Ice Slurry Ingestion and Physiological Strain During Exercise in Non-Compensable Heat Stress

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INTRODUCTION: Precooling with ice slurry ingestion attenuates the increase in rectal temperature (T_{re}) during subsequent running and cycling. It remains unclear how this cooling method affects physiological strain during work while wearing protective garments. This study investigated the effect of ice slurry ingestion on physiological strain during work in hot conditions while wearing firefighter protective clothing.

METHODS: In three counterbalanced trials, eight men (mean ± SD; age = 21 ± 2 yr, height = 179.5 ± 3.5 cm, mass = 79.1 ± 4.1 kg, body fat = 11.4 ± 3.7%) wore firefighter protective clothing and walked ($4\ \mathrm{km} \cdot \mathrm{h}^{-1}$, 12% incline, ~7 METs) for 30 min in hot conditions (35°C, 40% RH). Every 2.5 min, subjects ingested $1.25\ \mathrm{g} \cdot \mathrm{kg}^{-1}$ (relative total: $15\ \mathrm{g} \cdot \mathrm{kg}^{-1}$, absolute total: 1186.7 ± 61.3 g) of a tepid (22.4 ± 1.7°C), cold (7.1 ± 1.5°C), or ice slurry (-1.3 ± 0.2°C) beverage.

RESULTS: Heart rates (HR) were lower with ice slurry ingestion compared to both fluid trials starting 5 min into exercise (tepid = 158 ± 14, cold = 157 ± 11, ice slurry = 146 ± 13 bpm) and persisting for the remainder of the bout (min 30: tepid = 196 ± 10, cold = 192 ± 10, ice slurry = 181 ± 13 bpm). T_{re} was lower with ice slurry ingestion compared to cold and tepid trials (min 5: tepid = 37.17 ± 0.38, cold = 37.17 ± 0.39, ice slurry = 37.05 ± 0.43°C; min 30: tepid = 38.15 ± 0.29, cold = 38.31 ± 0.36, ice slurry = 37.95 ± 0.32°C). The physiological strain index (PSI) was lower with ice slurry ingestion compared to fluid trials starting at min 5 (tepid = 3.8 ± 0.7, cold = 3.8 ± 0.6, ice slurry = 3.0 ± 0.5) and remained lower throughout exercise (min 30: tepid = 8.2 ± 0.6, cold = 8.3 ± 0.9, ice slurry = 6.9 ± 1.2).

DISCUSSION: A large quantity of ice slurry ingested under non-compensable heat stress conditions mitigated physiological strain during exercise by blunting the rise in heart rate and rectal temperature.

KEYWORDS: cooling, hydration, thermoregulation, heart rate, protective clothing.

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Industrial, military, law enforcement, and firefighting occupational operations involve wearing layers of protective garments—often in hot environments—which can place an individual at risk of exertional heat stroke.[7] Metabolic heat production from physical activity increases the magnitude of heat dissipation necessary to maintain thermal homeostasis and avoid an excessive increase in core temperature. However, encapsulating clothing creates a microenvironment that traps heat dissipated from the skin, thereby blunting evaporative cooling and resulting in heat storage, which is reflected by increased rectal temperature (T_{re}).[7] These points demonstrate the importance of cooling during occupational work in protective clothing. Some of these occupational demands occur in a thermally stressful environment in which external cooling methods (e.g., ice vests, cold water immersion, etc.) can be impractical during work performance.[3,12] Therefore, internal cooling through ingestion of cold beverages that blunts the rise in core temperature, combined with improved hydration, could improve work tolerance and potentially reduce heat illness risks in hot environments when protective clothing is required.

Ice slurry ingestion is an internal cooling method that has received recent attention, mostly in relation to endurance exercise performance in hot environments when used as a precooling maneuver.[23,26,27] Precooling with ice slurry ingestion can

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reduce rectal temperature prior to exercise, creating a heat sink that increases the body's ability to store heat, resulting in longer run times to exhaustion compared to pre-exercise higher temperature fluid ingestion.[26,27] Few studies have investigated its effects during physical activity.[5,25,29] Additionally, previous studies examining ice slurry ingestion used cyclists and runners wearing typical competition clothing that permitted evaporative cooling during exercise.[23,26,27] In one investigation, 10 men ingested either ice slurry or warm fluid during 2 trials of 90-min steady state cycling, followed immediately by a time trial to measure exercise performance. Investigators attributed improved performance with ice slurry ingestion to a gastrointestinal (GI) heat sink, as measured by GI temperature.[4]

Due to the specific focus on endurance sports and individuals wearing exercise-specific clothing, results from these studies cannot be generalized to those who perform activity while wearing encapsulating clothing or protective equipment that limits evaporative heat loss. As a result, the effects of ice slurry ingestion on body temperature and physiological strain during performance of occupational work while wearing protective clothing remain unknown. The purpose of this study was to examine the effect of ice slurry ingestion on human core temperature and physiological strain during a work bout while wearing firefighter protective clothing. It was hypothesized that the rise in core temperature and physiological strain during exercise in a hot environment would be attenuated with an ice slurry beverage compared to that with warmer fluid beverages.

METHODS

Subjects completed three experimental trials. The counterbalanced treatment orders were randomly assigned to subjects. In each experimental trial, subjects dressed in firefighter protective clothing and walked on a treadmill in 35.2 ± 0.4°C, 39 ± 4% relative humidity (RH) for 30 min at a workload eliciting 7 metabolic equivalents (METs). Throughout each trial, subjects ingested a carbohydrate-electrolyte beverage in a tepid fluid (TEPID), cold fluid (COLD), or ice slurry (ICE) form. All experimental trials were identical except for the form of beverage ingested.

Subjects

Eight healthy men (mean ± SD) [age = 21 ± 2 yr, height = 179.5 ± 3.5 cm, mass = 79.1 ± 4.1 kg, percent body fat = 11.4 ± 3.7% (body density estimated from chest, abdominal, and thigh skinfolds[11] and subsequent percent body fat determined via calculation[28])] participated in the study. A power analysis[20] performed in advance revealed that the sample size of $N = 8$ was sufficient to detect a moderate effect size[21] for the treatment × time interaction. All subjects were participating in moderate-to-vigorous physical activity for 20 to 60 min, 3 to 5 d/wk for at least 3 mo. In order to reduce the risk of medical complications, subjects with a pacemaker or other internal electronic device, a history of heat illness, known cardiovascular, pulmonary, or metabolic disease(s), or a related sign or symptom were excluded. All subjects signed an informed consent statement approved by the local Institutional Review Board prior to commencement of participation.

Equipment and Procedures

Subjects were instructed to refrain from physical activity (any bodily movement that causes a substantial increase in energy expenditure) during the 36 h prior to each experimental trial, although otherwise they were encouraged to maintain training status by keeping their exercise routine (purposefully planned, structured, and repetitive physical activity schedule). They also kept a dietary intake log beginning 24 h before the first trial until 2 h prior to the commencement of the trial. Thereafter, only beverages associated with study treatments were consumed until the end of the visit. For the subsequent trials, subjects replicated dietary intake of the previous trial in order to ensure a similar nutrition status for each trial. In order to maintain a euhydrated state, subjects were instructed to drink 1 L of water on the night before each trial, 0.5 L upon awakening, and at least 0.5 L throughout the day until the commencement of the trial.

Hydration status was verified using a refractometer (SUR-NE, Atago USA, Inc., Bellevue, WA) to measure urine specific gravity (USG). USG ≤ 1.020 was required to be considered euhydrated.[6,24] Subjects were instructed to refrain from ingesting alcohol, nonprescription drugs, and caffeine prior to experimental trials, and they reported to the laboratory at the approximate same time of day (± 1 h) for each trial. Experimental trials were separated by 6 ± 4 d.

On the day of each experimental trial, subjects were instructed to arrive at the laboratory well hydrated, well rested, and at least 2 h after consuming any food. Upon reporting to the laboratory on the first visit, subjects completed a medical history, 24-h history to verify adherence to pretest instructions, physical activity history, and provided written informed consent, and then had height and skin folds (via three sites) measured[11], which were used to estimate percent body fat.[28] In a private room, subjects provided a urine sample for measurement of USG to confirm an adequate hydration status as described above, measured nude body mass using a digital scale (BWB-800, Tanita Corporation, Tokyo, Japan), strapped a heart rate (HR) monitor (RS800CX, Polar Electro Inc., Lake Success, NY) around the chest, and inserted a rectal thermometer (Model RET-1, Physitemp, Clifton, NJ) 12 cm beyond the anal sphincter.[16] Then they donned a cotton t-shirt, underwear, athletic shorts, socks, and shoes.

After dressing, thermocouples (HSTC-TT-T-20S-120-SMPW-CC, Omega Engineering, Inc., Stamford, CT) were taped on the upper right chest, right lateral deltoid, right anterior thigh, and right lateral calf for measurement of skin temperature. Next, a flexible venous catheter was inserted into an antecubital vein and kept patent with 0.9% normal saline. Subjects then put on firefighter protective clothing consisting of a jacket (Lion Apparel, Janesville, WI), pants (Lion Apparel), gloves (American Firewear Inc., Ohatchee, AL), hood (American Firewear Inc.), helmet (ED Bullard Company, Cynthiana, KY), breathing mask, and empty self-contained breathing apparatus (SURVIVAIR Inc., Santa Ana, CA). The breathing mask and the empty self-contained breathing apparatus were carried on the body during the work bout, but subjects breathed room air.

Upon entering the environmental chamber (TEPID: 35.2 ± 0.1°C, 38 ± 5% RH; COLD: 35.2 ± 0.1°C, 40 ± 4% RH; ICE: 35.2 ± 0.1°C, 39 ± 4% RH), subjects mounted the treadmill (Trackmaster TMX 425C, Full Vision Inc., Newton, KS) and began walking at $4.0\ \mathrm{km \cdot h^{-1}}$ on a 12% incline. This intensity of work was based on the 2011 Compendium of Physical Activities, which suggests individuals in the firefighting occupation experience MET levels between 6.8 and 9.[2] The speed and grade were determined to be sufficiently demanding based on pilot work and elicited 6.8 to 9.0 METs during experimental trials (TEPID: oxygen uptake ($\dot{V}O_2$) = $2.39 \pm 0.07\ \mathrm{L \cdot min^{-1}}$, 8.6 ± 0.3 METs; COLD: $\dot{V}O_2 = 2.39 \pm 0.08\ \mathrm{L \cdot min^{-1}}$, 8.6 ± 0.4 METs; ICE: $\dot{V}O_2 = 2.28 \pm 0.12\ \mathrm{L \cdot min^{-1}}$, 8.2 ± 0.6 METs).

During the exercise, subjects ingested $1.25\ \mathrm{g \cdot kg^{-1}}$ of a fruit punch flavored 5% carbohydrate-electrolyte beverage (Sqwincher Fruit Punch Flavor, The Sqwincher Corporation, Columbus, MS) every 2.5 min for a total of $15\ \mathrm{g \cdot kg^{-1}}$ (1186.7 ± 61.3 g). Subjects were instructed to ingest each dose within the 2.5 min before the next serving was administered; this allowed for continuous internal cooling. Beverages were ingested in the form of a tepid fluid (TEPID; 22.4 ± 1.7°C), cold fluid (COLD; 7.1 ± 1.5°C), or ice slurry (ICE; −1.3 ± 0.2°C). Beverages were fed in this manner to standardize the ingestion rate. Pilot testing revealed this beverage dose was large enough to elicit a cooling effect, but not so large that it was intolerable to consume. In previous research, a similar protocol of slurry ingestion demonstrated effective cooling of T_{re} and improved exercise performance,[23,26,27] albeit this had not been tested in people wearing firefighting protective clothing. After completing the work bout, subjects exited the environmental chamber and instrumentation was removed. They returned to the private room, towel dried all excess fluid from the body surface, and measured nude body mass. If subjects needed to void the bladder, they were instructed to do so after obtaining nude body mass.

Ice slurries were made using a commercially available slushy machine (BUNN Ultra-2, Bunn-O-Matic Corp., Springfield, IL). This device has preprogrammed settings to convert a fluid glucose solution into an ice slurry without additional ingredients. Its primary components consist of a cooling drum within a 3-gal tank that contains the fluid. An auger shaft wraps the cooling drum. To produce a slurry, the cooling drum lowers the temperature of the beverage, slowly crystallizing any fluid that makes direct contact with the drum. The auger shaft continuously rotates around the drum, scraping thin frozen layers of the beverage off the drum, at the same time stirring the mixture to disperse and suspend the small, crystalized particles throughout the fluid, eventually forming a slurry consistency.

During the exercise, T_{re} and skin temperature were recorded continuously using a thermocouple meter (TC-2000, Sable Systems International, North Las Vegas, NV) and data acquisition system (MP150 with AcqKnowledge 4 Software, BIOPAC, Goleta, CA). Mean skin temperature ($\overline{T}_{sk}$) was calculated using the formula of Ramanathan:[22]

$$\overline{T}_{sk} = 0.3\left(T_{chest} + T_{arm}\right) + 0.2\left(T_{thigh} + T_{leg}\right),$$

where T_{chest}, T_{arm}, T_{thigh}, and T_{leg} were the temperatures measured using the thermocouples affixed to the chest, arm, thigh, and calf, respectively. Mean body temperature ($\overline{T}_b$) was calculated using a weighted formula as described by Stolwijk and Hardy:[30]

$$\overline{T}_b = \left(0.8 \cdot T_{re}\right) + \left(0.2 \cdot \overline{T}_{sk}\right).$$

Heart rate was recorded continuously. Physiological strain index (PSI) was calculated with the formula of Moran et al.:[17]

$$\begin{aligned} \mathrm{PSI} = {} & 5\left(T_{ret} - T_{re0}\right) \cdot \left(39.5 - T_{re0}\right)^{-1} \\ & + 5\left(\mathrm{HR}_t - \mathrm{HR}_0\right) \cdot \left(180 - \mathrm{HR}_0\right)^{-1}, \end{aligned}$$

where T_{ret} and HR_t are measurements taken at a given time point, and T_{re0} and HR_0 are initial measurements.

At minutes 10 and 20 during the exercise, $\dot{V}O_2$ ($\mathrm{L \cdot min^{-1}}$) and respiratory exchange ratio (RER) were recorded for ~2 min via open-circuit spirometry (True-One 2400, Parvo Medics, Sandy, UT). The $\dot{V}O_2$ and RER values from respective time points were averaged and then used to estimate metabolic rate (*M*) with an equation from Kenny and Jay:[13]

$$M = \left(\dot{V}O_2 \cdot \left[\left(\left(\left(\mathrm{RER} - 0.7\right) \cdot 0.3^{-1}\right) \cdot e_c\right) + \left(\left(\left(1 - \mathrm{RER}\right) \cdot 0.3^{-1}\right) \cdot e_f\right)\right]\right) \cdot 60^{-1},$$

where *M* is expressed in Watts, $\dot{V}O_2$ is measured in $\mathrm{L \cdot min^{-1}}$, e_c is 21,130 J (the caloric equivalent per liter of oxygen for carbohydrate oxidation), and e_f is 19,630 J (the caloric equivalent per liter of oxygen for fat oxidation). External work rate (*W*) on a treadmill was estimated with the equation:[8]

$$W = 0.1634 \cdot \mathrm{speed} \cdot \left(\mathrm{grade} \cdot 100^{-1}\right) \cdot \mathrm{body\ mass},$$

where *W* is expressed in Watts, speed is expressed in $\mathrm{m \cdot min^{-1}}$, grade is expressed as a percentage, and body mass is measured in kg. The difference between *M* and *W* was taken as metabolic heat production (*M* – *W*)[13] and expressed in absolute terms and per unit body surface area (A):

$$\mathrm{Metabolic\ heat\ production} = \left(M - W\right) \cdot \mathrm{A}^{-1},$$

where *M* – *W* is expressed in $\mathrm{W \cdot m^{-2}}$.

Body surface area was calculated with the formula of Du Bois:[10]

$$\mathrm{A} = 0.0072 \cdot \mathrm{body\ mass}^{0.425} \cdot \mathrm{height}^{0.725},$$

where 0.0072 is a constant and body mass and height are measured in kg and cm, respectively. Heat storage (S) was calculated with the formula of Adams et al.:[1]

$$\mathrm{S} = \left(0.965 \cdot \mathrm{m} \cdot \Delta\overline{T}_b\right) \cdot \mathrm{A}^{-1},$$

where S is heat storage of the body (in $W \cdot m^{-2}$), 0.965 is the mean specific heat of the body (in $W \cdot kg^{-1} \cdot °C^{-1}$), m is body mass (in kg), and A is body surface area (in m^2). The mean of pre- and postexercise nude body mass was used to represent body mass in these equations.

Whole body sweat rate (SR) was calculated with a modified version of the formula by Casa et al.[6] to include metabolic mass loss:

$$\text{sweating rate} = \begin{bmatrix} (\text{pre-exercise body mass} - \text{post-exercise body mass}) \\ + \text{fluid intake} - \text{urine volume} - \text{metabolic mass loss} \end{bmatrix} \cdot \text{exercise time}^{-1},$$

where body mass and metabolic mass loss are entered in g and fluid intake and urine volume are measured in mL. Metabolic mass loss (in g) was calculated using the formula of Kenny and Jay:[13]

$$\text{metabolic mass loss} = t \cdot \left[\dot{V}O_2 (44 \cdot RER - 32) \cdot 22.4^{-1}\right],$$

where t is time of exercise (in min) and $\dot{V}O_2$ is oxygen uptake (in $L \cdot min^{-1}$). The $\dot{V}O_2$ and RER collected at their respective time points were averaged and then used as part of the metabolic mass loss equation.

A 2-mL blood sample was drawn into a tube (Vacutainer EDTA, Becton, Dickinson and Company, Franklin Lakes, NJ) before the initiation of exercise and at the termination of exercise. Subjects stood upright during all blood draws to eliminate potential plasma volume shifts caused by differences in hydrostatic pressure associated with postural changes. All blood samples were analyzed for hemoglobin (Hb) and hematocrit (Hct) content shortly after acquisition with a hemoglobin photometer (HemoPoint H2, Stanbio Laboratory, Boerne, TX) and microhematocrit and sedimentation reader (Micro-Capillary Reader, International Equipment Company, Boston, MA), respectively. Plasma volume change (%ΔPV) was calculated with the equations described by Dill and Costill:[9]

$$\begin{aligned} PV_{pre} &= 100 - Hct_{pre},\ PV_{post} = \left(100 \cdot Hb_{pre} \cdot Hb^{-1}_{post}\right) \\ &\quad - \left[\left(100 \cdot Hb_{pre} \cdot Hb^{-1}_{post}\right) \cdot \left(Hct_{post} \cdot 100^{-1}\right)\right],\ \%\Delta PV \\ &= 100\left[\left(PV_{pos} - PV_{pre}\right) \cdot PV^{-1}_{pre}\right), \end{aligned}$$

where PV_{pre} and PV_{post} are plasma volumes in 100 mL of blood before and after the expected change, respectively; Hb_{pre} and Hb_{post} are hemoglobin concentrations (in $g \cdot dL^{-1}$) before and after the expected change, respectively; Hct_{pre} and Hct_{post} are hematocrit before and after the expected change, respectively; and %ΔPV is the percentage change in plasma volume.

A perceptual rating of thermal sensation (RTS) was obtained every 5 min using a scale ranging from 0 (unbearably cold) to 8 (unbearably hot).[32] Rating of perceived exertion (RPE) was obtained every 5 min using the Borg 6 to 20 scale.

Statistical Analysis

Descriptive data were calculated for all test variables. Mean differences in T_{re}, $\overline{T}_{sk}$, $\overline{T}_b$, HR, PSI, RTS, and RPE among treatment conditions during the work bout were analyzed with separate treatment × time repeated measures analyses of variance (ANOVA). Mean differences in pre-exercise nude body mass, USG, *M* – *W*, S, SR, and %ΔPV among treatment conditions were analyzed with a one-way repeated measures ANOVA. Upon finding a significant omnibus *F*-ratio, a post hoc Bonferroni multiple comparison test was performed to detect significant differences. Statistical tests (e.g., Shapiro-Wilk, skewness, and kurtosis z-score analysis) as well as visual assessments (e.g., frequency distribution, Q-Q plot) of normality confirmed that all dependent variables conformed to a Gaussian distribution. All data are presented as mean ± SD unless otherwise indicated. Statistical significance was set at $\alpha = 0.05$. All analyses were performed using IBM SPSS Statistics 22.0 (IBM Corp., Armonk, NY).

RESULTS

Pre-exercise nude body mass was not different among trials [TEPID = 79.2 ± 4.0 kg, COLD = 78.9 ± 4.0 kg, ICE = 79.4 ± 4.3 kg; $F(2, 14) = 3.081$, $P = 0.08$]. Pre-exercise USG was below 1.020 and not different among trials [TEPID = 1.006 ± 0.004, COLD = 1.007 ± 0.004, ICE = 1.006 ± 0.004; $F(2, 14) = 0.323$, $P = 0.729$], indicating that subjects were in a euhydrated state prior to each trial.

Baseline core temperature was not different among treatments [TEPID: 37.11 ± 0.39°C, COLD: 37.09 ± 0.38°C, ICE: 37.05 ± 0.39°C; $F(1.209, 8.462) = 0.516$, $P = 0.53$]. Exercise resulted in elevated metabolic heat production and ultimately heat storage that caused T_{re} to increase over time (**Table I** and **Fig. 1**, respectively), but ICE was successful in blunting this increase. $\overline{T}_{sk}$ significantly increased by 6.6% [$F(6, 42) = 84.8$, $P < 0.001$] from 34.30 ± 0.72°C to 36.57 ± 0.48°C at the initiation and cessation of exercise, respectively, but there were no differences among treatments at any particular time point. $\overline{T}_b$ was 36.53 ± 0.38°C at the initiation of exercise and 37.82 ± 0.28°C at the end of exercise—a significant increase of 3.5% [$F(6, 42) = 158$,

Table I. Metabolic Heat Production, Heat Storage, Sweat Rate, and Plasma Volume Change During Beverage Treatments (mean ± SD) (*N* = 8).

VARIABLE	TEPID FLUID	COLD FLUID	ICE SLURRY
Metabolic Heat Production ($W \cdot m^{-2}$)	362.3 ± 12.8	362.2 ± 17.9	344.1 ± 23.1
Heat Storage ($W \cdot m^{-2}$)	49.3 ± 8.2	55.2 ± 15.3	44.9 ± 11.8
Sweat Rate ($mL \cdot h^{-1}$)	1895 ± 268	1821 ± 276	1445 ± 323*†
ΔPV (%)	−4.1 ± 3.7	−5.1 ± 5.3	−3.6 ± 4.0

ΔPV = plasma volume change.
* *P* = 0.04 vs. COLD; † *P* = 0.01 vs. TEPID.

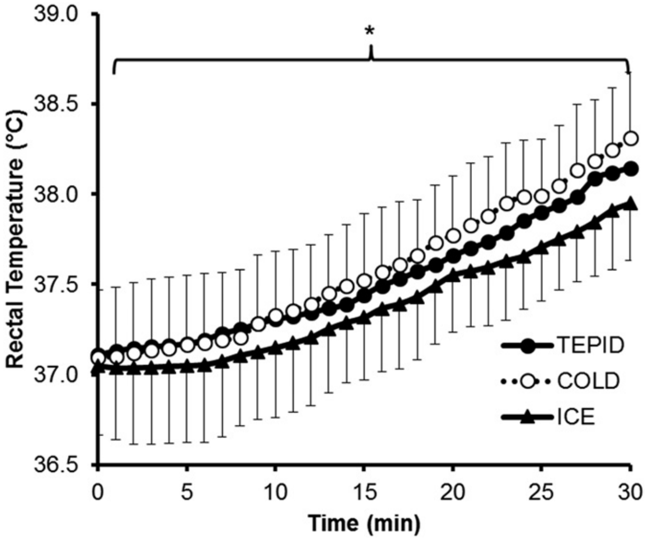

Fig. 1. Mean (± SD) rectal temperature during 30 min of walking with ingestion of tepid fluid (TEPID), cold fluid (COLD), or ice slurry (ICE) beverages ($N = 8$). $^*P \leq 0.05$ for interaction.

$P < 0.001$]—but, similar to $\overline{T}_{sk}$, there were no differences among treatments at any time point.

Heart rate was not different at baseline across treatments [$F(2, 14) = 1.353$, $P = 0.29$] and, as expected, values increased over time in response to exercise [$F(12, 84) = 6.4$, $P < 0.001$ for interaction; **Fig. 2**]. HR remained lower with ICE by 14 ± 2 bpm (8%) compared to TEPID ($P = 0.001$) and by 12 ± 2 bpm (7%) compared to COLD ($P = 0.01$) throughout exercise. TEPID and COLD were not different ($P = 0.63$).

Fig. 3 shows PSI increased across time in all experimental trials. That said, values remained lower during ICE compared to the other treatments [$F(12, 84) = 7.204$, $P < 0.001$ for interaction].

Beverage ingestion for each trial was successful in preventing excessive dehydration during the exercise bout as evidenced by the increase in body mass during each trial (TEPID: 0.3 ± 0.2%, COLD: 0.3 ± 0.2%, ICE: 0.6 ± 0.2%). Whole-body sweat rate was ~22% lower during ICE [$F(2, 14) = 13.5$, $P = 0.001$] compared to TEPID ($P < 0.01$) and COLD ($P = 0.04$). Even though whole-body sweat rate was lower with ICE, this did not result in differential losses of plasma volume among treatments [Table I; $F(2, 14) = 0.235$, $P = 0.79$].

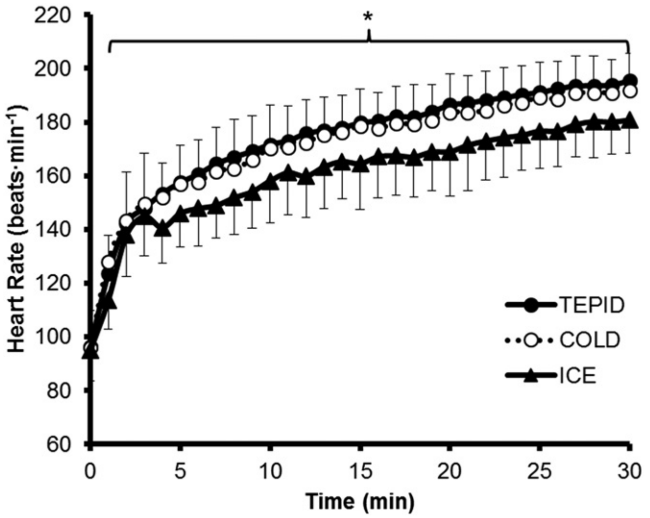

Fig. 2. Mean (± SD) heart rate during 30 min of walking with ingestion of tepid fluid (TEPID), cold fluid (COLD), or ice slurry (ICE) beverages ($N = 8$). $^*P \leq 0.05$ for interaction.

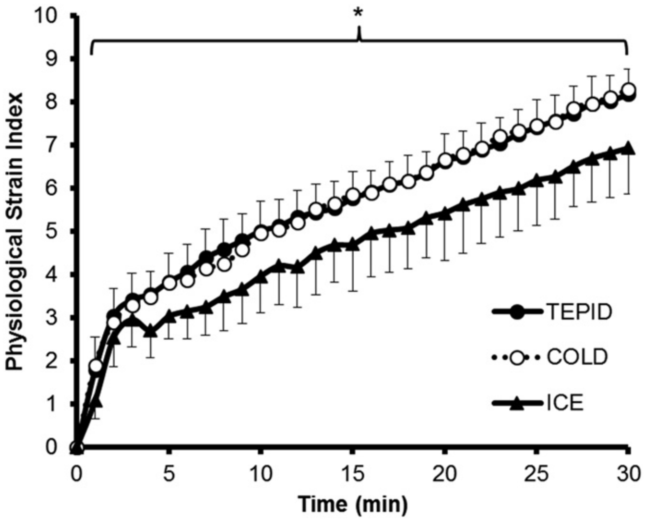

Fig. 3. Mean (± SD) physiological strain index during 30 min of walking with ingestion of tepid fluid (TEPID), cold fluid (COLD), or ice slurry (ICE) beverages ($N = 8$). $^*P \leq 0.05$ for interaction.

Table II shows that ICE blunted perception of thermal stress as evidenced by lower RTS during that trial compared to the others. Likewise, ICE blunted RPE as well, particularly in the last 10 min of the work bout (Table II).

DISCUSSION

The primary objective of the current study was to determine if ice slurry ingestion would attenuate human physiological strain during work while wearing protective clothing. The main finding was that ice slurry ingestion was effective in mitigating increases in PSI, T_{re}, and HR compared to the same volume of warmer fluid beverages during 30 min of vigorous intensity walking while wearing firefighter protective clothing in a hot environment. Practically, beverages to firefighters should be as cold as possible, as this can help mitigate heat strain.

T_{re} was lower with ingestion of ice slurry by more than 0.16°C compared to ingestion of cold and tepid fluid. This finding was different from previous literature which examined ice slurry ingestion, in that others did not observe an effect of ice slurry ingestion on core temperature. Burdon et al. had subjects perform three separate bouts of steady state cycling in a warm, humid environment (28°C, 70% RH) with ingestion of either cold fluid, thermoneutral fluid, or thermoneutral fluid with 30 g ice puree, but no differences in T_{re} were observed among treatments.[5]

In a follow-up study, the same investigators replicated the design and compared the effect of ice slurry ingestion to

Table II. Mean ± SD Perceptual Measures During Work While Wearing Protective Garments and While Ingesting Tepid (TEPID), Cold Fluid (COLD), or an Ice Slurry (ICE) ($N = 8$).

		TIME (min)						
VARIABLE	**TRIAL**	**0**	**5**	**10**	**15**	**20**	**25**	**30**
RTS	TEPID	4.5 ± 0.0	5.5 ± 0.5	5.5 ± 0.5	6.0 ± 0.5	6.5 ± 0.5	7.0 ± 1.0	7.0 ± 0.5
	COLD	4.5 ± 0.5	5.5 ± 0.5	6.0 ± 0.5	6.5 ± 0.5	6.5 ± 1.0	7.0 ± 0.5	7.0 ± 0.5
	ICE	4.5 ± 0.5	5.0 ± 0.5	5.5 ± 0.5	6.0 ± 0.5*	6.0 ± 1.0	6.5 ± 1.0	6.5 ± 1.0*†
RPE	TEPID	7 ± 1	11 ± 1	14 ± 2	14 ± 2	16 ± 2	17 ± 2	18 ± 2
	COLD	6 ± 1	12 ± 2†	14 ± 1	15 ± 1	16 ± 1	17 ± 1	18 ± 1
	ICE	7 ± 1	12 ± 1	13 ± 1	14 ± 1	15 ± 1*†	16 ± 2*†	16 ± 2*†

RTS = Rating of Thermal Sensation from 0 (unbearably cold) to 8 (unbearably hot); RPE = Rating of Perceived Exertion.
* $P \leq 0.05$ vs. COLD; $^{\dagger}P \leq 0.05$ vs. TEPID.

thermoneutral fluid ingestion during steady state exercise in a hot environment (32°C, 40% RH) and again did not observe differences in T_{re} among treatments.[4] Similarly, Schulze et al. compared ad libitum ingestion of fluid and ice slurry beverages during fixed rate exercise in a hot humid environment (30°C, 80% RH) and reported a small effect size in the rate of rise in T_{re} between trials that was characterized as "unclear."[25]

Along with T_{re}, HR was also used to determine PSI and, while ice slurry ingestion did not appear to affect T_{re} until 10 min into the exercise bout, the increase in HR was mitigated with ice slurry ingestion throughout the entire exercise period compared to the warmer beverages. Like T_{re}, this finding also was different from previous literature in that others did not observe an effect of ice slurry ingestion during exercise on HR.[5] In one study, 7 out of 10 subjects exhibited lower HR with ingestion of ice slurry by a range of 6 to 11 bpm, but the finding was not statistically different between trials, and the effect size was small and deemed "unclear" by the investigators.[4] In a study using a simulated triathlon, Stevens et al. reported that, while subsequent running performance was enhanced by ice slurry ingestion, there were no differences in HR between trials during the cycling portion of the simulation when the beverages were administered to subjects.[29]

Why are findings of the present study different from previous investigations? Methodological differences probably explain the discrepant results. When standardized to a period of 30 min, subjects of previous studies ingested ice slurry amounts between ~167 and 775 g[5,25,29] compared to ~1190 g over a 30-min period in our study. It is plausible that the amount of beverage ingested by subjects in the current study—over 50% greater than that in the cited studies—was apparently large enough to create a heat sink and blunt a rise in T_{re}.

The latent heat of fusion for water (quantity of energy needed to change the phase of water from solid to liquid) is 334 $\text{kJ} \cdot \text{kg}^{-1}$ (which equates to 80 $\text{kcal} \cdot \text{kg}^{-1}$). Assuming the ice slurry beverage was composed of ~75% ice, each 100-g dose would have contained 0.075 kg of ice, which—at a latent heat of 80 $\text{kcal} \cdot \text{kg}^{-1}$—means it would take 6 kcal of latent heat to melt the ice of each dose. Since subjects were exercising at ~12 $\text{kcal} \cdot \text{min}^{-1}$, and assuming ~20% efficiency (i.e., 9.6 $\text{kcal} \cdot \text{min}^{-1}$ released as heat), each dose would then provide ~0.625 min of a delay in heat gain (due to the heat sink provided by the ice). With 12 doses ingested over the duration of each trial, and with each dose delaying heat gain by ~0.625 min, the ice slurry treatment then might have provided ~7.5 min of delay in heat gain. In other words, there might be ~7.5 min of additional exercise time before reaching a T_{re} that would have been reached in the conditions without ice slurry. When the latent heat of fusion is added to the energy needed to raise the temperature of the whole solution from −1°C to deep body temperature, the ice slurry beverage should have provided a larger heat sink compared to the tepid and cold fluid beverages that have temperatures closer to body temperature and lack the incorporation of latent heat of fusion. If the data on Fig. 1 were extrapolated further, the trend suggests individuals might be able to exercise for 5–7 min longer with ice slurry ingestion before reaching a T_{re} near that of the TEPID and COLD conditions.

Another explanation for the differences between our study and previous studies could be that the magnitude of heat stress in our study was greater than that of previous studies. In the current study, subjects were fully encapsulated in protective clothing that limited heat dissipation via evaporation, thus increasing thermal stress. Metabolic heat production of our subjects was comparable to that of previous studies;[4] however, our subjects would have experienced a greater thermal burden as evidenced by greater heat storage compared to studies in which evaporative heat loss was not limited by protective clothing.[4]

Metabolic heat production of subjects of the current study was 685 to 720 W (or ~295 to 310 kcal over 30 min). It has been reported that the body loses 0.58 kcal of heat for each milliliter of sweat evaporated.[31] Accordingly, the volume of sweat needed to evaporate during the work bout to prevent heat storage (and an accompanying increase in core temperature) was estimated to be ~509 to 534 mL. Subjects in the current study sweated ~720 to 950 mL over 30 min—a volume more than sufficient to prevent heat gain if fully evaporated—but still experienced an increase in T_{re} by 0.9 to 1.2°C. This indicates that the evaporative heat loss mechanism was hindered because of the insulative and impermeable properties of the protective garments. Our findings of attenuated T_{re} and HR during ICE are consistent with those of Kenny et al., whose subjects exhibited reduced physiological strain (lower core temperature and HR) while wearing an ice vest underneath a nuclear, biological, and chemical protective suit—which also likely restricted evaporative heat loss—during exercise under non-compensable heat stress.[14] Furthermore, Nunneley et al. reported that head cooling attenuated an increase in T_{re} in a hot ambient environment (40°C), but had little effect under cooler conditions (20 and 30°C).[19] Taken together, it is plausible that the cooling effects of ice slurry ingestion during exercise may only be evident in the presence of severe or non-compensable heat stress and when evaporative heat loss is limited.

Body cooling via ice slurry ingestion could be beneficial in occupational settings as it appears to provide a means of mitigating thermal and cardiovascular strain during work in protective clothing under hot ambient conditions. Additionally, the intake of ice slurry beverages—while lowering physiological strain—can also provide fluid replacement.

The American College of Sports Medicine Position Stand on Exercise and Fluid Replacement recommends drinking during exercise to prevent excessive dehydration (>2% body mass loss).[24] The feeding strategy used in our study helped subjects avoid excessive dehydration as all subjects in all trials did not weigh less at the end of exercise than when they started the bout. Furthermore, the lack of differences among treatments in plasma volume change between the initiation and cessation of exercise further suggests that ice slurry beverages effectively hydrated subjects just as much as the fluid beverages.

Previous literature suggested body cooling during exercise can improve performance, especially when cardiovascular and thermal strain are blunted.[14] Although performance was not measured in the current study, since cardiovascular and thermal strain were blunted one can surmise that performance would have been positively impacted as well.

Interestingly, estimated heat storage was not different among trials, but whole-body sweat rate was lower with ingestion of ice slurry than both warmer fluid beverages. This is consistent with the findings of Lamarche et al.,[15] whose subjects cycled for 75 min in 25°C and experienced greater sweat loss with ingestion of hot (50°C) water compared to cold (1.5°C) water; body heat storage did not differ between conditions. They concluded that humans regulate sweating in a way that compensates for the differences in beverage temperature so that heat balance is maintained.[15] When compared to 37°C fluid, Morris et al. reported a lower net heat loss and greater heat storage with ICE compared to fluid ingestion, attributing this to thermoreceptors, likely in the abdominal wall, that caused a reduction in local sweat rate, thereby lowering evaporative heat loss from the skin.[18] The current study is novel in that subjects donned encapsulating clothing which limited evaporative heat loss in all conditions, and—similar to the findings of Morris et al.—ICE resulted in lower whole-body sweat loss. In a situation where evaporative cooling is restricted by impermeable clothing, blunting sweat loss would be a favorable outcome in order to avoid excessive dehydration and a resultant increase in physiological strain.

It is acknowledged that the hot laboratory environment does not replicate the radiant heat experienced during actual fire exposure; however, there are other duties that involve dressing in full firefighter protective clothing without necessarily exposing individuals to a fire (e.g., working in areas with risk of exposure to unknown agents). While the treatment was successful in lessening physiological strain and preventing dehydration, our subjects were fed a very large amount of the beverage; dehydration was not only prevented, subjects actually gained weight by the end of the trials. Workers wearing protective clothing are not likely to ingest as much in the field, possibly due to limited availability of and/or access to ice slurry beverages during work as well as discomfort during ingestion. Also, while firefighters occasionally wear a breathing mask to protect themselves in environments with harmful substances in the air, subjects in this study did not breathe through the mask but instead attached it to the jacket to mimic the load of the clothing ensemble. Nonetheless, this study establishes proof of concept that ice slurry ingestion can be beneficial during work in protective clothing. If the method of delivery is optimized, ice slurry ingestion might be a favorable option for body cooling during work.

In conclusion, when ingested in large quantities and during non-compensable heat stress, ice slurry ingestion was effective in mitigating physiological strain as indicated by attenuation of increases in T_{re} and HR during work in protective garments. Combined with previous literature, these findings suggest that the effectiveness of body cooling via ice slurry ingestion during work is positively associated with the level of heat stress imposed and inversely related to the evaporative heat loss potential. Future research should explore this connection as well as continue to examine effective and practical methods of application and their effects on exercise capacity.

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REFERENCES

1. Adams WC, Mack GW, Langhans GW, Nadel ER. Effects of varied air velocity on sweating and evaporative rates during exercise. J Appl Physiol (1985). 1992; 73(6):2668–2674.
2. Ainsworth BE, Haskell WL, Herrmann SD, Meckes N, Bassett DR, et al. 2011 Compendium of Physical Activities: a second update of codes and MET values. Med Sci Sports Exerc. 2011; 43(8):1575–1581.
3. Barr D, Reilly T, Gregson W. The impact of different cooling modalities on the physiological responses in firefighters during strenuous work performed in high environmental temperatures. Eur J Appl Physiol. 2011; 111(6):959–967.
4. Burdon CA, Hoon MW, Johnson NA, Chapman PG, O'Connor HT. The effect of ice slushy ingestion and mouthwash on thermoregulation and

endurance performance in the heat. Int J Sport Nutr Exerc Metab. 2013; 23(5):458–469.

5. Burdon C, O'Connor H, Gifford J, Shirreffs S, Chapman P, Johnson N. Effect of drink temperature on core temperature and endurance cycling performance in warm, humid conditions. J Sports Sci. 2010; 28(11):1147–1156.
6. Casa DJ, Armstrong LE, Hillman SK, Montain SJ, Reiff RV, et al. National athletic trainers' association position statement: fluid replacement for athletes. J Athl Train. 2000; 35(2):212–224.
7. Cheung SS, McLellan TM, Tenaglia S. The thermophysiology of uncompensable heat stress. Physiological manipulations and individual characteristics. Sports Med. 2000; 29(5):329–359.
8. Cooper CB, Storer TW. Exercise testing and interpretation: a practical approach. Cambridge (United Kingdom): Cambridge University Press; 2001:27–32.
9. Dill DB, Costill DL. Calculation of percentage changes in volumes of blood, plasma, and red cells in dehydration. J Appl Physiol. 1974; 37(2):247–248.
10. Du Bois D, Du Bois EF. A formula to estimate the approximate surface area if height and weight be known. 1916. Nutrition. 1989; 5(5): 303–311.
11. Jackson AS, Pollock ML. Practical assessment of body composition. Phys Sportsmed. 1985; 13(5):76–90.
12. Katica CP, Pritchett RC, Pritchett KL, Del Pozzi AT, Balilionis G, Burnham T. Effects of forearm vs. leg submersion in work tolerance time in a hot environment while wearing firefighter protective clothing. J Occup Environ Hyg. 2011; 8(8):473–477.
13. Kenny GP, Jay O. Thermometry, calorimetry, and mean body temperature during heat stress. Compr Physiol. 2013; 3(4):1689–1719.
14. Kenny GP, Schissler AR, Stapleton J, Piamonte M, Binder K, et al. Ice cooling vest on tolerance for exercise under uncompensable heat stress. J Occup Environ Hyg. 2011; 8(8):484–491.
15. Lamarche DT, Meade RD, McGinn R, Poirier MP, Friesen BJ, Kenny GP. Temperature of ingested water during exercise does not affect body heat storage. Med Sci Sports Exerc. 2015; 47(6):1272–1280.
16. Lee JY, Wakabayashi H, Wijayanto T, Tochihara Y. Differences in rectal temperatures measured at depths of 4–19 cm from the anal sphincter during exercise and rest. Eur J Appl Physiol. 2010; 109(1):73–80.
17. Moran DS, Shitzer A, Pandolf KB. A physiological strain index to evaluate heat stress. Am J Physiol. 1998; 275(1, Pt. 2):R129–R134.
18. Morris NB, Coombs G, Jay O. Ice slurry ingestion leads to a lower net heat loss during exercise in the heat. Med Sci Sports Exerc. 2016; 48(1):114–122.
19. Nunneley SA, Troutman SJ, Webb P. Head cooling in work and heat stress. Aerosp Med. 1971; 42(1):64–68.
20. Park I, Schutz RW. "Quick and easy" formulae for approximating statistical power in repeated measures ANOVA. Meas Phys Educ Exerc Sci. 1999; 3(4):249–270.
21. Potvin PJ, Schutz RW. Statistical power for the two-factor repeated measures ANOVA. Behav Res Methods Instrum Comput. 2000; 32(2): 347–356.
22. Ramanathan NL. A new weighting system for mean surface temperature of the human body. J Appl Physiol. 1964; 19(3):531–533.
23. Ross ML, Garvican LA, Jeacocke NA, Laursen PB, Abbiss CR, et al. Novel precooling strategy enhances time trial cycling in the heat. Med Sci Sports Exerc. 2011; 43(1):123–133.
24. Sawka MN, Burke LM, Eichner ER, Maughan RJ, Montain SJ, et al. American College of Sports Medicine position stand. Exercise and fluid replacement. Med Sci Sports Exerc. 2007; 39(2):377–390.
25. Schulze E, Daanen HA, Levels K, Casadio JR, Plews DJ, et al. Effect of thermal state and thermal comfort on cycling performance in the heat. Int J Sports Physiol Perform. 2015; 10(5):655–663.
26. Siegel R, Mate J, Brearley MB, Watson G, Nosaka K, Laursen PB. Ice slurry ingestion increases core temperature capacity and running time in the heat. Med Sci Sports Exerc. 2010; 42(4):717–725.
27. Siegel R, Mate J, Watson G, Nosaka K, Laursen PB. Pre-cooling with ice slurry ingestion leads to similar run times to exhaustion in the heat as cold water immersion. J Sports Sci. 2012; 30(2):155–165.
28. Siri WE. Body composition from fluid spaces and density: analysis of methods. Nutrition. 1993; 9(5):480–491.
29. Stevens CJ, Dascombe B, Boyko A, Sculley D, Callister R. Ice slurry ingestion during cycling improves Olympic distance triathlon performance in the heat. J Sports Sci. 2013; 31(12):1271–1279.
30. Stolwijk JA, Hardy JD. Partitional calorimetric studies of responses of man to thermal transients. J Appl Physiol. 1966; 21(3):967–977.
31. Wenger CB. Heat of evaporation of sweat: thermodynamic considerations. J Appl Physiol. 1972; 32(4):456–459.
32. Young AJ, Sawka MN, Epstein Y, Decristofano B, Pandolf KB. Cooling different body surfaces during upper and lower body exercise. J Appl Physiol. 1987; 63(3):1218–1223.