculated using Ramanathan's formula (35): $T_{sk} = 0.3(T_{chest} + T_{arm}) + 0.2(T_{thigh} + T_{calf})$. Mean body temperature (T_b) was calculated using the formula of Colin et al. (9): $T_b = 0.66(T_{re}) + 0.34(T_{sk})$ at rest and during drink ingestion and $T_b = 0.79(T_{re}) + 0.21(T_{sk})$ during exercise. Heat storage was calculated at 5-min increments using the formula of Adams et al. (1): heat storage $= 0.965m\Delta T_b/A_D$, where 0.965 is the specific heat storage capacity of the body (W$\cdot$kg$^{-1}\cdot$°C^{-1}), m is the mean body mass (kg) during the trial, and A_D is the body surface area (m^2) according to Du Bois and Du Bois (11): $A_D = 0.202m^{0.425} \times \text{height}^{0.725}$.

HR was monitored continuously throughout the trial and reported as 5-min averages. Rating of thermal sensation (9-point scale ranging from unbearably cold [0] to unbearable hot [8] (42)) was recorded every 5 min during drink ingestion and exercise, whereas RPE (4) was recorded every 5 min throughout the course of exercise.

Serum osmolality was measured from blood serum using a freezing point depression osmometer (Model 3250; Advanced Instruments, Inc., Norwood, MA) after samples were centrifuged for 15 min at 3000 rpm (1942g) and 4°C. Urine samples were assessed for urine osmolality using a freezing point depression osmometer (Model 3250; Advanced Instruments, Inc.) and urine specific gravity using a handheld refractometer (No. 503; Nippon Optical Works Co., Ltd., Tokyo, Japan). Changes in nude body mass were used to assess fluid loss to the nearest 10 g. For the purpose of this study, 10 g of body mass lost was assumed to equate to 10 mL of fluid lost from sweat. Sweat rate was estimated using the formula: sweat rate (L$\cdot$h^{-1}) = pre-m (kg) + fluid ingested (L) $-$ post-m (kg).

Environmental conditions in the climate chamber were monitored continuously using a wet bulb globe temperature heat stress monitor (Microtherm; Casella Measurement Ltd., Bedford, UK) and averaged at 5-min intervals.

Statistical analyses. Data were analyzed in two phases: during the drinking period and during exercise. Differences in time to exhaustion, physiological variables at a single time point, sweat rate, heat storage, and hydration status between conditions were analyzed using a paired Student's t-test. Mean differences in physiological variables between conditions and over time were compared using a two-way (drink $\times$ time) repeated-measures ANOVA. When a significant main effect or interaction effect was identified, differences were delineated using a paired Student's t-test with Bonferroni adjustment. For all comparisons, significance was set at $P < 0.05$. All data are presented as means ± SD. Statistical analyses were performed using SPSS version 17.0 (SPSS, Inc., Chicago, IL).

BASIC SCIENCES

RESULTS

Environmental conditions and preexercise hydration status. During the drinking period, mean ambient temperature was similar between trials (24.4°C ± 0.9°C vs 24.6°C ± 1.3°C, $P = 0.809$). Similarly, during exercise, there were no significant differences in mean ambient temperature (34.1°C ± 0.2°C vs 34.0°C ± 0.3°C, $P = 0.503$) and relative humidity (55.9% ± 5.2% vs 53.8% ± 6.4% RH, $P = 0.075$) between conditions. Subjects were considered similarly euhydrated before each trial, as demonstrated by equivalent measures of preexercise body mass (80.23 ± 11.04 vs 80.18 ± 11.26 kg, $P = 0.782$), urine specific gravity (1.015 ± 0.008 vs 1.013 ± 0.009, $P = 0.349$), urine osmolality (543 ± 268 vs 465 ± 328 mOsm$\cdot$kg^{-1}, $P = 0.447$), and serum osmolality (296 ± 4 vs 296 ± 6 mOsm$\cdot$kg^{-1}, $P = 0.761$; ice slurry vs cold water ingestion, respectively). During the drinking period, 3 of 10 subjects experienced sphenopalatine ganglioneuralgia (brain freeze) with ice slurry ingestion, whereas no subjects experienced this with cold water ingestion.

Running times to exhaustion. As shown in Figure 1, all 10 subjects ran for longer time (range = 2.4–14.2 min) after ice slurry (50.2 ± 8.5 min) compared with cold water ingestion (40.7 ± 7.2 min). This equated to a mean running time increase of 9.5 ± 3.6 min (19% ± 6%, $P = 0.001$).

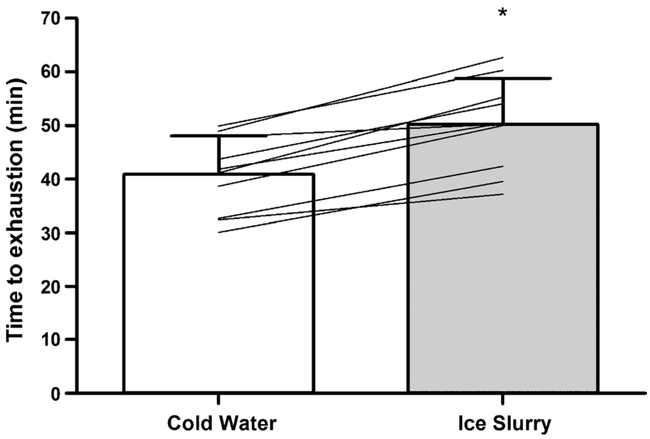

FIGURE 1—Mean ± SD run time to exhaustion during the two experimental conditions. *Lines* denote individual data (*n* = 10). Time to exhaustion was longer (*) after ice slurry compared with cold water ingestion (*P* = 0.001).

Rectal temperature (T_{re}). Figure 2A illustrates mean T_{re} data recorded over the two trials. After the 15-min resting period before drink ingestion, there were no differences in T_{re} between conditions (37.21°C ± 0.19°C vs 37.13°C ± 0.11°C; ice slurry vs cold water ingestion, respectively, P = 0.130). However, ice slurry ingestion resulted in a greater (P = 0.001) reduction in T_{re} (0.66°C ± 0.14°C) compared with cold water ingestion (0.25°C ± 0.09°C). Consequently, T_{re} was 0.32°C ± 0.14°C cooler after ice slurry compared with cold water ingestion before the start of exercise (P = 0.001). During exercise, T_{re} increased (P = 0.001) but remained lower after ice slurry compared with cold water ingestion for the first 30 min of exercise (P = 0.001). Subjects achieved a significantly higher (0.78% ± 0.27%) T_{re} at exhaustion (39.36°C ± 0.41°C vs 39.05°C ± 0.37°C, P = 0.001) after ice slurry compared with cold water ingestion (Fig. 3). Despite a larger observed rate of change occurring in T_{re} during ice slurry compared with cold water ingestion (0.27°C ± 0.04°C vs 0.25°C ± 0.06°C·5 min^{-1}), this comparison did not reach significance (P = 0.052).

Mean skin temperature (T_{sk}). Figure 2B compares the mean T_{sk} over the two conditions. Initially before the commencement of drink ingestion, there were no differences in T_{sk} between conditions (32.57°C ± 0.54°C vs 32.73°C ± 0.68°C, P = 0.134). During the preexercise period, mean T_{sk} was significantly lower after ice slurry compared with cold water ingestion (P = 0.017), specifically after 20 min (32.48°C ± 0.46°C vs 32.70°C ± 0.63°C, P = 0.038), 25 min (32.45°C ± 0.44°C vs 32.71°C ± 0.57°C, P = 0.014), and 30 min of drinking (32.41°C ± 0.42°C vs 32.64°C ± 0.53°C, P = 0.008), as well as before the commencement of exercise (32.59°C ± 0.52°C vs 32.95°C ± 0.54°C, P = 0.001). Once exercise commenced, T_{sk} increased continuously (P = 0.001); however, there were no differences between conditions (P = 0.992).

Mean body temperature (T_b) and heat storage. Figure 2C shows the mean T_b over the two conditions. T_b was similar between conditions after the 15-min resting period (35.63°C ± 0.20°C vs 35.63°C ± 0.23°C, P = 1.000). Ice slurry ingestion led to a significantly greater drop in T_b (0.43°C ± 0.13°C) compared with cold drink ingestion (0.09°C ± 0.10°C, P = 0.001). T_b was 0.38°C ± 0.22°C (P = 0.001) cooler before the start of exercise and remained cooler for the first 30 min of exercise (P = 0.007). T_b increased continuously during exercise (P = 0.001), and at exhaustion, was significantly higher (P = 0.001) after ice slurry (38.53°C ± 0.48°C) compared with cold water ingestion

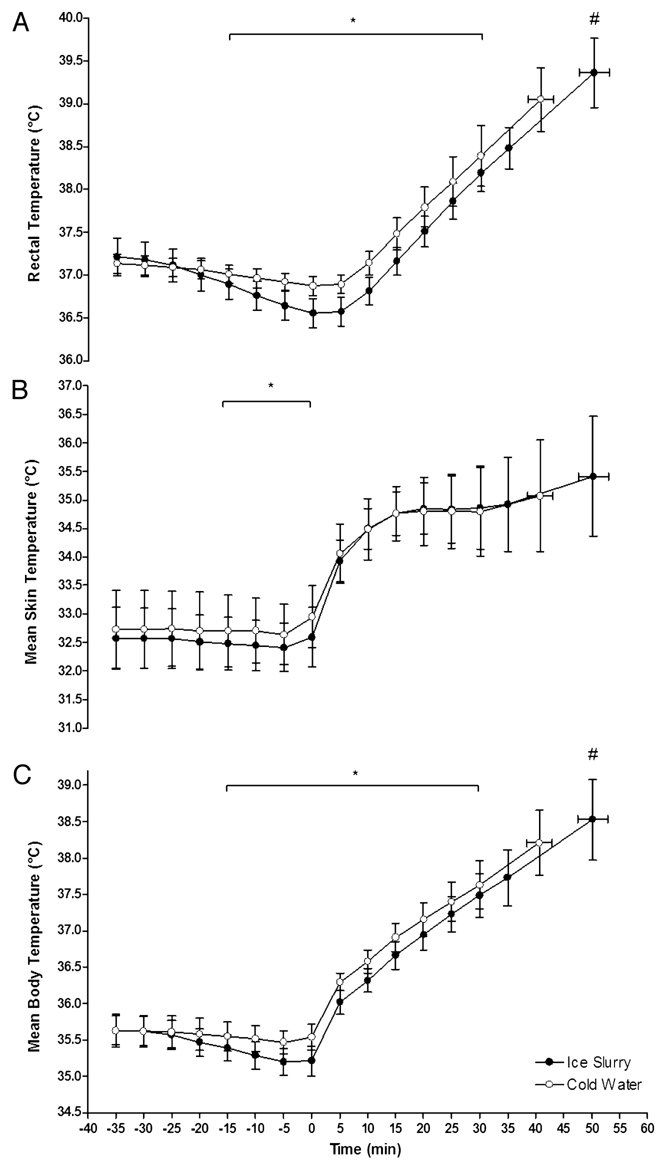

FIGURE 2—Rectal temperature (T_{re}; A), mean skin temperature (T_{sk}; B), and mean body temperature (T_b; C) during each experimental condition (means ± SD). T_{re} was lower (*) with ice slurry compared with cold water ingestion from the 20-min time point of drink ingestion until 30 min of exercise (P < 0.05). At exhaustion, T_{re} was greater (#) after ice slurry ingestion (P = 0.001). T_{sk} was lower (*) for the final 15 min of drinking, as well as before the commencement of exercise with ice slurry ingestion (P < 0.05). T_b was lower (*) with ice slurry ingestion from the 20-min time point of drink ingestion until 30 min of exercise (P < 0.05). At exhaustion, T_b was greater (#) after ice slurry ingestion (P = 0.001).

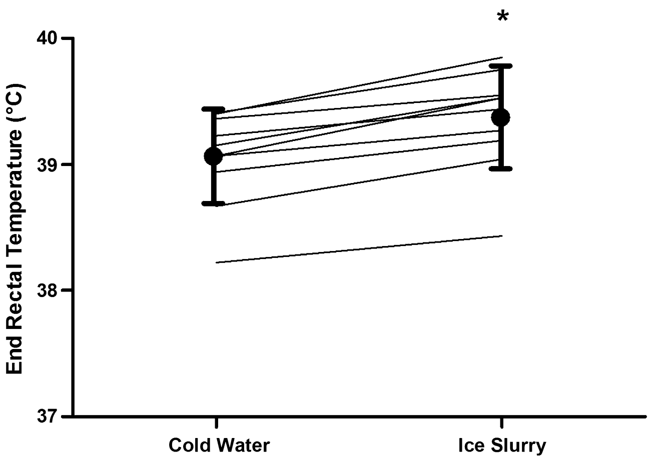

FIGURE 3—Mean ± SD rectal temperature (T_{re}) at exhaustion during the two experimental conditions. *Lines* denote individual data (*n* = 10). T_{re} was higher (*) at exhaustion after ice slurry compared with cold water ingestion (*P* = 0.001).

(38.21°C ± 0.45°C). Heat storage during the drinking period was significantly lower (*P* = 0.001) after ice slurry (−18.28 ± 5.68 W·m^{-2}) compared with cold water ingestion (−7.84 ± 3.13 W·m^{-2}). During exercise, subjects stored significantly more heat (*P* = 0.005) after ice slurry (100.10 ± 25.00 W·m^{-2}) compared with cold water ingestion (78.93 ± 20.52 W·m^{-2}). Mean rates of heat storage were similar between trials (10.98 ± 2.95 vs 10.10 ± 2.72 W·m^{-2}·5 min^{-1}, *P* = 0.234).

HR. Figure 4A shows the mean HR response over the two conditions. HR did not differ significantly between conditions before drink ingestion (65 ± 8 vs 65 ± 8 beats·min^{-1}, *P* = 0.891). During the drinking period, HR decreased (*P* = 0.001) but was not affected by drink type (*P* = 0.625). During exercise, HR increased continuously (*P* = 0.001) and remained similar between conditions (*P* = 0.122) including at exhaustion (185 ± 7 vs 183 ± 6 beats·min^{-1}).

Sweat rate and postexercise hydration status. Sweat rate for the ice slurry trial (1.89 ± 0.61 L·h^{-1}) was not significantly different (*P* = 0.242) from that of the cold water trial (2.05 ± 0.43 L·h^{-1}). After exercise, hydration status was also similar between conditions, as demonstrated by comparable measures of body mass (79.29 ± 10.91 vs 79.40 ± 11.18 kg, *P* = 0.621), urine specific gravity (1.012 ± 0.007 vs 1.013 ± 0.009, *P* = 0.650), urine osmolality (395 ± 236 vs 459 ± 283 mOsm·kg^{-1}, *P* = 0.444), and serum osmolality (294 ± 3 vs 294 ± 3 mOsm·kg^{-1}, *P* = 0.720).

Ratings of thermal sensation and perceived exertion. Figure 4 shows the mean ratings of thermal sensation (B) and perceived exertion (C) recorded during the two trials. Before drinking, ratings of thermal sensation were similar between trials (4.0 ± 0.3 vs 4.1 ± 0.3, *P* = 0.168). Thermal sensation was lower after drink ingestion (2.1 ± 0.8 vs 3.7 ± 0.5, *P* = 0.001) and before exercise (3.5 ± 0.6 vs 4.2 ± 0.5, *P* = 0.001) and remained lower for the first 30 min of exercise (*P* = 0.029) for ice slurry versus cold water ingestion, respectively. During exercise, mean ratings of thermal sensation (*P* = 0.001) and perceived exertion (*P* = 0.022) were lower after ice slurry ingestion. RPE values were lower at the 10- (*P* = 0.04), 20- (*P* = 0.04), 25- (*P* = 0.024), and 30-min (*P* = 0.012) exercise time points after ice slurry compared with cold water ingestion trials. At exhaustion, thermal sensation (7.9 ± 0.2 vs 7.9 ± 0.2, *P* = 0.343) and RPE (20 ± 0 vs 20 ± 0, *P* = 1.000) were similar between trials.

Pulmonary function. Ice slurry ingestion caused a greater reduction (*P* = 0.038) in FVC (0.21 ± 0.14 L) compared with cold water ingestion (0.07 ± 0.18 L). There

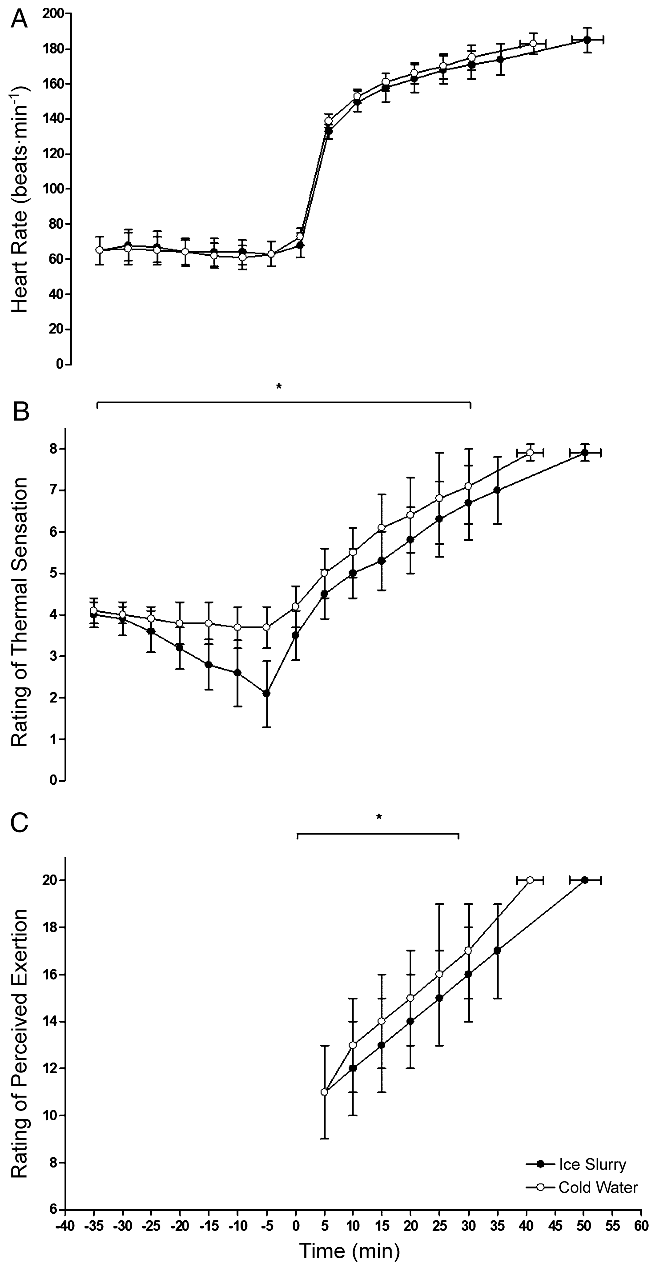

FIGURE 4—HR (A) and ratings of thermal sensation (B) and perceived exertion (C) during the two experimental conditions (mean ± SD). HR was unaltered by drink type. Mean ratings of thermal sensation (*P* = 0.001) and perceived exertion (*P* = 0.022) were lower (*) after ice slurry compared with cold water ingestion.

were no significant changes between conditions in forced expiratory volume in 1 s after drink ingestion (0.16 ± 0.16 vs 0.06 ± 0.18, $P = 0.278$).

DISCUSSION

The present study has shown at least three novel findings. First, ingestion of 7.5 g·kg^{-1} of ice slurry (−1°C) significantly reduced T_{re} compared with cold water (4°C) ingestion (0.66°C ± 0.14°C vs 0.25°C ± 0.09°C) in normothermic individuals. Second, ice slurry ingestion before exercise in a hot environment significantly prolonged run time to exhaustion (+9.5 ± 3.6 min; 19% ± 6%). Third, precooling using ice slurry ingestion resulted in a significantly higher T_{re} at exhaustion compared with the cold water ingestion trial (39.36°C ± 0.41°C vs 39.05°C ± 0.37°C). These results are the first to show the practical effectiveness of ice slurry ingestion as a precooling maneuver not only for delaying the time to reach a critically high T_c and in turn improving exercise performance but also for allowing a higher tolerable T_c before exhaustion.

It is generally accepted that the attainment of a critically high T_c is the primary reason for the termination of prolonged exercise in hot environments (15,29). Gonzalez-Alonso et al. (15) observed that subjects who cycled in the heat (40°C, 19% RH) at 60% $\dot{V}O_{2max}$ reached volitional fatigue at the same esophageal temperature (T_{es}; 40.1°C–40.2°C), despite a different starting T_{es}. In that study (15), preexercise T_{es} was lowered using water immersion (35.9°C ± 0.2°C vs 37.4°C ± 0.1°C in the control condition of no cooling), which elicited a significantly longer cycling time to exhaustion (63 ± 3 vs 46 ± 3 min). This was thought to be due to the increased heat storage capacity that prolonged the time to reach a critically high T_c (15). Similar mechanisms were likely involved in the current study. Decreasing T_{re} via ice slurry ingestion likely elicited a larger heat sink (−18.28 ± 5.68 vs −7.84 ± 3.13 W·m^{-2}), which increased the body's capacity to store heat (100.10 ± 25.00 vs 78.93 ± 20.52 W·m^{-2}). The delayed attainment of a high T_c and the increased running time found with ice slurry ingestion are both likely due to the ice slurry's capacity to create an expanded heat sink compared with cold water ingestion.

The larger heat sink created by the ingestion of the ice slurry is the result of the unique thermodynamic characteristics of H_2O and the changing of physical states. Specific heat capacity (C_p) refers to the quantity of energy required to increase 1 g of a substance by 1 K. In a solid form, C_p of ice is 2.108 kJ·kg^{-1}·K^{-1}, whereas liquid H_2O is 4.204 kJ·kg^{-1}·K^{-1}. However, the energy required for H_2O to change phase also requires the introduction of 334 kJ·kg^{-1} of energy. Combining both solid and liquid H_2O into an ice slurry solution has the added heat sink benefit of the C_p from both the solid and liquid H_2O, as well as the enthalpy of fusion needed for the phase change. Summing these thermodynamic properties in an ice slurry mixture yields a larger heat storing capacity than liquid H_2O alone. Hence, ingestion of an ice slurry drink has the potential to reduce the rate of heat retention in the body. It is important to note that, although there was ~5°C difference in drink temperatures, the large difference in T_{re} observed between conditions was predominantly due to the enthalpy of fusion rather than to the difference in drink temperature *per se*. Using the equation $Q = mC_p\Delta T$ (where Q is the quantity of heat gained/lost (kJ), m is the mass of the substance (kg), and ΔT is the change in temperature (K)), the expected change in T_c from drinking 7.5 g·kg^{-1} of cold water and ice slurry can be calculated. For the subjects in the current investigation, a reduction in T_c of ~0.30°C and ~1.07°C would be expected from drinking equal volumes of cold water and ice slurry drinks, respectively. This substantial difference is due almost entirely to the additional energy required for the phase change, as if subjects were to ingest 0°C water, the expected reduction in T_c would only be ~0.34°C.

In the present investigation, subjects achieved a significantly higher T_{re} at exhaustion after the ingestion of ice slurry versus cold water (39.36°C ± 0.41°C vs 39.05°C ± 0.37°C, $P = 0.001$; Fig. 3). This does not concur with current literature, which suggests that subjects exercising in hot environments will reach volitional exhaustion at similar T_c (15,29). This also holds true in studies where a precooling maneuver has been performed (15,16,22). Although it is difficult to discount the possibility of a placebo effect, this is unlikely because ratings of thermal sensation (7.9 ± 0.2 vs 7.9 ± 0.2) and perceived exertion (20 ± 0 vs 20 ± 0) were similar at the point of exhaustion. It is possible that differences in T_{re} observed between conditions at the point of exhaustion may be explained by increased brain cooling achieved by ice slurry ingestion. Because the ice slurry was ingested through the mouth, it is reasonable to suggest that its consumption caused a physiologically meaningful reduction in brain temperature, hence delaying the attainment of critically high brain temperature. This may have allowed subjects to run longer and generate and store more metabolic heat in their core, all of which could account for the observed increase in T_{re} at the point of exhaustion. A similar effect has been shown in canines, whereby brain cooling via cold water (~8°C) nasal irrigation significantly increased the T_c tolerated by the dogs by 0.5°C–1.0°C while being heated in a hot water bath (7). The importance of brain temperature during prolonged exercise in the heat was shown in goats by Caputa et al. (6). They showed that goats reached the point of exhaustion at hypothamalic temperatures between 42.0°C and 42.9°C, irrespective of trunk temperature. In humans, Ansley et al. (2) showed that head cooling during exercise in warm conditions increased cycling time to exhaustion by 51% (45 vs 24 min), despite similarities in T_{re} throughout exercise. The authors postulated that the increased performance was due to lower brain temperatures throughout the cooling trial.

Another possible explanation for the differences in T_{re} observed at exhaustion in the present study might be due to

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differences in thermoreception. Although it has been established that thermoreceptors are in both the hypothalamus monitoring the temperature of blood flow through the brain (14) and the skin in humans (17), it has been hypothesized that thermoreceptors might also be located near or within the core itself (14). This is in fact true in other species, with thermoreceptors in the mouth, esophagus, spinal cord, abdominal viscera (17), abdominal cavity (36), and the muscle (3). If this is also true in humans, ice slurry ingestion could have directly affected T_c afferents and had a significant effect on critical T_c attainment. In addition, the glossopharyngeal (ninth cranial) nerve carries impulses for temperature sensation from the posterior third of the tongue and upper pharynx to the brain (31). As such, subjects may have perceived exercise at a given T_{re} as easier during the ice slurry trial, in turn prolonging running time, thus increasing metabolic heat production and T_{re} at exhaustion. In the present investigation, attainment of a higher T_{re} was associated with the positive effect of further extending running time before volitional exhaustion occurred. However, it is important to note that this could also be considered as a negative consequence because increasing T_{re} above the normal tolerable limits could result in heat illness.

Mean T_{re} at exhaustion for both trials was 39.21°C ± 0.41°C; values lower than those normally considered to be "critical." This is likely because subjects in the current study were not highly trained. Selkirk and McLellan (37) established that trained subjects were able to tolerate higher T_{re} during exercise in the heat than untrained subjects. The authors suggested this was because of the familiarization of achieving high T_c during training rather than increased aerobic capacity *per se* because they found no correlation between T_{re} at exhaustion and $\dot{V}O_{2peak}$.

Ice slurry ingestion caused a small, yet statistically significant reduction in T_{sk} for the final 15 min of drinking, so that on commencement of running, it was 0.36°C ± 0.25°C lower than after cold water ingestion. This reduction in T_{sk} is much smaller than that witnessed with external cooling methods. For example, Quod et al. (34) found that a combination treatment of cold water immersion followed by wearing an ice jacket reduced T_{sk} by 8.1°C compared with the control condition of no cooling. The drop in T_{sk} shown in the present study is unlikely to be physiologically significant because once exercise began, differences were no longer seen between conditions. The similarity in T_{sk} between conditions may have been due to similar rates of evaporative sweat loss between trials (sweat rate = 1.89 ± 0.61 vs 2.05 ± 0.43 $L \cdot h^{-1}$) (19). These findings do not correspond with some studies that have demonstrated reduced sweat rates after an external precooling maneuver (18,30). The increased running time to exhaustion observed despite similarities in T_{sk} between trials lends support to the study by Morrison et al. (28), who showed that changes in T_c, rather than T_{sk}, are the primary cause for reductions in exercise performance in the heat, likely due to central impairment of neuromuscular activation.

HR in the present study was also unaltered by ice slurry ingestion, a finding that conflicts with the majority of studies investigating the effect of precooling on thermoregulatory responses during exercise. This finding also may be explained by the similarities in T_{sk} shown during exercise because skin blood flow was likely similar between conditions (19). Other studies that have shown a reduction in HR during exercise after precooling have also shown reductions in T_{sk} (16,21,41).

Subjects reported feeling cooler throughout the drinking and exercise periods after ice slurry ingestion. Sweat rate and T_{sk}, both previously shown to influence ratings of thermal sensation (12), were similar between conditions. Therefore, the lower ratings of thermal sensation were likely due to the reduced T_{re} and T_b because feelings of heat-related fatigue have been shown to be a result of both increased T_{sk} and T_{re} (39). Subjects' RPE were also lower throughout the exercising period after consuming the ice slurry. It is likely that subjects perceived exercise after ice slurry ingestion to be easier at each time point because of the lower thermal strain and T_{re}. Indeed, it has previously been shown that increases in RPE during exercise in the heat are predominantly due to increases in T_{re} (38).

Costill and Saltin (10) showed that fluid volume remaining in the stomach was less after the ingestion of colder (5°C) compared with warmer fluids (35°C). This might suggest differences in blood volume and cardiovascular strain between conditions in the current study as a result of the different drink temperatures. Moreover, a faster gastric-emptying rate could lead to a greater availability of carbohydrate, which paradoxically has been shown to increase endurance performance in the heat (8). However, more recent studies have shown no differences in gastric-emptying rates between drinks of different temperatures ranging from 4°C to 58°C (20,25). Because gastric-emptying rates are only slowed until drink temperature becomes neutral, and considering the total length of time for emptying, the minor difference in temperature between drinks in the present investigation (~5°C) would be physiologically insignificant (5). Consequently, the improvements in exercise performance observed after ice slurry ingestion can be attributed to the reduction in T_c that it elicited rather than the changes in blood volume or carbohydrate availability.

Because of the temperature (−1°C) of the ice slurry mixture, we investigated the effects of ingestion on bronchial constriction. Ice slurry ingestion caused a significantly greater reduction in FVC compared with cold water ingestion (0.21 ± 0.14 vs 0.07 ± 0.18 L); however, it is unlikely that such a small reduction would have had any influence on exercise performance at the relatively low intensity selected (V_{T1}).

Currently, many of the extensively researched precooling maneuvers, although shown to be effective in a laboratory setting, are somewhat impractical for use in major sporting competitions. Cold water immersion can be uncomfortable for the athlete and can take up to 30–60 min to gain a

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physiologically significant reduction in T_c (33). Furthermore, access to much water, as well as electricity to maintain desired water temperature, may be an issue in the field. Although considered somewhat more practical, anecdotal evidence suggests that ice vests/jackets are heavy and uncomfortable, and it is also a concern to some coaches and practitioners that wearing such garments during a warm-up may adversely affect sports-specific mechanics. Moreover, Quod et al. (34) showed that wearing an ice jacket for 40 min before exercise did not significantly lower T_{re} or improve cycling time trial performance in the heat. Ice slurry ingestion provides a practical precooling maneuver that can easily be used in a field setting. What is more, in addition to its cooling benefits, ice slurry consumption can also be used to hydrate athletes before competition.

In conclusion, the present study has shown that ice slurry ingestion before exercise in the heat was able to significantly reduce preexercise T_{re} and prolong run time to exhaustion at V_{T1} running speed compared with cold water ingestion. In addition, ice slurry ingestion resulted in a higher T_{re} at the point of exercise termination. Ice slurry ingestion may serve as a practical precooling maneuver for improving endurance exercise performance in the heat compared with some of the more traditionally proven strategies, such as using ice jackets or cold water immersion baths.

This study was funded by the School of Exercise, Biomedical and Health Sciences, Edith Cowan University. The results of the present study do not constitute endorsement by the American College of Sports Medicine.

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