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PRIORITY REPORT

Ad libitum drinking prevents dehydration during physical work in the heat when adhering to occupational heat stress recommendations

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ABSTRACT

Government entities issue recommendations that aim to maintain core temperature below 38.0°C and prevent dehydration [>2% body mass loss] in unacclimated workers exposed to heat. Hydration recommendations suggest drinking 237 mL of a cool sport drink every 15–20 min. This is based on the premise that *ad libitum* drinking results in dehydration due to inadequate fluid replacement, but this has never been examined in the background of recommendation compliant work in the heat. Therefore, we tested the hypothesis that *ad libitum* drinking results in >2% body mass loss during heat stress recommendation compliant work. Ten subjects completed four trials consisting of 4 hours of exposure to wet bulb globe temperatures (WBGT) of 24.1 ± 0.3°C (A), 26.6 ± 0.2°C (B), 28.5 ± 0.2°C (C), 29.3 ± 0.6°C (D). Subjects walked on a treadmill and work-rest ratios were prescribed as a function of WBGT [work:rest per hour – A: 60:0, B: 45:15, C: 30:30, D: 15:45] and were provided 237 mL of a cool sport drink every 15 min to drink *ad libitum*. Mean core temperature was higher in Trial A (37.8 ± 0.4°C; $p = 0.03$) and Trial B (37.6 ± 0.3°C; $p = 0.01$) versus Trial D (37.3 ± 0.3°C) but did not differ between the other trials ($p \geq 0.20$). Body mass loss (A: −0.9 ± 0.7%, B: −0.7 ± 0.5%, C: −0.3 ± 0.5%, D: −0.4 ± 0.6%) was greater in Trial A compared to Trial D ($p = 0.04$) and was different from 2% body mass loss in all trials ($p \leq 0.01$). *Ad libitum* drinking during recommendation compliant work in the heat rarely resulted in dehydration. Registered Clinical Trial (NCT04767347)

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Occupational heat stress; hydration; dehydration; hypohydration; heat strain; hyperthermia; recommendations

Introduction

Heat stress is a physical hazard frequently experienced in the workplace under conditions of high ambient temperatures and/or humidity, which is compounded by clothing, personal protective equipment, and increased metabolic heat production (e.g. physical work) [1]. Excessive heat stress and subsequent elevations in core body temperature can increase the risk of heat-related illness [1], elevate the risk of workplace accidents [2,3], reduce productivity [4,5], and stimulate long-term adverse health outcomes [6,7].

Federal and non-federal entities (e.g. National Institute for Occupational Safety and Health [NIOSH], American Conference of Governmental Industrial Hygienists) and health organizations (e.g. World Health Organization) issue guidance and recommendations stipulating the exposure limits for heat stress [8]. For example, the NIOSH heat stress recommendations aim to maintain average core body temperature over an 8-hour day to within thresholds set by World Health Organization (i.e. ≤38.0°C in unacclimatized & ≤38.5°C in acclimatized workers). These heat stress recommendations prescribe work-rest ratios based on the function of environmental factors (wet-bulb globe temperature [WBGT]) and metabolic heat production (an average of estimated work intensity) [8]. Indeed, field data have shown that these guidelines have a high sensitivity for the prediction of both fatal and non-fatal heat-related illnesses [9]. That said, the deleterious effects of occupational heat stress frequently persist [10,11], likely due to poor implementation and/or adherence to heat stress recommendations [11–13].

Occupational heat stress can be exacerbated by pre-workday dehydration or the development of dehydration (i.e. loss in body water) throughout the workday [4], which reduces a worker's capacity for evaporative heat loss (i.e. sweating) [14,15] and the ability to maintain a relatively constant core

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body temperature across the workday. Therefore, hydration recommendations are issued for workers exposed to heat stress to prevent dehydration (defined as ≥2% body mass loss [16]). For instance, NIOSH recommends drinking 237 mL (1 cup) of a cool sport drink every 15 to 20 minutes during work in the heat that exceeds 2 hours [8]. This drinking regimen is based on the premise that *ad libitum* drinking (or "drinking to thirst") typically results in progressive dehydration due to inadequate drinking [17], particularly during long-duration work and/or heat stress [14,16–19]. However, to our knowledge, this hydration recommendation has not been directly examined in the background of compliance to the heat stress recommendations that, theoretically, are being practiced in the healthy workplace. Therefore, the purpose of the present study was to test the hypothesis that *ad libitum* drinking during heat stress recommendation compliant work in the heat will result in >2% body mass loss.

Methods

The study was approved by the Institutional Review Board at Indiana University (IRB# 1,902,420,140). The study conformed to the Declaration of Helsinki. Before participating in any study-related activities, each subject was fully informed of the experimental procedures and possible risks before providing informed written consent. The data presented herein are a sub-analysis to test a unique hypothesis within a larger, registered clinical trial (NCT04767347).

Ten healthy subjects (4 female; age: 27 y [range: 21, 38], body mass index: 25 kg•m^{-2} [range: 18, 29], body surface area: 1.9 m^{2} [range: 1.7, 2.2]) participated in the study. All subjects self-reported to be nonsmokers and not taking medications known to affect the cardiovascular, metabolic, neurological, or renal systems. Additionally, subjects were free of any known cardiovascular, metabolic, neurological, or renal diseases, were not heat acclimated, and self-reported to regularly engage in physical activity. Females were not pregnant as confirmed through a urine pregnancy test prior to each visit, self-reported to be normally menstruating, and had no diagnosis of a menstrual cycle-specific disorder. To maintain external validity, females were tested at any point during their menstrual cycle because in real-world settings, females work across their entire menstrual cycle.

Subjects visited the laboratory on five occasions separated by at least 7 d to minimize any potential carryover effects and prevent heat acclimation. The first visit involved screening and exercise testing, and visits two through five were experimental trials. During visit one, subjects completed demographic, health, and physical activity screening questionnaires (e.g. physical activity readiness questionnaire, international physical activity questionnaire) and had anthropometric measurements (i.e. height and weight) taken. Following screening, subjects completed an exercise test on a motorized treadmill to determine the treadmill parameters (i.e. treadmill speed [km•h^{-1}], grade [%]) that elicited a target metabolic heat production of approximately 430 W, which is the average metabolic heat production for activities commonly completed by outdoor workers in the United States (e.g. shoveling, raking, walking, etc.) according to the Compendium of Physical Activities [20]. These treadmill parameters (treadmill speed: 5.0 km•h^{-1} [range: 4.8, 5.6]; treadmill grade: 4.0% [range: 0.5, 6.0]) were used during the treadmill walking portion of the subsequent four experimental trials. The four experimental trials consisted of 4 hours (half a workday) of exposure to WBGTs of 24.1 ± 0.3°C (Trial A), 26.6 ± 0.2°C (Trial B), 28.4 ± 0.2°C (Trial C), 29.7 ± 1.6°C (Trial D) (see *Results* for additional details on environmental conditions). Subjects walked on a treadmill evoking an average rate of metabolic heat production of 448 ± 108 W (Trial A), 466 ± 94 W (Trial B), 475 ± 90 W (Trial C), and 465 ± 108 W (Trial D) and was not different between trials ($p = 0.7411$). It is important to note that the average metabolic heat production exceeded our desired target of ~430 W due to the exercise mode (i.e. treadmill walking), which did not permit sensitive enough adjustments in external workload (± 0.5% grade) and the prolonged duration of the protocol that caused drift over time. NIOSH-compliant work-rest ratios were prescribed as a function of WBGT and absolute metabolic heat production (work:rest per hour [in min] – Trial A: 60:0, Trial B: 45:15, Trial C:

30:30, and Trial D: 15:45; Figure 1a). Notably, we did not scale the rate of metabolic heat production to body surface area to prescribe these work-to-rest ratios. This was by design given that the tasks in the workplace are not scaled to body surface area. Thus, the absolute rate of metabolic heat production was determined from a standard body surface area of 1.8 m^2, which is consistent with the NIOSH recommendations [8]. The experimental trials were completed in a block-randomized order and subjects were blinded to the environmental conditions (i.e. ambient temperature and humidity). All experimental trials were completed throughout the calendar year (June 2021 – March 2022) in Bloomington, IN, a climate that has been shown to induce minimal heat acclimatization [21].

The experimental protocol timeline is presented in Figure 1b. All experimental trials commenced in the morning (between 0800 and 0900 hours) and took place at the same time of day to control for circadian effects. Subjects avoided exercise, alcohol, and caffeine for at least 12 hours prior to arrival at the laboratory, and all subjects were instructed to eat a light breakfast approximately 2 hours before arriving. Upon arrival, subjects provided a urine sample by completely voiding their bladder in a collection urinal. Euhydration, defined as a urine-specific gravity (USG) ≤1.020 [18], which was confirmed (A: 1.016 ± 0.008; B: 1.017 ± 0.008; C: 1.017 ± 0.008; and D: 1.014 ± 0.008; $p = 0.5355$). Following urine collection subjects weighed nude and then drank a bolus of cool tap water (0.5% body mass [381 ± 61 mL]) to ensure that subjects started similarly euhydrated. Subjects then rested supine for ~60 minutes in a temperate thermal environment (dry bulb temperature: ~22°C; relative humidity ~50%).

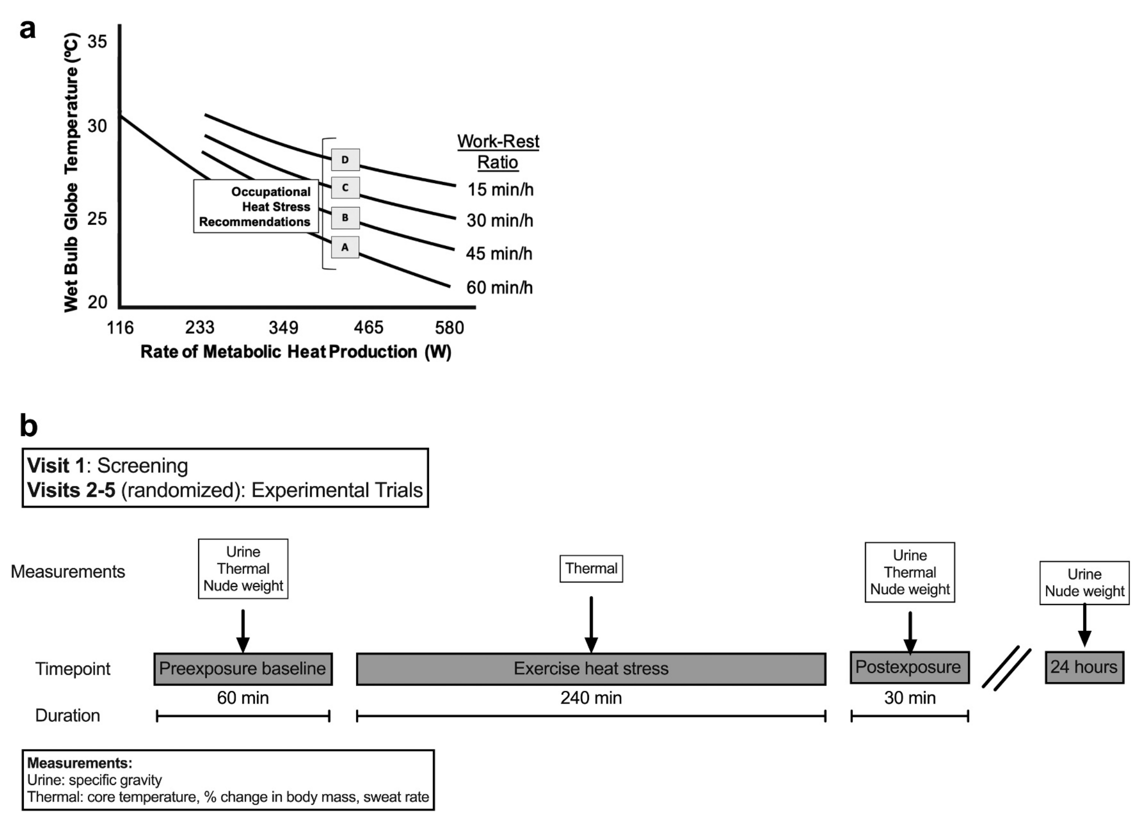

Figure 1. A) Study design and experimental trials based on the National Institute of Occupational Safety and Health [NIOSH] heat stress recommendations. Subjects walked on a treadmill at NIOSH-compliant work-rest ratios that were prescribed as a function of wet-bulb globe temperature [WBGT] and metabolic heat production [work:rest per hour (in min) – A: 60:0, B: 45:15, C: 30:30, D: 15:45]. Modified from Jacklitsch et al. [8]. B) Schematic of study protocol. In a block-randomized crossover design, subjects completed four experimental trials (*Visits* 2–5) consisting of 4 hours (half a workday) of exposure to WBGTs of 24.1 ± 0.3°C (a), 26.6 ± 0.2°C (b), 28.5 ± 0.2°C (c), and 29.8 ± 1.7°C (d). Subjects were provided 237 mL of a cool (9.2 ± 4.0°C) flavor preferred sport drink (Gatorade) every 15 min and drank *ad libitum*. Measurements were taken preexposure, immediately postexposure, and 24 hours following the exposure.

Table 1. Indexes of hydration measured preexposure, immediately postexposure, and 24 hours following the start of the exposure.

Variable	Timepoint			Mixed-Effects Model		
Trial	Pre-	Post-	24 hours	Time	Trial	Time x Trial
Body Mass, kg				0.0055	0.8535	0.2660
Trial A	77.5 ± 13.4	76.8 ± 13.4[P]	79.0 ± 12.6			
Trial B	77.2 ± 13.3	76.7 ± 13.2[P]	77.1 ± 14.1			
Trial C	77.2 ± 13.5	77.0 ± 13.1	76.7 ± 13.4[P]			
Trial D	77.7 ± 13.1	77.5 ± 13.2	77.5 ± 13.3			
Δ Body Mass, %				0.0020	0.3920	0.1912
Trial A	-	−0.9 ± 0.7[P]	−0.5 ± 0.5			
Trial B	-	−0.7 ± 0.5[P]	−0.6 ± 0.9			
Trial C	-	−0.3 ± 0.5	−0.7 ± 0.6[P]			
Trial D	-	−0.4 ± 0.6	−0.4 ± 0.9			
Urine specific gravity				0.0030	0.2137	0.5478
Trial A	1.006 ± 0.005	1.014 ± 0.009	1.015 ± 0.009[P]			
Trial B	1.008 ± 0.007	1.013 ± 0.006	1.015 ± 0.007			
Trial C	1.007 ± 0.005	1.011 ± 0.007	1.018 ± 0.008[P]			
Trial D	1.005 ± 0.004	1.010 ± 0.006	1.012 ± 0.009[P]			

Data are presented as an absolute mean ± SD (body mass and urine specific gravity) or as a change from preexposure (Δ body mass). n= 10 except for 24 hours in Trial A (n= 9). Data were analyzed using a repeated measures mixed-effects model (time X trial) and exact p-values reported. If a significant interaction or main effect was found, *post hoc* analyses were completed using Šídák's multiple comparisons tests. P indicates different from preexposure ($p < 0.05$).

During this rest period, baseline vital signs were measured. After 60 minutes, subjects voided their bladder in a separate collection urinal to measure preexposure USG (*Table 1*). After this preexposure urine sample, subjects weighed nude and then donned a standard uniform of long pants and shirt, a short sleeve cotton t-shirt, and athletic shoes. The estimated insulation of the clothing ensemble was 0.87 clo [22].

Subjects then entered the temperature and humidity controlled environmental chamber and the 4-hour exposure commenced. Compliant with the NIOSH guidelines, subjects were provided 237 mL of a cool (9.2 ± 4.0°C) flavor preferred sport drink (i.e. Gatorade) every 15 minutes and were permitted to drink *ad libitum*. Subjects were instructed that they were allowed to drink as much (or as little) as they would like of the 237 mL available during each 15-mintue time period. The fluid was placed within arm's reach and adjacent to the treadmill or chair (during rest periods) for immediate access. The temperature and volume of fluid consumed every 15 minutes was recorded. Total volume (L) of fluid consumed was calculated across each 4-hour exposure and presented as absolute and as a percentage of potential total volume (i.e. total volume consumed divided by 3.55 L multiplied by 100). During rest periods, subjects remained seated on a mesh chair except for a clothed body weight measurement or to urinate, which was permitted as needed. Subjects were not allowed to eat at any time during the experimental trials.

Following the 4-hour exposure, subjects returned to the patient exam room, weighed nude and completely voided their bladder in a urine collection container. Finally, approximately 24 hours following the start of the exposure, subjects returned to the laboratory for a follow-up visit. During this overnight period, subjects were permitted to eat and drink fluids *ad libitum* (except for caffeine and alcohol) and were asked to replicate this diet and fluid intake on each visit. Upon arrival back at the laboratory subjects completely voided their bladder in a urine collection container and then were weighed nude to provide an index of hydration status.

Dry bulb temperature and relative humidity were measured (Kestrel 3000 Weather Meter, Kestrel Instruments, Boothwyn, PA) within ~1 m of the subject every 15 minutes throughout the exposure and are presented as mean ± SD across each 4-hour trial. Height was measured with a custom stadiometer and body mass measured with a scale (Scale-Tronics 5201, Welch-Allyn, Chicago, IL). Nude body mass was measured pre- and postexposure as indicated above, and clothed body weight was measured preexposure and every hour during each exposure to provide an estimate of changes in hydration status during the exposure.

Core temperature was measured via telemetry pill that subjects swallowed ~6–8 hours before each experimental trial (HQ Inc., Palmetto, FL) (*n*= 8). The timing of ingestion was chosen to ensure that the temperature pill was within the gastrointestinal tract throughout the entire duration of each experimental trial and remained unaffected by ingestion of cool fluids. If subjects were contraindicated to taking the telemetry pill (e.g. history of gastrointestinal disease or surgery), core temperature was measured via a self-inserted rectal temperature probe inserted ~10 cm beyond the sphincter (*n*= 2).

Heart rate was measured using a heart rate monitor (Polar T31, Polar Electro Inc., NY) and reported as a mean across the 4-hour exposure in each trial. The rates of oxygen uptake and carbon dioxide production were measured using indirect calorimetry over a 5-minute period before and during the first 5 minutes of treadmill walking in each hour during each experimental trial. These data were collected via a metabolic cart (ParvoMedics, Provo, UT).

Urine samples were collected pre- and postexposure, and 24 hours postexposure during each experimental trial. Urine samples were collected by subjects completely voiding their bladder into a collection urinal. USG was measured in duplicate using a refractometer (ATAGO CO., LTD, Tokyo, Japan).

Ambient water vapor pressure [23] and wet bulb temperature [24] were calculated from dry bulb temperature and relative humidity. Wet bulb globe temperature was estimated during exposure using standard equations. Body surface area was calculated from height and weight [25]. Percentage changes in nude body mass provided an accurate measure of body fluid losses [16] and average hourly sweat rate, after correction for fluid consumption and urine loss. The rate of metabolic heat production was calculated from oxygen uptake and the respiratory exchange ratio measured via indirect calorimetry [26].

Data are presented as individual values, absolute mean ± SD and/or as a percentage change from preexposure, except for percentage time with core temperature above 38°C, which is reported as median (interquartile range). The primary outcome (i.e. percentage body mass change from pre- to postexposure) was analyzed two ways: 1) using a one-sample *t test* to compare the change in body mass (%) against a hypothetical mean (i.e. −2% change in body mass), which provided a direct test of our hypothesis that *ad libitum* drinking would result in dehydration, and 2) as a repeated measures, mixed effects model to examine differences between experimental trials. Core temperature presented over time (Figure 2a), body mass (absolute), body mass change (%), and USG (*Table 1*) were analyzed with a repeated measures mixed-effects model (time x trial). Notably, the mixed-effects model can accommodate any missing values (indicated in figure legends). This occurred on occasion and is noted in the results. When applicable, the Geisser-Greenhouse correction was applied if sphericity could not be assumed. If a significant interaction or main effect was found [27], *post hoc* analyses were completed using Šídák's multiple comparisons tests. Mean and peak core temperature, total fluid consumption, percentage of potential fluid volume consumed, sweat rate, and all perceptions were analyzed using a repeated measures mixed-effects model one-way ANOVA. If a significant effect was found, *post hoc* analyses were completed using Šídák's multiple comparisons tests. Finally, percentage time with core temperature above 38°C was analyzed using nonparametric, Friedman's test. All data were analyzed using GraphPad Prism software (version 8, La Jolla, CA). Statistical significance was set *a priori* at $p \leq 0.05$, and actual p-values are reported where possible.

Results

Dry bulb temperature (Trial A: 29.9 ± 0.3°C; Trial B: 31.8 ± 0.3°C; Trial C: 33.8 ± 0.2°C; Trial D: 34.9 ± 1.9°C; $p < 0.0001$), relative humidity (Trial A: 47.3 ± 0.8%; Trial B: 53.1 ± 1.2%; Trial C: 53.6 ± 0.7%; Trial D: 55.3 ± 2.9%; $p < 0.0001$), wet bulb temperature (Trial A: 21.7 ± 0.3°C; Trial B: 24.4 ± 0.2°C; Trial C: 26.2 ± 0.1°C; Trial D: 27.5 ± 1.5°C; $p < 0.0001$), water vapor pressure (Trial A: 4.2 ± 0.1 kPa; Trial B: 4.7 ± 0.1 kPa; Trial C: 5.2 ± 0.1 kPa; Trial D: 5.6 ± 0.6 kPa; $p < 0.0001$), and estimated WBGT (Trial A: 24.1 ± 0.3°C; Trial B: 26.6 ± 0.2°C; Trial C: 28.5 ± 0.2°C; Trial D: 29.3 ± 0.6°C; $p < 0.0001$)

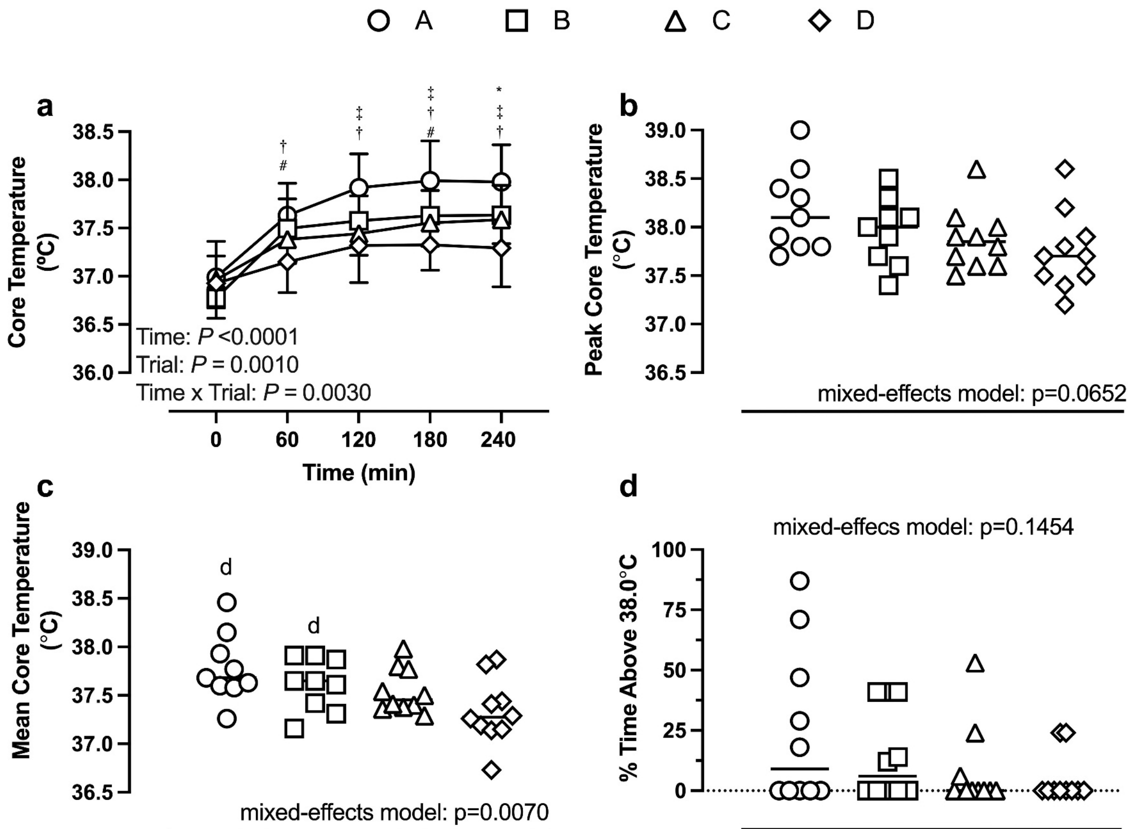

Figure 2. Core temperature responses in four experimental trials consisting of a 4-hour exposure to wet-bulb globe temperatures: Trial A (24.1 ± 0.3°C; *open circles*), Trial B (26.6 ± 0.2°C; *open squares*), Trial C (28.5 ± 0.2°C; *open triangles*), and Trial D (29.8 ± 1.7°C; *open diamonds*). *A*) Core temperature presented as an absolute mean and reported preexposure and every hour during the exposure. Data were analyzed using a two-way, repeated measures mixed-effects model and exact p-values reported. *B*) Peak core temperature responses across the entire 4-hour exposure presented as individual values and mean (*line*). Data were analyzed using a one-way, repeated measures mixed-effects model. *C*) Mean core temperature responses across the entire 4-hour exposure presented as individual values and mean (*line*). Data were analyzed using a one-way, repeated measures mixed-effects model. *D*) Percentage time with core temperature above 38°C calculated from the number of counts (i.e. core temperature measurements every 15 minutes) divided by total number of measurements (n = 17) multiplied by 100. Data are presented as individual values and mean (*line*) and data analyzed using a one-way, repeated measures mixed-effects model. *Post hoc* analyses were completed using Šídák's multiple comparisons tests. *n = 10* except for Trial A and Trial B (*n = 9* due to missing data and/or technical issues with the core temperature pills). d different from Trial D (p ≤ 0.05); † Trial A > Trial D (p ≤ 0.05); ‡ Trial A > Trial C (p ≤ 0.05); * Trial A > Trial B (p ≤ 0.05); # Trial B > Trial D (p ≤ 0.05).

were all different between experimental trials and in a stepwise fashion.

All core temperature parameters are presented in Figure 2a-d. Briefly, preexposure core temperature did not differ between trials (Trial A: 37.0 ± 0.4°C; Trial B: 36.8 ± 0.4°C; Trial C: 37.0 ± 0.3°C; Trial D: 36.9 ± 0.4°C; p = 0.3236). Core temperature increased over time in all trials (p < 0.0001) and increased to a greater extent in Trial A and/or Trial B at various timepoints (see Figure 2a; p≤0.0342). Mean core temperature (Trial A: 37.8 ± 0.4°C; Trial B: 37.6 ± 0.3°C; Trial C: 37.5 ± 0.2°C; Trial D: 37.3 ± 0.3°C; Figure 2c) was different between trials (p = 0.0070), and was higher in Trial A (p = 0.0331) and Trial B (p = 0.0132) compared to Trial D. Peak core temperature (Trial A: 38.2 ± 0.4°C; Trial B: 38.0 ± 0.3°C; Trial C: 37.9 ± 0.3°C; Trial D: 37.74 ± 0.40°C; Figure 2b) was not different between trials (p = 0.0652). Finally, percentage of time with core temperature above 38°C did not differ between trials (Trial A: 9% [IQR: 0, 42.5%]; Trial B: 6% [IQR: 0, 34.3%]; Trial C: 0% [IQR: 0, 4.5%]; Trial D: 0% [IQR: 0, 0%]; p = 0.1454). Mean heart rate differed between trials (Trial A: 121 ± 18 bpm; Trial B: 114 ± 15 bpm; Trial C: 104 ± 14 bpm; Trial D: 92 ± 17 bpm; p < 0.0001).

Mean heart rate was higher in Trial A (p = 0.0002) and Trial B (p = 0.0021) compared to Trial D.

All indexes of hydration are presented in *Table 1* and Figure 3a-d. All subjects were euhydrated at preexposure and body mass did not differ between trials (p = 0.8909; *Table 1*). Absolute body mass decreased from pre- to postexposure in Trial A and Trial B (p ≤ 0.0095). Percentage change in body mass was greater in Trial A (−0.9 ± 0.7%; p = 0.0431) compared to Trial D (−0.4 ± 0.6%) but was not different between any other trial. Importantly, all percentage changes in body mass from pre- to postexposure in each trial (Figure 3a) were different than the hypothetical mean body mass loss of 2% (p ≤ 0.0009). Interestingly, in Trial C, subjects reported to the laboratory 24 hours postexposure with a percentage body mass change different from preexposure (−0.7 ± 0.6%; p = 0.0121) but not in any other trial (p ≥ 0.2603; *Table 1*). Total fluid consumed *ad libitum* did not differ between any trials (Trial A: 1.6 ± 0.5 L; Trial B: 1.5 ± 0.4 L; Trial C: 1.7 ± 0.5 L; Trial D: 1.5 ± 0.6 L; p = 0.6142). Furthermore, the percentage of potential total fluid consumed (i.e. % of 3.55 L) was not different between trials (p = 0.5994). Average sweat rate was different across the experimental trials (p = 0.0249) and was higher in Trial A (0.5 ± 0.1 L•h^{-1}; p = 0.0030) and Trial B (0.5 ± 0.1 L•h^{-1}; p = 0.0040) compared to Trial D (0.3 ± 0.1 L•h^{-1}). Finally, USG was not different from pre- to postexposure in any trial (p ≥ 0.0650) but was higher than preexposure at 24 hours in Trial A (p = 0.0118), Trial C (p = 0.0032), and Trial D (p = 0.0338). It is important to note, however, that mean USG never exceeded 1.020 (i.e. the threshold for dehydration [16]) at any timepoint or experimental trial.

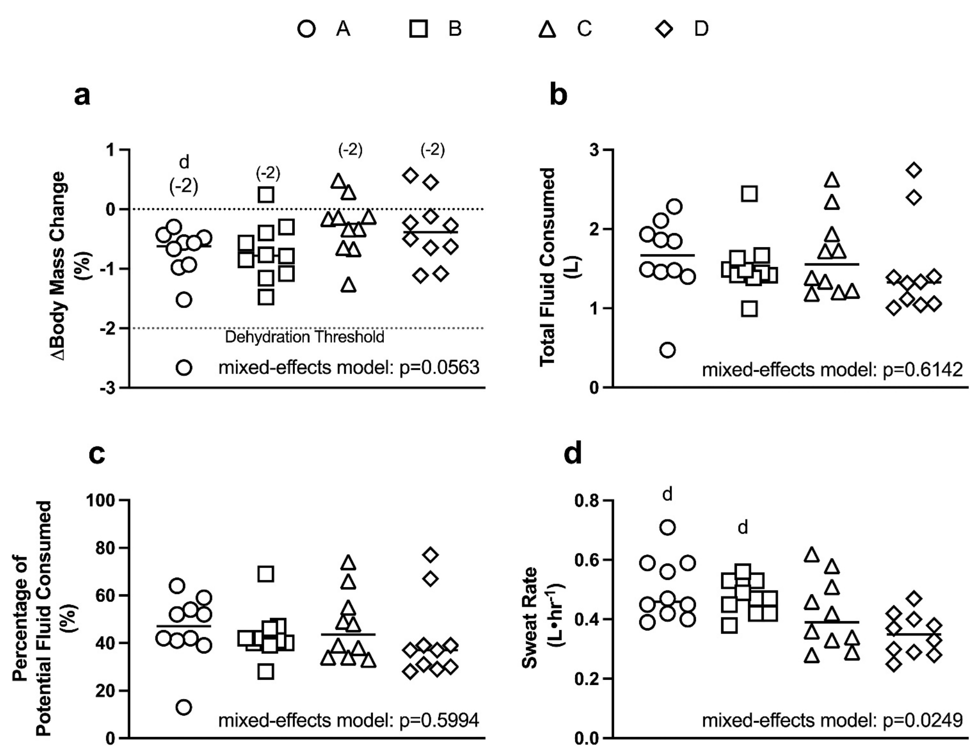

Figure 3. Hydration responses and fluid consumption in four experimental trials consisting of a 4-hour exposure to wet-bulb globe temperatures: Trial A (24.1 ± 0.3°C; *open circles*), Trial B (26.6 ± 0.2°C; *open squares*), Trial C (28.5 ± 0.2°C; *open triangles*), and Trial D (29.8 ± 1.7°C; *open diamonds*). *A*) Percentage change in body mass from pre- to postexposure and data analyzed using a one sample *t test* (for comparison to the dehydration threshold of −2% body mass). *B*) Total fluid (i.e. flavor preferred sports drink) consumed across the 4-hour exposure. *C*) Percentage of total potential fluid consumed (i.e. 3.55 L) across the 4-hour exposure. *D*) Average sweat rate across the 4-hour exposure calculated from the difference in pre- and postexposure nude body mass plus fluid intake minus urine output divided by four. All data were analyzed using a one-way, repeated measures mixed-effects model and *post hoc* analyses were completed using Šídák's multiple comparisons tests. Data are presented as individual values (*n = 10*) and mean (*line*). (−2) different from −2% change in body mass (dehydration threshold) (p ≤ 0.05); d different from Trial D (p ≤ 0.05).

Discussion

The purpose of the present study was to test a unique hypothesis within a larger registered clinical trial (NCT04767347) that *ad libitum* drinking during heat stress recommendation compliant physical work in the heat would result in >2% body mass loss. In contrast to our hypothesis, *ad libitum* drinking prevented dehydration (i.e. <2% body mass loss; Figure 3a) in all experimental trials across a spectrum of exposures that varied markedly in WBGT and duration of physical work at a fixed metabolic heat production. These findings serve to challenge the premise that *ad libitum* drinking during prolonged exposure to heat stress will result in insufficient fluid replacement and subsequent progressive dehydration. Indeed, with all barriers removed (e.g. competing motivation, accessibility) *ad libitum* drinking staves off progressive dehydration during physical work in the heat.

Heat stress is a function of the thermal environment and is quantified as WBGT, clothing or personal protective equipment ensemble, and the rate of metabolic heat production [28]. Heat stress, as frequently experienced by both outdoor and indoor workers can result in heat strain hallmarked by an increase in core temperature potentiating the risk of heat-related illness and other direct and indirect adverse effects (e.g. accidents, loss in productivity). In the present study, we directly assessed the published NIOSH heat stress recommendations that aim to minimize such heat strain [8] and maintain an average core temperature ≤38.0°C in unacclimatized individuals [8,29,30]. Indeed, strict adherence to these recommendations (Figure 1a) prevented average (i.e. across a 4-hour exposure [half workday]) core temperature from exceeding 38.0°C in most, but not all subjects in the present study (Figure 2c). Two subjects exceeded an average core temperature of 38.0°C during Trial A (i.e. continuous walking at a WBGT of ~24°C). It is important to note that these recommendations were developed based on the standard "70 kg man" with a body surface area of ~1.8 m^2 [8]. However, we demonstrate that adherence to these recommendations in both males and females and across a spectrum of body masses (range: 59–93 kg) and body surface areas (range: 1.7–2.2 m^2) was successful in maintaining a mean core temperature ≤38.0°C across a 4-hour exposure. Interestingly, only some subjects (Trial A: $n = 5$; Trial B: $n = 5$; Trial C: $n = 3$; Trial D: $n = 2$) had a peak core temperatures ≥38.0°C in each experimental trial (Figure 2b) and only in Trial A was the average peak core temperature >38.0°C. Finally, the percentage of time with core temperature >38.0°C did not differ between experimental trials, albeit was quite variable between subjects. Taken together, the present study design permitted the direct assessment of *ad libitum* drinking on dehydration in the background of adherence to the heat stress recommendations. Furthermore, it should be noted that under laboratory-controlled conditions, these heat stress recommendations may be overly cautious, particularly under conditions of higher WBGTs, but lower work durations at a fixed metabolic heat production (Figure 2). However, in practice, heat stress and risk for heat illnesses persist [31,32] potentially highlighting the importance for overly cautious recommendations due to imperfect or lack of adherence.

To our knowledge, the NIOSH hydration recommendations have not been assessed during exposures that strictly adhere to the heat stress recommendations. In the present study, we clearly demonstrate that *ad libitum* drinking (up to 237 mL per 15 minute interval) of a flavor-preferred sports drink during prolonged exposure to a spectrum of environmental temperatures and duration of physical work prevents dehydration (i.e. <2% body mass loss; Figure 3a). Moreover, only in one subject and one experimental trial (Trial A) did body mass loss exceed 2% (i.e. −2.7%; Figure 3a). This finding is in contrast to our primary hypothesis and to the NIOSH hydration recommendations that advise against *ad libitum* drinking because it usually results in incomplete fluid replacement causing progressive body water losses and dehydration [17,33]. Indeed, during heat stress, the body relies on sweating to promote heat loss [34]. If body fluids are not adequately replaced, high sweat rates can bring about dehydration [35,36]. To this end, sweat rates (Figure 3d) were quite modest and paralleled the mild increases in core temperature across each experimental trial. The loss in body water due to sweating was combated by adequate *ad libitum* fluid replacement throughout each experimental trial. Interestingly, there was no difference to total volume consumed and the percentage of potential total volume (i.e. 3.55 L) between the experimental trials (Figures 3B-c). It is important to note that during heat stress NIOSH recommends prescribed drinking of 237 mL (i.e. 1 cup) of fluid every 15–20 min (~0.95 $L{\bullet}h^{-1}$) to ensure that decreases in body mass are <1.5% [8]. Had this been employed in the present study, subjects would have had an average net increase in body mass in each experimental trial (Trial A: +1.7%; Trial B: +2.0%; Trial C: +2.2%; Trial D: +2.5%) indicating a potential for over prescription of fluid replacement if such recommendations are strictly adhered to [37]. Ultimately, the findings from the present study serve to corroborate previous work that demonstrates efficacy for *ad libitum* drinking during heat stress to prevent dehydration during both laboratory [38] and field-based [39] studies.

There are a few methodological considerations that warrant mentioning. First, the results of the present study are potentially constrained to the study employed. Strict adherence to the NIOSH heat stress recommendations was only made possible under laboratory-controlled, internally valid conditions. For instance, environmental conditions and the rate of metabolic heat production were tightly controlled and remained stable across the 4-hour exposure – an unlikely scenario given the changes in environmental conditions and job tasks across a workday. Second, *ad libitum* drinking was permitted under optimal conditions. Subjects had immediate access (i.e. adjacent to the treadmill and/or chair during rest) and were allowed to drink at any point during the exposures. The fluid was prepared and provided to the subjects and did not require any effort to obtain fluids. Under real-world conditions workers would likely have to stop work or wait until a scheduled break to obtain fluids and/or drink, which may be counterproductive depending on the occupation. This is highlighted as a primary issue in adherence to both heat stress and hydration recommendations [11–13]. However, this suggests that competing motivations and/or inaccessibility likely contributes to under drinking (and subsequent development progressive dehydration) and not due to impairments in thirst-dependent drinking per se. Third, we chose to primarily utilize changes in body mass loss to provide an indication of fluid balance and have not reported other measures (e.g. plasma osmolality, changes in plasma volume). This was by design given the focus of hydration recommendations to limit changes in body mass during physical work in the heat to <2%. As noted in the *Methods*, this manuscript is a sub-analysis of a larger clinical trial and we expect to present additional measures of fluid regulation in future reports. Notably, not reporting these additional data likely does not limit the impact the data in the present manuscript.

In conclusion, the present study demonstrates that when NIOSH heat stress recommendations (i.e. work-rest ratios at a given WBGT and fixed metabolic heat production) are strictly adhered to during physical work in the heat, *ad libitum* drinking is sufficient to preventing dehydration.

List of abbreviations

"BML" – body mass loss
"NIOSH" – National Institute for Occupational Safety and Health
"T_c" – core temperature
"USG" – urine specific gravity
"WBGT" – wet bulb globe temperature

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Author contributions

H.W.H. and Z.J.S. conceived and designed research; H.W.H., T.B.B., M.L.T., and Z.J.S. performed experiments; H.W. H. analyzed the data; H.W.H. and Z.J.S. interpreted results of experiments; H.W.H. prepared figures; H.W.H. and Z.J. S. drafted manuscript; H.W.H., T.B.B., M.L.T., D.H., and Z.J. S. edited and revised manuscript; H.W.H., T.B.B., M.L.T., D. H., and Z.J.S. approved final version of manuscript.

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