Temperature of Ingested Water during Exercise Does Not Affect Body Heat Storage

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ABSTRACT

LAMARCHE, D. T., R. D. MEADE, R. MCGINN, M. P. POIRIER, B. J. FRIESEN, and G. P. KENNY. Temperature of Ingested Water during Exercise Does Not Affect Body Heat Storage. *Med. Sci. Sports Exerc.*, Vol. 47, No. 6, pp. 1272–1280, 2015. **Purpose**: The objective of this study was to examine the effect of ingested water temperature on heat balance during exercise as assessed by direct calorimetry. **Methods**: Ten healthy males (25 ± 4 yr) cycled at 50% $\dot{V}O_{2peak}$ (equivalent rate of metabolic heat production (M-W) of 523 ± 84 W) for 75 min under thermocomfortable conditions (25°C, 25% relative humidity) while consuming either hot (50°C) or cold (1.5°C) water. Four 3.2 $mL \cdot kg^{-1}$ boluses of hot or cold water were consumed 5 min before and at 15, 30, and 45 min after the onset of exercise. Total heat loss (H_L = evaporative heat loss (H_E) ± dry heat exchange (H_D)) and M-W were measured by direct and indirect calorimetry, respectively. Change in body heat content (ΔH_b) was calculated as the temporal summation of M-W and H_L and adjusted for changes in heat transfer from the ingested fluid (H_{fluid}). **Results**: The absolute difference for H_L (209 ± 81 kJ) was similar to the absolute difference of H_{fluid} (204 ± 36 kJ) between conditions ($P = 0.785$). Furthermore, the difference in H_L was primarily explained by the corresponding changes in H_E (hot: 1538 ± 393 kJ; cold: 1358 ± 330 kJ) because H_D was found to be similar between conditions ($P = 0.220$). Consequently, no difference in ΔH_b was observed between the hot (364 ± 152 kJ) and cold (363 ± 134 kJ) conditions ($P = 0.971$) during exercise. **Conclusion**: We show that ingestion of hot water elicits a greater H_L relative to cold water ingestion during exercise. However, this response was only compensated for the heat of the ingested fluid as evidenced by similar ΔH_b between conditions. Therefore, our findings indicate that relative to cold water ingestion, consuming hot water does not provide a thermoregulatory advantage. Both hot and cold water ingestion results in the same amount of heat stored during prolonged moderate-intensity exercise. **Key Words:** THERMOREGULATION, DIRECT CALORIMETRY, HEAT DISSIPATION, LOCAL SWEAT RATE

Prolonged physical activity without fluid replacement is associated with progressive dehydration, which can impair cardiovascular and thermoregulatory control (4,27–29). Thus, it is recommended that fluids be ingested during prolonged bouts of physical activity in order to maintain a euhydrated state, which ultimately will sustain cardiovascular stability and heat dissipation. Although the effect of different types of fluid (i.e., water and sport drinks) on hydration has received much attention in the past (5,28,37), recent studies have suggested that the temperature of ingested fluid may have a confounding influence on whole-body heat dissipation and subsequently body heat storage during exercise (1,19,20). As such, water temperature may be an important determinant when implementing hydration strategies for individuals. However, these studies are not consistent in their results regarding reported changes in body heat storage. Specifically, it has recently been demonstrated that ingesting hot (50°C) water reduces body heat storage compared with ingesting cold (1.5°C) water (1). However, others have shown cold (10°C) water to reduce body heat storage compared with hot (50°C) water (20), whereas another study reported no effect of fluid temperature on body heat storage (19). Consequently, how (if at all) the temperature of ingested water affects heat storage and thus core temperature regulation during exercise remains inconclusive.

Despite the different ingestion strategies (i.e., water temperature, water volume, and ingestion frequency) used to determine the effects of water temperature on thermoregulatory control, prior studies (1,19,20) have all relied upon indirect methods (thermometric models and partitional calorimetry) to assess heat storage during exercise. It is well known that there are inherent limitations associated with these indirect approaches concerning measurements of heat dissipation and thereby body heat storage (12,13). Although these techniques can provide reasonable estimations of the change in body heat storage over prolonged exercise periods, measuring momentary changes in heat dissipation, and thereby heat storage, is not possible. That being the case, a recent study by Morris et al. (23) reported a reflex increase and decrease in local

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sweat rate (LSR) during ingestion of 50°C and 1.5°C water ingestion, respectively. These findings suggest that water temperature may induce transient changes in whole-body heat dissipation and thereby body heat storage; however, prior reports indicate that whole-body heat loss is not always reflected by local measurements (16,33). Consequently, it remains unclear whether the temperature of ingested water induces transient changes in whole-body heat dissipation during exercise, and whether this response would lead to differences in whole-body heat storage.

As hydration can be of a pivotal importance during prolonged physical activity for athletes, military personnel, and occupational workers, it is necessary to consider the effect of water temperature on thermoregulatory function during exercise. Therefore, the purpose of the present study was to evaluate whether the ingestion of either hot (50°C) or cold (1.5°C) water modulates whole-body heat loss and therefore changes in body heat storage during steady-state cycling under thermocomfortable conditions. To assess the transient changes in body heat storage, we simultaneously measured the rate of metabolic heat production via indirect calorimetry and whole-body heat loss using direct calorimetry. We evaluated the hypothesis that the periodic ingestion of hot and cold water during exercise would elicit a transient increase and decrease in whole-body heat dissipation, respectively. Furthermore, based on a recent investigation (1), we evaluated the hypothesis that the increase in whole-body heat loss under the hot condition would lead to a reduction in body heat storage compared with that under the cold condition.

METHODS

Ethical Approval

The current experimental protocol was approved by the University of Ottawa Health Sciences and Science Research Ethics Board and conforms to the *Declaration of Helsinki*. Written informed consent was obtained from all volunteers before their participation in the study.

Participants

Ten males volunteered for one screening visit and two experimental sessions. Age, height, body mass, body surface area, and peak oxygen uptake ($\dot{V}O_{2peak}$) of the participants (mean ± SD) were as follows: 25 ± 4 yr, 1.75 ± 0.05 m, 79.2 ± 13.7 kg, 1.94 ± 0.14 m^2, and 47.9 ± 9.8 $mL \cdot kg^{-1} \cdot min^{-1}$, respectively. Participants were healthy, nonsmoking, and normotensive with no history of respiratory, metabolic, or cardiovascular disease. Participants reported being physically active for at least 30 min for three or more sessions per week.

Experimental Design

Preliminary session. Measurements of body height, mass, and surface area as well as $\dot{V}O_{2peak}$ were determined during the screening visit. Body height was measured using a stadiometer (model 2391; Detecto, Webb City, MO) and body mass was determined using a digital high-performance weighing terminal (model CBU150X; Mettler Toledo Inc., Mississauga, ON, Canada). Body surface area was subsequently calculated from the measurements of body height and mass (6). Indirect calorimetry (MCD Medgraphics Ultima Series; MGC Diagnostics Corporation, Saint Paul, MN) was used to measure $\dot{V}O_{2peak}$ during a progressive incremental exercise protocol performed on a semirecumbent constant-load cycle ergometer (Corival, Lode B.V., Groningen, the Netherlands). The protocol started with an external workload of 100 W for the first minute and increased by 20 W every minute thereafter until the participant could not maintain a pedalling cadence of at least 60 rpm or attained volitional fatigue. Subsequently, $\dot{V}O_{2peak}$ was calculated as the peak value of oxygen consumption averaged over 30 s.

Experimental sessions. Participants were instructed to abstain from exercise, caffeine, and alcohol for 24 h before both experimental sessions and asked to consume 500 mL of water no more than 2 h before the start of the experimental session. Experimental trials were randomized, performed at the same time of day for a given participant, and separated by a minimum of 48 h. Upon arrival to the laboratory, participants first changed into athletic shorts and wore no shoes or sandals. Thereafter, they provided a urine sample and voided their bladder before a nude body mass measurement was obtained. After instrumentation, the participants entered the calorimeter, which was regulated to an ambient air temperature of 25°C and relative humidity of ~25%. After a 15-min baseline period in an upright seated position, continuous semirecumbent cycling at ~70 rpm was performed for 75 min at 50% of each participant's respective $\dot{V}O_{2peak}$. This intensity was equivalent to an external workload of 98 ± 22 W.

Similar to previous studies (1,23), four boluses of tap water measured to 3.2 $mL \cdot kg^{-1}$ of either hot (50°C) or cold (1.5°C) water were consumed 5 min before exercise and at 15, 30, and 45 min during the exercise period. Drinks were consumed within 3 min using a custom mask (plastic tubing inside mouthpiece with a manual valve) fitted to enable drinking while maintaining a sealed environment and continuous measurements of indirect calorimetry. Participants were taught how to use the mask during the instrumentation period, and the mask was properly fitted and sealed before each session. The temperature of the water was measured within 30 s of each ingestion using a standard thermocouple probe (Mon-a-therm; Mallinckrodt Medical, St. Louis, MO).

Measurements. The modified Snellen whole-body direct air-flow calorimeter was employed to measure the rate of evaporative heat loss and dry (radiation + convection + conduction) heat exchange yielding an accuracy of ±2.3 W for the measurement of the rate of total heat loss (26). The calorimeter inflow and outflow values of absolute humidity and air temperature were collected at 8-s intervals. Absolute humidity was measured using high-precision dew point hygrometry (model 373H; RH Systems, Albuquerque, NM), whereas air temperature was measured using high-precision resistance temperature detectors (±0.002°C, Black Stack model 1560, Fluke Calibration, American Fork, UT). Air mass flow through the calorimeter was measured by differential thermometry over a known heat source (2 × 750 W of heating elements) placed in the effluent air stream. The real-time data for absolute humidity, air temperature, and air mass flow were displayed and recorded on a personal computer with LabVIEW software (version 7.0; National Instruments, Austin, TX). The rate of evaporative heat loss was calculated using the calorimeter outflow–inflow difference in absolute humidity, multiplied by the air mass flow ($\text{kg-air}\cdot\text{s}^{-1}$) and the latent heat of vaporization of sweat ($2{,}426\ \text{J}\cdot\text{g sweat}^{-1}$). The rate of dry heat exchange was calculated using the calorimeter outflow–inflow difference in air temperature, multiplied by the air mass flow and specific heat capacity of air ($1{,}005\ \text{J}\cdot\text{kg-air}^{-1}\cdot{}^{\circ}\text{C}^{-1}$). Notably, the Snellen whole-body calorimeter ensures full evaporation of the sweat produced, thereby giving indication of whole-body sweat production. This characteristic was ensured by circulating a high mass flow ($9.17 \pm 0.17\ \text{kg-air}\cdot\text{min}^{-1}$) of dry air (specific humidity of $5.61 \pm 1.74\ \text{g}\cdot\text{kg}^{-1}$) through the calorimeter.

The rate of metabolic energy expenditure was simultaneously measured using indirect calorimetry. Expired gas samples were drawn from a 6-L fluted mixing box located within the calorimeter and subsequently analyzed for oxygen (O_2, with an error of ±0.01%) and carbon dioxide (CO_2, with an error of ±0.02%) concentrations using electrochemical gas analyzers (AMETEK model S-3A/1 and CD 3A; Applied Electrochemistry, Pittsburgh, PA). Thereafter, expired air was recycled back into the calorimeter chamber in order to account for respiratory dry and evaporative heat loss. Gas mixtures of 17% O_2 and 4% CO_2 (balance nitrogen) were used to calibrate the gas analyzers before each experimental session. A 3-L syringe was also used to calibrate the turbine ventilometer (error of ±3%, typically <1%).

Esophageal (T_{es}) and rectal (T_{re}) temperatures were measured using pediatric thermocouple temperature probes (Mon-a-therm). The esophageal probe was inserted 40 cm past the entrance of the nostril (22), whereas the rectal probe was inserted to a minimum of 12 cm past the anal sphincter. Skin temperature was measured at four locations (i.e., upper back, chest, thigh, and calf) over the right side of the body using 0.3-mm-diameter T-type (copper/constantan) thermocouples (Concept Engineering, Old Saybrook, CT). Mean skin temperature (T_{sk}) was subsequently calculated using the following weighting: 30% upper back, 30% chest, 20% thigh, and 20% leg. All temperature data were collected using a data acquisition module (HP Agilent model 3497A; Agilent Technologies Canada Inc., Mississauga, ON, Canada) at a sampling rate of 15 s and simultaneously displayed and recorded in spreadsheet format on a personal computer with LabVIEW software (version 7.0, National Instruments).

LSR on the right forearm, right upper back, and forehead was measured from 3.8-cm^2 ventilated capsules attached to the skin with adhesive rings and topical skin glue (Collodion HV; Mavidon Medical Products, Lake Worth, FL). Anhydrous compressed nitrogen was passed through each capsule at a known flow rate of $1\ \text{L}\cdot\text{min}^{-1}$. Water content of the effluent air was measured at a sampling rate of 5 s using capacitance hygrometers (Vaisala Inc., Woburn, WA). LSR was calculated using the difference in water content between effluent and influent air multiplied by the flow rate and normalized for the skin surface area under the capsule ($\text{mg}\cdot\text{min}^{-1}\cdot\text{cm}^{-2}$).

Urine specific gravity was assessed using a hand-held total solid refractometer (Reichert TS 400 total solids refractometer, Reichert Inc., Depew, NY) to ensure a similar state of hydration before the start of each water temperature condition.

Data Analysis

Data were collected from two experimental conditions: one condition ingesting 50°C water (hot) and another condition ingesting 1.5°C water (cold). The primary outcome measures included whole-body heat loss (as the sum of whole-body evaporative heat loss and dry heat exchange), the rate of metabolic heat production, and the change in body heat content, calculated as the discrepancy between the amount of heat produced and the amount of heat dissipated. Furthermore, the heat load of the ingested water (H_{fluid}) was included to adjust for the associated heat transfer. Secondary outcome measures included thermometry (T_{es}, T_{re}, and T_{sk}) and LSR data (forearm, upper back, and forehead). Data during the baseline period are averaged over 10 min, whereas values at 5 min before exercise are an average between the first drink and the onset of exercise (i.e., a 5-min average). Thereafter, all values are presented as a 5-min average with the exception of LSR, which was presented at 1-min intervals. H_{fluid} was determined for each ingestion period and was calculated using an equation used previously (1,13):

$$H_{\text{fluid}} = \frac{(T_{\text{fluid}} - T_{\text{re}})(C_{\text{p(fluid)}})(\text{mass}_{\text{fluid}})}{1000}$$

where T_{re} is rectal temperature measured immediately before fluid ingestion (°C), T_{fluid} is the temperature of the water (°C), $C_{\text{p(fluid)}}$ is the specific heat capacity of water ($4.186\ \text{J}\cdot\text{g}^{-1}\cdot{}^{\circ}\text{C}^{-1}$), $\text{mass}_{\text{fluid}}$ is the mass of water consumed (kg) and 1000 is the conversion factor to kJ. Subsequently, the following version of the human heat balance equation was used to determine the change in body heat content:

$$\Delta H_{\text{b}} = \frac{\int (\text{M-W}) \pm H_{\text{D}} - H_{\text{E}}}{1000} + H_{\text{fluid}}$$

where ΔH_{b} is the amount of stored heat, M-W is the amount of metabolic heat produced, and H_{D} (dry heat exchange) and H_{E} (evaporative heat loss) sum to yield of total heat loss (H_{L}). ΔH_{b} was calculated over the 75-min exercise as well as for each 15-min interval during exercise. Thermometry data were reported immediately before each drink and during the last minute of exercise. The change in T_{es}, T_{re}, and T_{sk} was calculated as the difference at the end of exercise from baseline. Mean LSR was reported as the average of the sweat rates obtained from the forearm, back, and forehead. All data are reported as mean ± SD.

Statistical Analysis

Statistical analyses were completed using SPSS version 21.0 for Windows (IBM, Armonk, NY). A two-way repeated-measures ANOVA with factors of time (sixteen levels: min 0, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75 of exercise) and condition (two levels: hot and cold) was used to analyze the rate of evaporative heat loss, dry heat exchange, total heat loss, and metabolic heat production. A two-way repeated-measures ANOVA was also conducted for the amount of heat stored using the factors of time (five levels: 0–15, 15–30, 30–45, 45–60, and 60–75 min) and condition (two levels). Forearm, upper back, forehead, and mean LSR data ($n = 9$) were analyzed using a two-way repeated-measures ANOVA with factors of time (five levels: average of 9–15, 17–23, 32–38, 47–53, and 69–75 min as done previously (23)) and condition (two levels). When a significant main effect was found, *post hoc* comparisons were assessed using Student's paired *t*-tests while maintaining a fixed probability (alpha level of 5%) of making a type I error by using a Holm–Bonferroni correction for multiple comparisons. Additionally, paired sample *t*-tests were performed to evaluate differences in body heat storage and the separate cumulative change values for metabolic heat production, total heat loss, evaporative heat loss, dry heat exchange, H_{fluid}, water volume ingested, and environmental conditions.

RESULTS

Experimental Sessions

There were no differences in ambient temperature ($P = 0.728$) or relative humidity ($P = 0.734$) between the hot (25.9°C ± 0.9°C, 24% ± 8%) and cold (25.9°C ± 1.0°C, 25% ± 11%) conditions. Participants were similarly euhydrated as indicated by urine specific gravity at the commencement of the hot (1.012 ± 0.007) and cold (1.010 ± 0.005) experimental sessions and ingested a similar volume of water during both the hot (1014 ± 174 mL) and cold (1010 ± 182 mL) conditions ($P = 0.407$). The rates of metabolic heat production and relative intensity were similar between the hot and cold conditions such that participants cycled at an average rate of 524 ± 86 and 523 ± 87 W ($P = 0.654$) or an equivalent exercise intensity of 50% ± 1% and 49% ± 1% of the individuals' predetermined $\dot{V}O_{2\text{peak}}$ ($P = 0.589$), respectively.

Direct Calorimetry

There was an interaction between condition and time for H_L ($P < 0.001$). Specifically, H_L under the hot condition was greater than that of the cold condition from 0 to 70 min of exercise (all $P < 0.024$, Fig. 1). Furthermore, this difference in H_L between conditions was primarily due to an interaction between condition and time for H_E ($P < 0.001$) from 10 to 65 min of exercise as no main effect of condition was detected for H_D ($P = 0.213$). As mentioned above, the rate of metabolic heat production was similar between conditions and this resulted in a similar amount of heat produced over the 75-min exercise bout (Table 1, $P = 0.743$). Furthermore, the cumulative amount of H_L was significantly greater under the hot condition compared with that under the cold condition ($P < 0.001$), which was due to a greater cumulative H_E ($P = 0.001$), whereas no differences were detected for H_D ($P = 0.220$) (Table 1). In addition, the absolute difference in the H_L (209 ± 81 kJ) between the hot and cold conditions was similar to that of H_{fluid} (204 ± 36 kJ) ($P = 0.785$), ultimately leading to a similar ΔH_b between conditions ($P = 0.971$, Fig. 2). Furthermore, the time-dependant change in

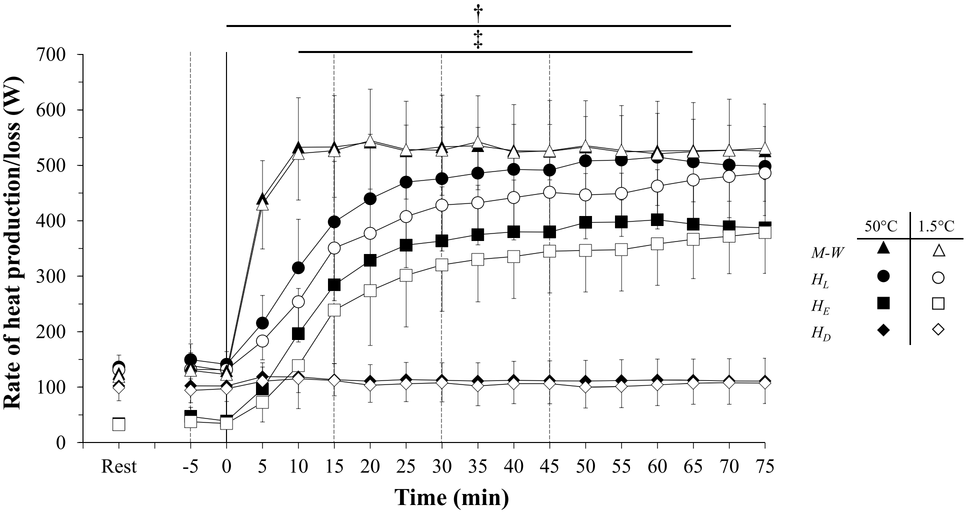

FIGURE 1—Rate of metabolic heat production (M-W, *triangles*), total heat loss (H_L, *circles*), evaporative heat loss (H_E, *squares*), and dry heat exchange (H_D, *diamonds*) unadjusted for the heat content of ingested water at rest and during 75 min of exercise at 50% $\dot{V}O_{2\text{peak}}$ in a thermocomfortable environment with periodic ingestion of hot (50°C, *filled shapes*) and cold (1.5°C, *open shapes*) water. Time of water ingestion indicated by *dashed line*. *Solid black line* marks the start of exercise. Values are mean ± SD; 50°C upward bars, 1.5°C downward bars. †H_L significantly different between conditions. ‡H_E significantly different between conditions (all $P < 0.05$).

TABLE 1. Cumulative values for components of the human heat balance equation measured using direct calorimetry after 75 min of exercise at 50% $\dot{V}O_{2peak}$ under thermocomfortable conditions with the periodic ingestion of 50°C and 1.5°C water.

	50°C	1.5°C
M-W	2357 ± 387 kJ	2351 ± 391 kJ
H_E	1538 ± 393 kJ*	1358 ± 330 kJ
H_D	508 ± 147 kJ	479 ± 149 kJ
H_L	2046 ± 364 kJ*	1838 ± 329 kJ
H_{fluid}	−54 ± 10 kJ*	150 ± 27 kJ
ΔH_b	364 ± 152 kJ	363 ± 134 kJ

M-W, metabolic heat production; H_E, evaporative heat loss; H_D, dry heat exchange; H_L, total heat loss; H_{fluid}, heat transfer from the ingested water to the body; ΔH_b, change in body heat content (adjusted for H_{fluid}).

*Significant difference between the 50°C and 1.5°C conditions, $P \leq 0.05$.

ΔH_b expressed every 15 min was not different between conditions (Table 2, $P = 0.960$).

Thermometry

There was a main effect of time for T_{es}, T_{re}, and T_{sk} (all $P < 0.001$) such that all temperatures increased throughout exercise from baseline values. However, T_{es}, T_{re}, and T_{sk} were not different as a function of condition (Table 3, all $P > 0.05$).

Local Sweat Rate

There was an interaction between condition and time for all measurement sites and mean LSR ($P < 0.004$). Specifically, mean LSR was elevated during the hot condition when the water was ingested at 15, 30, and 45 min of exercise compared with the cold condition (all $P \leq 0.007$). Similarly, forearm LSR was found to be increased at 15, 30, and 45 min of exercise in the hot relative to the cold condition (all $P \leq 0.030$). Finally, upper back LSR was found to be different at 45 min only ($P = 0.037$), whereas forehead LSR was found not to be different between conditions throughout the exercise period (all $P > 0.05$).

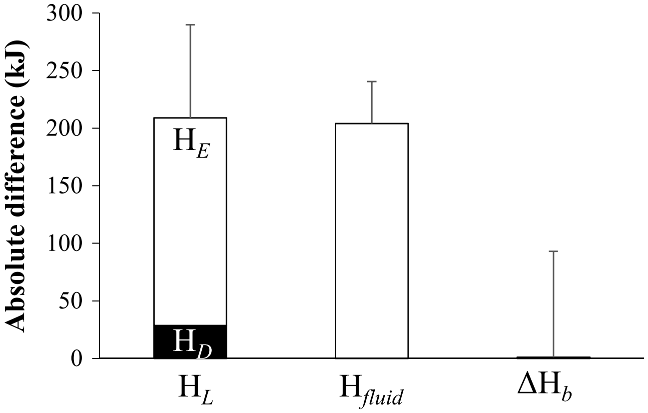

FIGURE 2—Comparison of the absolute difference in total heat loss (H_L), heat of water ingested (H_{fluid}), and the change in body heat content (ΔH_b) between 50°C and 1.5°C water during 75 min of exercise at 50% $\dot{V}O_{2peak}$ in a thermocomfortable environment. Values were calculated as the cumulative sum in the hot condition minus the cumulative sum in the cold condition (for H_E, H_D, H_{fluid}, and ΔH_b). The contributions of evaporative heat loss (H_E) and dry heat exchange (H_D) are included within the H_L column. Columns are given in mean ± SD. No differences were detected between H_L and H_{fluid}.

DISCUSSION

We used direct whole-body calorimetry to evaluate whether the periodic ingestion of either hot (50°C) or cold (1.5°C) water while exercising in a thermocomfortable environment would alter whole-body heat loss and thereby influence the amount of heat stored in the body during 75 min of exercise. Consistent with our hypothesis, we show that whole-body heat loss was greater when ingesting hot water compared with consuming cold water. However, when adjusting for the heat of the ingested water, the change in body heat content was similar between conditions. Our findings suggest that adjustments in whole-body heat loss occur to compensate for the heat content of the ingested water. Therefore, we show that the temperature of ingested water during moderate-intensity exercise does not influence whole-body heat storage during exercise performed under compensable conditions.

Previous studies having examined the effect of drink temperature on body heat storage during prolonged exercise have often reported conflicting observations. For instance, Lee et al. (19) reported a similar amount of heat stored after the ingestion of 10°C and 50°C of water. However, Bain et al. (1) recently reported a reduction in body heat storage after the ingestion of 50°C water compared with 1.5°C water. Specifically, the authors reported an increase in whole-body heat loss (due solely to the increase in evaporative heat loss as the rate of dry heat exchange was unchanged) during hot compared with cold water ingestion. It was surmised that the resultant decrease in body heat storage during the consumption of hot water was due to a disproportionately greater reflex adjustment in evaporative heat loss brought about by the ingestion of the hot water (1). In the present study, we reported a greater level of evaporative heat loss during 10 to 65 min of the exercise bout, which is consistent with the notion that hot and cold water can increase and decrease heat dissipation, respectively (Fig. 1). Importantly, our observations were found despite similar esophageal, rectal, and mean skin temperatures between conditions throughout the exercise bout, thereby likely implicating that thermal afferents from other sources may have a role in this response. In fact, it was recently postulated by Morris et al. (23) that the reflex change in heat loss to hot and cold water ingestion is mediated by abdominal thermoreceptors. However, whereas previous studies have indicated that hot and cold water ingestion induces a transient reflex response to changes in heat loss (1,23), we found no reflex increase in evaporative heat loss at the time of fluid ingestion that would amount to a reduction in body heat storage. Rather, we observed a steady and consistent separation in whole-body evaporative heat loss between

TABLE 2. Change in body heat content adjusted for the heat of the ingested water (hot, 50°C; and cold, 1.5°C) every 15 min during 75 min of exercise at 50% $\dot{V}O_{2peak}$ in a thermocomfortable environment.

	0–15 min	15–30 min	30–45 min	45–60 min	60–75 min[a]
50°C	187 ± 44 kJ	78 ± 42 kJ	49 ± 31 kJ	28 ± 30 kJ	23 ± 26 kJ
1.5°C	170 ± 30 kJ	79 ± 40 kJ	42 ± 27 kJ	30 ± 31 kJ	43 ± 32 kJ

[a] No water was ingested during this interval. No differences were found at any time point.

TABLE 3. Esophageal (T_{es}), rectal (T_{re}), and mean skin (T_{sk}) temperatures during baseline (10 min average) and before each drink as well as during the final minutes of exercise (End-Ex) at 50% $\dot{V}O_{2peak}$ for the periodic ingestion of 50°C and 1.5°C water.

			Drink 1	Drink 2	Drink 3	Drink 4	End-Ex	
		Rest (°C)	−5 min (°C)	15 min (°C)	30 min (°C)	45 min (°C)	75 min (°C)	ΔT (°C)
50°C	T_{es}	37.07 ± 0.26	37.03 ± 0.27	37.58 ± 0.34	37.68 ± 0.37	37.75 ± 0.32	37.70 ± 0.32	0.63 ± 0.26
	T_{re}	37.16 ± 0.24	37.16 ± 0.27	37.34 ± 0.29	37.64 ± 0.31	37.79 ± 0.34	37.91 ± 0.33	0.76 ± 0.26
	T_{sk}	32.75 ± 0.69	32.78 ± 0.72	33.19 ± 0.73	33.78 ± 0.67	33.87 ± 0.76	33.77 ± 0.74	0.87 ± 0.86
1.5°C	T_{es}	37.00 ± 0.30	36.99 ± 0.27	37.37 ± 0.42	37.51 ± 0.47	37.57 ± 0.42	37.56 ± 0.46	0.56 ± 0.34
	T_{re}	37.14 ± 0.25	37.14 ± 0.21	37.23 ± 0.26	37.61 ± 0.27	37.79 ± 0.31	37.95 ± 0.34	0.80 ± 0.35
	T_{sk}	32.67 ± 0.74	32.72 ± 0.88	32.90 ± 0.91	33.45 ± 0.76	33.69 ± 0.50	33.78 ± 0.50	0.96 ± 0.79

Change in temperature from start to end of exercise (ΔT) is included for T_{es}, T_{re}, and T_{sk}.
No differences were found at any time point.

conditions (Fig. 1). However, both Morris et al. (23) and Takamata et al. (35) noted that the act of drinking and swallowing itself does not alter thermoeffector response in euhydrated individuals. Therefore, the whole-body modulation of evaporative heat loss observed in the present study is likely only mediated by the abdominal thermoreceptors when stimulated by the heat content of the ingested water. Moreover, our findings are consistent with a recent study by Gagnon et al. (7), which demonstrated that the rate of evaporative heat loss during steady-state exercise is dependent primarily (>90%) on the rate required to offset the exercise (and/or environmental)-induced heat load and achieve heat balance. We show that the heat load associated with the ingested water also defines the rate of evaporative heat loss required for heat balance.

As mentioned above, hot water ingestion has previously been associated with a reduction in body heat storage (1), albeit this response is not consistent across studies (19,20). Similar to the study by Bain et al. (1), we observed marked differences in total heat loss (achieved by adjustments in evaporative heat loss) during hot and cold water ingestion. However, the difference in total heat loss between conditions amounted to ~209 kJ and the difference between the heat of the ingested water was ~204 kJ. Therefore, when we accounted for the heat of the ingested water in the present study, we found similar levels of body heat storage during the hot (~364 kJ) and cold (~363 kJ) water conditions. This is in contrast to reports by Bain et al. (1) as we show that the adjustments in evaporative heat loss during exercise were made only to compensate for the heat of the ingested water. Specifically, the difference in evaporative heat loss between conditions in the current study accounted for ~90% of the heat from the ingested water, whereas Bain et al. (1) reported

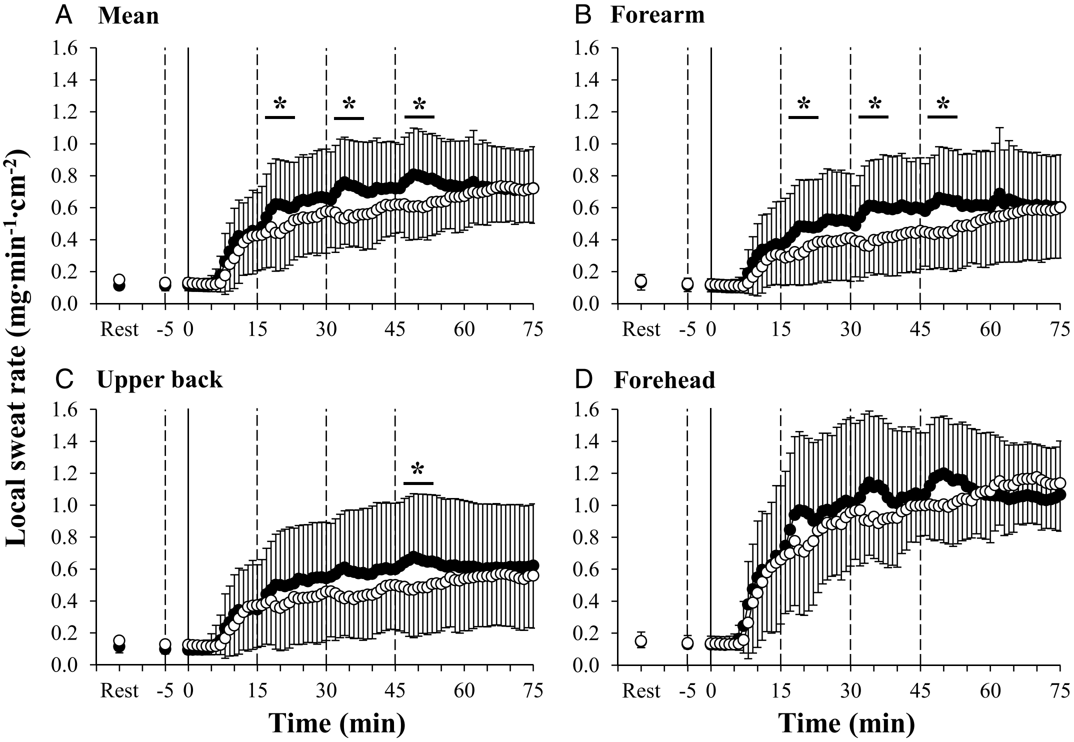

FIGURE 3—Mean (panel A) of forearm, upper back, and forehead as well as each individual LSR site (panels B, C, and D, respectively) at rest and during 75 min of exercise at 50% $\dot{V}O_{2peak}$ in a thermocomfortable environment with the periodic ingestion of hot (50°C, *filled shapes*) and cold (1.5°C, *open* shapes) water. Time of water ingestion indicated by a *dashed line*. *Solid black line* marks the start of exercise. Values are presented as mean ± SD; 50°C upward bars, 1.5°C downward bars. *Significantly different between conditions (P < 0.05).

a disproportionately greater increase in heat loss of ~141%. These conflicting results occurred despite also performing 75 min of exercise at the same relative intensity under comparable environmental conditions. Moreover, their participants also ingested similar volumes of water (3.2 $\text{mL}\cdot\text{kg}^{-1}$). Taken together, this disparity suggests that differences in body heat storage measured between studies may be the result of the methodological approach used to quantify evaporative heat loss. Specifically, Bain et al. (1) estimated evaporative heat loss by partitional calorimetry, whereas we quantified whole-body evaporative heat loss using direct calorimetry. The former requires certain assumptions in the calculation of heat loss, whereas a whole-body direct calorimeter provides an accurate measurement of the heat emitted by the human body (13).

In addition to our measurements of whole-body heat loss, we also evaluated LSR at the mid-anterior forearm, upper back, and forehead to determine whether the whole-body response was paralleled by regional differences in local sweating. Our mean LSR response is consistent with a recent study (23) showing a transient increase and decrease when ingesting 50°C and 1.5°C water periodically during exercise, respectively (Fig. 3). However, these transient reflex changes in local sweating were not paralleled by whole-body evaporative heat loss. Rather, we observed a steady separation between heat loss in the two conditions. Although reasons for these conflicting results are unclear, it has been previously observed that whole-body evaporative heat loss does not always parallel changes in LSR (16,33) and vice versa. Furthermore, we observed regional variations in the local sweating response as a function of the temperature of the ingested water at the three skin sites. The forearm skin site in our study exhibited a reflex response to hot and cold water ingestion at each drink during exercise which was consistent with observations by Morris et al. (23). However, although a similar local sweating response was previously shown at multiple skin sites (i.e., at the forearm, upper back, and forehead (19)), we observed regional variations such that a separation in LSR immediately followed the final drink at the upper back, with no differences in local sweating at the forehead skin site (Fig. 3). It is unclear why our findings contradict those of Morris et al. (23); however, local sweating responses can vary depending on the site of measurement from a variety of factors (i.e., the sensitivity of the measurement site, and the output and the density of sweat glands for a given level of heat stress (15)). Additionally, regional variations between individuals and between skin sites are typically observed in humans (11,15,25,36,38).

Considerations. The present study was conducted in thermocomfortable conditions at a moderate exercise intensity. However, it is unknown if our findings would extend to a greater heat load induced by exercise of greater intensity alone or in combination with hotter ambient conditions (i.e., ≥35°C). Additionally, it is unknown whether modulations in local and whole-body heat loss would parallel the observations in the present study with exercise performed under uncompensable conditions (i.e., increased ambient humidity and/or when clothing is worn). Furthermore, our results are specific to young males and our findings may not necessarily be replicated in populations that have a reduced capacity to dissipate heat as has been shown with females (8), older individuals (17,18), and individuals with chronic health disorders such as type 1 and 2 diabetes (3,14).

The ingestion of ice slurries before exercise has been suggested to improve endurance performance secondary to increasing the body's capacity to store heat (i.e., from the heat required to transform ice to water) compared with cold water (31,32). However, we speculate that the findings of the present study apply regardless of the medium (liquid or ice) ingested such that an ice slurry ingestion would not decrease body heat storage during exercise relative to the ingestion of cold (or hot) water. Further work is required to determine whether the increases in endurance performance associated with cold water and/or ice slurry ingestion are a result of a reduction in body heat storage, behavioral factors, or a combination of both.

Perspectives. Given the continued and growing commercial and scientific interest into the importance of hydration as it relates to the performance of athletic and occupational activities (27,29) in various population groups, advancing our understanding of the effect of drink temperature may have on the body's physiological capacity to dissipate heat during exercise is of importance. Currently, the few published studies are inconclusive and do not yet warrant feasible recommendations concerning an optimal drink temperature to consume during exercise from a thermoregulatory perspective. In any case, although our findings indicate that the temperature of ingested water during exercise does influence whole-body heat loss, it does not affect the amount of heat stored. Importantly, the benefits of adequate hydration during exercise cannot be discounted (9,27–30), nor can behavioral aspects in regard to the palatability of ingesting water of different temperatures (34). With respect to the latter, Szlyk et al. (34) found that individuals ingested 37% more water and lost ~33% less weight during 6 h of treadmill walking when offered cool (15°C) versus warm (40°C) water *ad libitum*. Taking our results together with other studies indicating that colder fluids are more beneficial to *ad libitum* hydration (24,34) and increasing time to exhaustion (2,10,21,24), we recommend athletes periodically consume water at a colder (<15°C) temperature during physical activity as opportunities allow.

In summary, the change in whole-body heat content was similar after periodically ingesting 50°C and 1.5°C water after 75 min of exercise in a thermocomfortable environment. This stemmed from a compensatory adjustment in whole-body heat loss to the heat content of the ingested fluid such that heat loss was greater under the hot condition compared with the cold condition. Importantly, this difference in heat loss was explained by modulations in evaporative heat loss as no differences in dry heat exchange were observed. Moreover, mean LSR displayed transient reflex responses to ingestion of hot and cold water (albeit regional variations in the response were observed), which is not consistent with our observation of a steady separation in whole-body heat loss observed during much of the exercise bout (i.e., 0 to 70 min of the 75-min exercise period).

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