ORIGINAL RESEARCH

Influence of Fluid Delivery Schedule and Composition on Fluid Balance, Physiologic Strain, and Substrate Use in the Heat

Alejandro M. Rosales, MS; Walter S. Hailes, MS; Patrick S. Dodds, BS; Alexander N. Marks, MS; Brent C. Ruby, PhD

University of Montana, Montana Center for Work Physiology and Exercise Metabolism, Missoula, MT

Introduction—Wildfire suppression is characterized by high total energy expenditure and water turnover rates. Hydration position stands outline hourly fluid intake rates. However, dose interval remains ambiguous. We aimed to determine the effects of microdosing and bolus-dosing water and microdosing and bolus-dosing carbohydrate-electrolyte solutions on fluid balance, heat stress (physiologic strain index [PSI]), and carbohydrate oxidation during extended thermal exercise.

Methods—In a repeated-measures cross-over design, subjects completed four 120-min treadmill trials (1.3 m·s^{-1}, 5% grade, 33°C, 30% relative humidity) wearing a US Forest Service wildland firefighter uniform and a 15-kg pack. Fluid delivery approximated losses calculated from a pre-experiment familiarization trial, providing 22 doses·h^{-1} or 1 dose·h^{-1} (46±11, 1005±245 mL·dose^{-1}). Body weight (pre- and postexercise) and urine volume (pre-, during, and postexercise) were recorded. Heart rate, rectal temperature, skin temperature, and steady-state expired air samples were recorded throughout exercise. Statistical significance ($P<0.05$) was determined via repeated-measures analysis of variance.

Results—Total body weight loss (n=11, –0.6±0.3 kg, $P>0.05$) and cumulative urine output (n=11, 677±440 mL, $P>0.05$) were not different across trials. The micro-dosed carbohydrate-electrolyte trial sweat rate was lower than that of the bolus-dosed carbohydrate-electrolyte, bolus-dosed water, and microdosed water trials (n=11, 0.8±0.2, 0.9±0.2, 0.9±0.2, 0.9±0.2 L·h^{-1}, respectively; $P<0.05$). PSI was lower at 60 than 120 min (n=12, 3.6±0.7 and 4.5±0.9, respectively; $P<0.05$), with no differences across trials. The carbohydrate-electrolyte trial's carbohydrate oxidation was higher than water trial's (n=12, 1.5±0.3 and 0.8±0.2 g·min^{-1}, respectively; $P<0.05$), with no dosing style differences.

Conclusions—Equal-volume diverse fluid delivery schedules did not affect fluid balance, PSI, or carbohydrate oxidation during extended thermal work.

Keywords: hydration, thermal stress, carbohydrate oxidation

Introduction

Wildland firefighters (WLFF) complete 12 to 18 h work shifts on 14-d assignments under arduous conditions.[1] Total energy expenditure ranges between 12 and 26 MJ·d^{-1} (2868-6214 kcal·d^{-1}).[1,2] The metabolic cost of WLFF load carriage hiking (via the Pimental and Pandolf equation[3]) is 22±12 mL·kg^{-1}·min^{-1} (mean±SD), varying between 19 and 34 mL·kg^{-1}·min^{-1} depending on hike classification (ingress, shift, egress, or more intense training hikes).[4] Water turnover measurements from multiple investigations demonstrate aggressive hydration demands (6.7±1.4 L·d^{-1},[5] 7.0±1.7 L·d^{-1},[1] and 9.5±1.7 L·d^{-1}[2]). Digital flowmeter drinking technology has also revealed varied hourly volume and intake intervals.[6]

WLFF appear to modify their behavior in response to thermal strain by self-selecting sustainable work rates and avoiding unnecessary heat.[2,7] However, inadequate fluid ingestion during extended exercise at a constant work rate can lead to reductions in plasma volume and thermoregulatory strain from increases in heart rate (HR) and

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Corresponding author: Brent C. Ruby, PhD, The University of Montana, 32 Campus Drive, McGill Hall, IPAT, Missoula, MT 59812; e-mail: brent.ruby@mso.umt.edu.

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core temperature.[8,9] Appropriately administered fluid volume has been shown to alleviate[10-13] and transiently alleviate[14] HR and core temperature increases otherwise resulting from hypohydration.

The American College of Sports Medicine,[15] the National Athletic Trainers' Association,[16] and US Army Training and Doctrine Command Regulation 350-29[17] outline hourly fluid intake recommendations designed to limit dehydration to <2% loss of initial body weight. These recommendations propose that minimizing dehydration ensures attenuation of thermoregulatory strain. However, recommendations for the fluid ingestion interval between doses to comply with suggested hourly intake remain ambiguous.

Research has examined fluid intake strategies after[18-22] and during[14,23,24] exercise. Postexercise rehydration strategies have demonstrated that volume,[20] composition,[20-22] and administration interval[18,22] collectively influence fluid retention. Intermittent fluid administration has been shown to be more effective than a bolus dose at recovering net fluid balance postexercise,[18] with further improvements when higher energy density or sodium is included in the rehydration beverage.[22] Intermittent, as opposed to bolus, delivery of beverages after exercise is thought to enhance rehydration by reducing urinary output resulting from rapid gastric emptying rates. However, when a similar strategy is employed during moderate-intensity extended thermal exercise, concluding hematic hydration markers do not differ when ingested fluids allow dehydration to >2% of body weight.[14]

Sports drink solutions are often formulated with carbohydrates (CHO) and electrolytes for use during extended exercise in lieu of water alone to improve fluid balance and accommodate CHO oxidation. The contribution of exogenous CHO oxidation to total CHO oxidation during exercise is improved when CHO sources are delivered at 10- to 15-min intervals.[25-27] Large amounts of ingested CHO (70-100 $g \cdot h^{-1}$) have been shown to shift the proportion of exogenous fuel use rates toward peak values,[27,28] but it is unclear whether the provision of frequent small oral doses will alter total CHO oxidation.

Matching fluid ingestion to fluid loss while altering the administration interval of identical fluid volumes and differing compositions during moderate-intensity extended thermal stress could contribute to an enhanced ability to maintain euhydration status and transiently regulate thermal strain during a WLFF work shift. The primary purpose of this study was to determine the influence of altered fluid delivery schedules (microdosing vs bolus dosing) of identical hourly volumes on fluid retention and physiologic strain index (PSI) while exercising in the heat. A secondary purpose examined fluid retention and substrate use when superimposing a carbohydrate-electrolyte (CE) solution on an altered fluid delivery schedule during an identical exercise environment. We hypothesized that 1) microdosing fluids would improve overall fluid retention regardless of composition and 2) inclusion of a CE solution would further improve fluid retention. We additionally hypothesized 3) that microdosing a CE solution would maintain a higher CHO oxidation rate during exercise.

Methods

SUBJECTS

Healthy males were recruited and deemed fit for activity and free of injury via the 2019 physical activity readiness questionnaire. The University of Montana's institutional review board approved all methodologies. Subjects were informed of the procedures and risks associated with participating in the study and provided informed written consent.

PRELIMINARY TESTING

Body composition and $VO_{2\ peak}$ testing

Subjects arrived having fasted overnight and refrained from alcohol, caffeine, and exercise during the 24 h leading up to the first visit. After recording of mass (CW-11, Ohaus, Pine Brook, NJ) and measuring height, body composition was obtained via hydrodensitometry (Exertech, Dresbach, MN) using residual volume estimates[29] for conversion to percent body fat.[30]

Peak oxygen uptake ($VO_{2\ peak}$) was determined on a motorized treadmill (4Front, Woodway USA Inc., Waukesha, WI) via a graded exercise test[31] to volitional exhaustion and achievement of at least 2 of the following criteria: respiratory exchange ratio > 1.10, plateau in VO_2, HR within 10 beats of age predicted maximum (220–age in y), or a rating of perceived exertion (RPE, Borg scale[32]) > 17. A calibrated metabolic cart (ParvoMedics Inc., Salt Lake City, UT) collected expired gas samples throughout the test. During the final 30 s of each stage, HR from a watch and chest strap (Polar Electro, Kempele, FL) and RPE were recorded. VO_2 peak was calculated as the highest 15 s average oxygen uptake before volitional exhaustion.

Metabolic rate prediction

An equation outlined by Pimental and Pandolf[3] was used to determine the appropriate treadmill speed, grade, and load combination to elicit a VO_2 approximating 22.5 $mL \cdot kg^{-1} \cdot min^{-1}$ during all trials. The equation is outlined, where W is the subject mass in kg, L is the external load in kg, η is the terrain factor, V is the velocity in $m \cdot s^{-1}$, and G is the grade in percent. A terrain factor of 1 was selected to represent the surface of the treadmill.

$$\text{Metabolic Rate (watts)} = 1.5W + 2.0\,(W + L)\,(L/W)^2 + \eta\,(W + L)\left(1.5V^2 + 0.35VG\right)$$

Familiarization trial

Subjects completed a 60-min familiarization trial at least 24 h after $VO_{2\ peak}$ test and 7 d before beginning the experimental trials. In addition to the aforementioned restrictions surrounding alcohol, caffeine, and exercise, subjects were instructed to fast for 12 h, consume 500 mL of water 60 min before bed the evening prior, and refrain from consuming any fluids the morning of all trials. Each subject kept a 24 h food and fluid consumption log to be repeated for each trial.

Upon entering the laboratory, subjects voided their bladder, drank 500 mL of water, and sat for 30 min in a temperate environment before providing a baseline urine void and nude body weight. Subjects then dressed in a WLFF Nomex shirt (FedMall, Fort Belvoir, VA), flame-resistant pants (FedMall), cotton base layer t-shirt (Hanes, Winston-Salem, NC), 15-kg pack (fireline pack NFES# 0674, FedMall), and their own footwear. Subjects entered the environmental chamber (Tescor Inc., Warminster, PA) set at 33°C with a relative humidity of 30% and immediately began walking for 60 min on a motorized treadmill (1.3 $m \cdot s^{-1}$, 5% grade). No fluid was administered to subjects during this trial.

After the familiarization trial, subjects immediately voided and toweled off before providing a nude body weight. The pre- to postfamiliarization trial body weight change was used to predict hourly water loss for appropriate fluid delivery volume during the experimental trials ($mL \cdot h^{-1}$).

EXPERIMENTAL TRIAL

Overview

Subjects completed 4 trials in a repeated-measures crossover design. Subjects were assigned to 1 of 4 intervention orders, completing 2 delivery styles of the same composition before completing the second composition. Each trial was separated by 7 d, and each composition was separated by a 2-wk washout period to control for potential heat acclimation. Fluid composition consisted of plain water or a CE solution (Gatorade, PepsiCo, Chicago, IL). The fluid interventions were bolus-dosed CE (BCE), bolus-dosed water (BW), microdosed CE (MCE), and microdosed water (MW).

Subjects were instructed to abide by the same parameters and restrictions as outlined in the familiarization trial, while adhering to their food and fluid consumption logs. The procedure was identical to the familiarization trial: Subjects urinated, drank 500 mL of water, and sat for 30 min in a temperate environment before providing a baseline urine void and nude body weight. Each 120-min experimental trial began immediately upon the subject entering the chamber and occurred under the aforementioned conditions and clothing, but with consumption of BCE, BW, MCE, or MW. HR, rectal temperature (T_c) (RET-1, PhysiTemp, Clifton, NJ), and skin temperature (T_s, sensor placed 5 cm above the left nipple on pectoralis major muscle) (SST-1, PhysiTemp) were continuously measured via a portable data logger (SDL200, Extech Instruments, Nashua, NH). Urine was collected during and after exercise. Steady-state expired gas was collected during exercise. Nude body weight was also recorded after exercise.

Treadmill and fluid administration protocol

Subjects walked for 2 sets of 55 min with 5 min standing rest to accommodate urine collection. Fluids were kept in the heat chamber for 12 h before each trial and were served at the chamber temperature (33°C) to ascertain fluid temperature across trials and mimic fluid ingestion temperature on the fireline. Micro-dosed fluids were delivered with 60 mL syringes (BD, Franklin Lakes, NJ) every 2 min in equal increments from 5 to 25, 28 to 50, 65 to 85, and 88 to 110 min, with final hourly doses delivered at 53 and 113 min (22 $doses \cdot h^{-1}$, 46±11 $mL \cdot dose^{-1}$). Bolus-dosed intake was administered near the top of each hour (5 and 65 min) in 2 equal amounts (1005±245 $mL \cdot h^{-1}$) with 5 min to ingest the entire volume. Total administered fluid volumes were identical within subjects, matching the fluid loss predicted from the pre-experiment familiarization trial.

Heart rate, core temperature, skin temperature, and physiologic strain index

HR, T_c, and T_s were measured using the aforementioned equipment and recorded within the last 30 s of 5, 53, and 113 min. PSI was calculated using the following equation.[33] T_{ct} and HR_t are simultaneous measurements at the time point of interest, and T_{c0} and HR_0 are initial measurements from the beginning of each trial:

$$PSI = 5\,(T_{ct} - T_{c0})\,(39.5 - T_{c0})^{-1} + 5\,(HR_t - HR_0)\,(180 - HR_0)^{-1}$$

Body weight, urine output, and sweat rate

Nude body weight was measured before, after, and 60 min after exercise. Urine was collected and measured for volume and urine specific gravity (USG) (URC-NE, Atago, Cohasset, MA) before, during (60 and 120 min), and 60 min after exercise. Sweat rate was calculated using nude body weight changes in kg (*BW*), urine output in kg (*U*), fluid consumption in kg (*FC*), respiratory water loss in kg (*RWL*),[34] and water vapor pressure[35]:

$$\text{Sweat rate}\left(\text{L}\cdot\text{h}^{-1}\right) = \frac{[(\text{BW}_{\text{PRE}} - \text{BW}_{\text{POST}} + \text{FC}) - (\text{U} + \text{RWL})]}{\text{h}}$$

$$\text{RWL}\left(\text{g}\cdot\text{min}^{-1}\right) = (0.0019)\left(\text{VO}_2\ \text{L}\cdot\text{min}^{-1}\right)(44 - \text{Water vapor pressure})$$

$$\text{Water vapor pressure} = 13.955 - 0.6584\,(\text{Temperature}) + 0.0419\,(\text{Temperature})^2$$

Substrate utilization

Gas exchange was measured using a metabolic cart, as mentioned earlier. Steady-state expired gas samples were collected from 0 to 5 min during the first hour to act as baseline. Subsequent gas samples were recorded during 50 to 53 and 110 to 113 min. Steady-state values of VO_2 ($L \cdot min^{-1}$) and VCO_2 ($L \cdot min^{-1}$) were used to calculate total CHO oxidation and energy expenditure with the assumption that protein oxidation was negligible[36]:

$$\text{CHO oxidation}\left(\text{g}\cdot\text{min}^{-1}\right) = (4.344\cdot\text{VCO}_2) - (3.061\cdot\text{VO}_2)$$

$$\text{Energy Expenditure}\left(\text{kcal}\cdot\text{min}^{-1}\right) = (0.575\cdot\text{VCO}_2) - (4.435\cdot\text{VO}_2)$$

STATISTICAL ANALYSIS

A 2-way analysis of variance (time × trial) with repeated measures was used to evaluate body weight (pre-, post-, and 60 min postexercise), HR (5, 60, and 120 min during exercise), T_c (5, 60, and 120 min during exercise), T_s (5, 60, and 120 min during exercise), PSI (60 and 120 min during exercise), urine by void (60 and 120 min during exercise and 60 min postexercise), substrate utilization (5, 60, and 120 min during exercise), and energy expenditure (5, 60, and 120 min during exercise). A 1-way analysis of variance (trial) with repeated measures was used for relative exercise intensity, exercise sweat rate, cumulative urine output, exercise urine output, and postexercise urine output. A 2-tailed paired t-test was used to evaluate oxygen consumption (VO_2) measured during exercise and estimated from the Pimental and Pandolf equation.[3] Statistical significance was set at a type I probability error of <5% ($P<0.05$), with data expressed as mean±SD. Sphericity was evaluated using Mauchly's test of sphericity and, when violated, was corrected using the Greenhouse-Geisser ($\varepsilon<0.75$) or Huynh-Feldt ($\varepsilon>0.75$) procedures. Statistical analysis was completed using SPSS (IBM, Chicago, IL) and Excel (Microsoft Corporation, Redmond, WA).

Results

All subjects (males, n=12, age 25±4 y, weight 78±12 kg, 15±4% body fat, VO_{2peak} 55.4±6.6 $mL \cdot kg^{-1} \cdot min^{-1}$) completed each trial.

EXERCISE INTENSITY AND ENERGY EXPENDITURE

Relative intensity estimated from the Pimental and Pandolf[3] equation and measured during the experimental trials was not significantly different (21.8±0.6 and 22.0±1.3 $mL \cdot kg^{-1} \cdot min^{-1}$, $P>0.05$). Similarly, relative intensity was not significantly different across trials ($P>0.05$) (Table 1). Energy expenditure at 60 and 120 min was significantly higher than at 5 min, and energy expenditure at 120 min was significantly higher than at 60 min (7.4±0.9, 8.3±1.0, and 8.5±1.1 $kcal \cdot min^{-1}$ for 5, 60, and 120 min, respectively; $P<0.05$); however, there were no differences across trials ($P>0.05$).

BODY WEIGHT AND SWEAT RATE

One subject vomited immediately after exercise and was removed from body weight and sweat rate analyses. Body weight post- and 60 min postexercise was significantly lower than pre-exercise (n=11, $P<0.05$) (Table 1), and body weight 60 min postexercise was significantly lower than postexercise (n=11, $P<0.05$) (Table 1). However, total body weight loss at the end of the 60-min post-exercise rest period was not significantly different across trials (n=11, $P>0.05$) (Table 1). Exercise sweat rate during the MCE trial was significantly lower than during the BCE, BW, and MW trials (n=11, $P<0.05$) (Table 1).

URINE OUTPUT AND URINE SPECIFIC GRAVITY

The same subject who vomited immediately after exercise was also removed from all urine-oriented analyses. Another subject could not provide a baseline void and

Table 1. Relative exercise intensity; body weight before, after, and 60 min postexercise; urine output; and sweat rate for 120 min of extended walking in the heat (mean±SD)

	BCE	*BW*	*MCE*	*MW*	*Grand mean*
Relative intensity (mL·kg^{-1}·min^{-1})	22.1±1.3	21.9±1.3	22.0±1.3	21.8±1.5	22.0±1.3
Body weight (kg) (n=11)					
Pre	79.4±11.3	79.6±10.7	79.5±11.2	79.2±10.8	79.4±10.6
Post	79.1±11.2	79.3±10.8	79.3±11.2	79.1±10.8	79.2±10.6[a]
60 min post	78.8±11.2	78.9±10.70	79.0±11.2	78.7±10.8	78.9±10.6[a,b]
Pre to 60 min post total loss (kg)	–0.6±0.2	–0.6±0.3	–0.5±0.2	–0.5±0.3	–0.6±0.3
Cumulative urine output (mL) (n=11)	634±455	724±462	692±497	659±399	677±440
Sweat rate (L·h^{-1}) (n=11)	0.9±0.2	0.9±0.2	0.8±0.2[c]	0.9±0.2	0.9±0.2
Exercise urine output (mL) (n=12*)*	431±355	469±338	448±365	421±289	442±328
Postexercise urine output (mL) (n=11)	169±131	225±166	211±175	216±127	205±147

BCE, bolus dosing carbohydrate-electrolyte; BW, bolus dosing water; MCE, microdosing carbohydrate-electrolyte; MW, microdosing water. Data presented as mean±SD.

[a]Body weight postexercise and 60 min postexercise is different from pre-exercise (time effect, $P<0.05$).

[b]Body weight at 60 min postexercise is different from postexercise (time effect, $P<0.05$).

[c]Sweat rate at MCE is different from BCE, BW, and MW (trial effect, $P<0.05$).

was removed from USG analysis. Cumulative urine output across trials during exercise and after 60 min of recovery was not significantly different across trials (n=11, $P>0.05$) (Table 1). Similarly, urine void by time was not significantly different across trials (n=11, 242±169, 231±174, 205±147 mL for 60 min, 120 min, and 60 min postexercise, respectively; $P>0.05$). USG was significantly lower than baseline at 60 min, 120 min, and 60 min postexercise (n=10, 1.016±0.006, 1.006±0.004, 1.006±0.005, and 1.009±0.007 for baseline, 60 min, 120 min, and 60 min postexercise, respectively; $P<0.05$), whereas USG at 120 min was significantly lower than at 60 min postexercise ($P<0.05$).

HEART RATE, CORE TEMPERATURE, PHYSIOLOGIC STRAIN INDEX, AND SKIN TEMPERATURE

HR in BCE was significantly higher than in MW (trial effect, $P<0.05$) (Figure 1A). Within each trial (BCE, BW, MCE, MW), HR at 60 and 120 min was significantly higher than at 5 min, and HR at 120 min was significantly higher than at 60 min ($P<0.05$) (Figure 1A). Within each trial (BCE, BW, MCE, MW), T_C at 60 and 120 min was significantly higher than T_c at 5 min, and T_c at 120 min was significantly higher than at 60 min ($P<0.05$) (Figure 1B). Within each trial (BCE, BW, MCE, MW), T_s at 60 and 120 min was significantly higher than at 5 min ($P<0.05$) (Figure 1C) Within each trial (BCE, BW, MCE, MW), PSI at 120 min was significantly higher than at 60 min ($P<0.05$) (Figure 2).

CARBOHYDRATE OXIDATION

At 60 and 120 min, the BCE and MCE trials demonstrated significantly higher rates of total CHO oxidation than at 5 min ($P<0.05$) and in comparison with the BW and MW trials (time × trial interaction, $P<0.05$) (Figure 1D). CHO oxidation between dosing styles of identical composition was not significantly different ($P>0.05$) (Figure 1D).

Discussion

The purpose of this study was to evaluate the influence of altered fluid delivery schedules of identical volume on fluid retention, heat stress, and CHO use during extended exercise in the heat. We hypothesized that, regardless of composition, microdosed fluid administration would improve fluid retention, and the inclusion of a CE solution would provide further fluid retention benefits. We also hypothesized that microdosed oral delivery of CHO would maintain a higher CHO oxidation rate than bolus-dosed oral delivery. Our findings did not confirm our hypotheses.

Our findings demonstrate similar physiologic outcomes when consuming fluids as either a microdose or bolus dose (22 doses·h^{-1} and 1 dose·h^{-1}, respectively) that approximate body weight loss during low- to moderate-intensity (22.0±1.3 mL·kg^{-1}·min^{-1}, 40±5% $VO_{2\ peak}$) extended exercise in the heat. Altered fluid delivery schedules were not differentially advantageous in maintaining euhydration status when evaluating body weight loss or urine metrics across trials. Despite a lower sweat rate during the MCE trial when compared to the BCE, BW, and MW trials and a higher HR in the BCE compared the MW trial, PSI was not different across trials and suggests no thermoregulatory advantage among interventions when subjects are similarly euhydrated. Total CHO oxidation during the BCE and MCE trials was

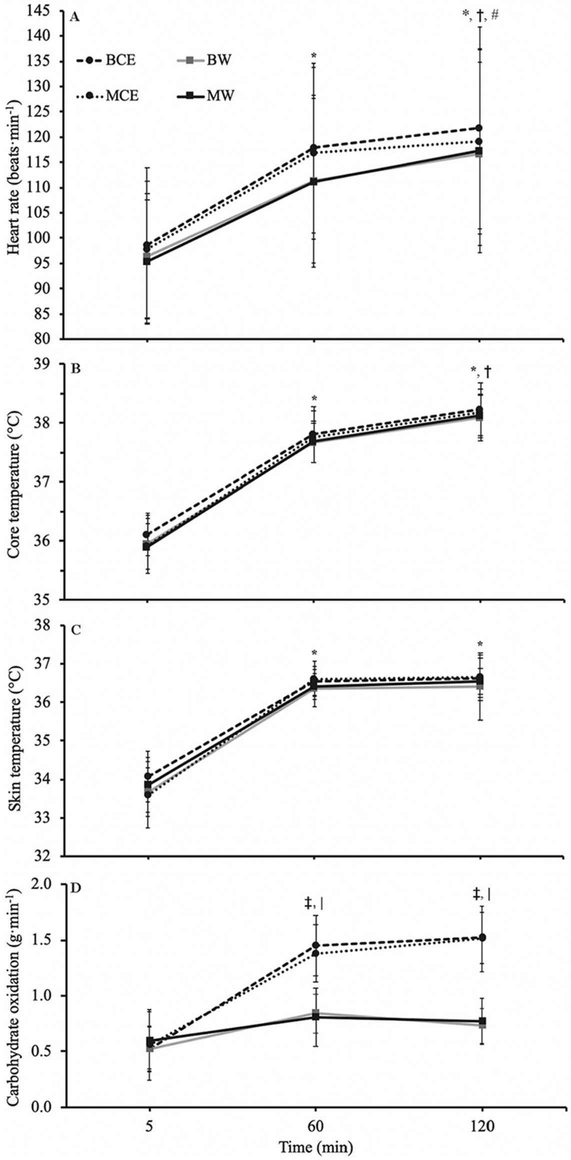

Figure 1. Heart rate (A), core temperature (B), skin temperature (C), and carbohydrate oxidation (D) during 120 min of extended walking in the heat (n=12, mean±SD). BCE, bolus dosing carbohydrate-electrolyte; BW, bolus dosing water; MCE, microdosing carbohydrate-electrolyte; MW, microdosing water. *60 and 120 min are different from 5 min (P<0.05). †120 min is different from 60 min (P<0.05). #Heart rate (A) in BCE is different from MW (P<0.05). ‡Carbohydrate oxidation (D) at 60 and 120 min is different from 5 min in BCE and MCE, (P<0.05). |Carbohydrate oxidation (D) at 60 and 120 min is different from BW and MW (P<0.05).

also not different, indicating comparable digestion and delivery to working muscle. These findings showcase that the advantages of manipulating fluid volume, composition, or delivery interval to optimize postexercise fluid recovery[18-22] do not persist during exercise. If total hourly needs are met, fluids can be ingested under diverse and flexible schedules during exercise.

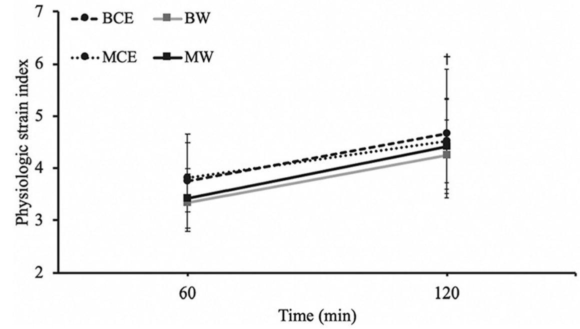

Figure 2. Physiologic strain index during 120 min of extended walking in the heat (n=12, mean±SD). BCE, bolus dosing carbohydrate-electrolyte; BW, bolus dosing water; MCE, microdosing carbohydrate-electrolyte; MW, microdosing water. †PSI at 120 min is different than at 60 min (P<0.05).

The rationale for this project developed from our previous WLFF field research that demonstrates physiologic and fluid delivery demands during wildfire suppression. The use of stable isotope tracers on wildfire work shifts has elucidated water turnover rates as high as 10 $L \cdot d^{-1}$,[1,2,5] outlining the necessity of adequate fluid provision. Similarly, digital flowmeter drinking technology examining ad libitum drinking behavior during wildfire suppression has shown both bolus-dose and microdose type fluid consumption strategies.[6] Fluid intake interval throughout a fireline work shift can average approximately 10 $drinks \cdot h^{-1}$, with hourly water intakes of 504±472 $mL \cdot h^{-1}$ that reach peak volumes at hours 6 to 13 of a work shift (approximately 800 $mL \cdot h^{-1}$).[6] The advantage to the microdose administration strategy is that it could be practically implemented with a reservoir-type hydration apparatus, but unless automated, it would require closer attention to dose delivery regularity.

At rest, after a dehydrating bout of exercise, intermittent as opposed to bolus delivery of fluids has been shown to more effectively promote fluid retention.[18,22] The premise behind intermittent fluid delivery is to attenuate large volume-dependent gastric emptying rates and subsequent alterations to plasma volume and osmolality that promote higher urine production rates. The present study implemented a microdosing and bolus-dosing intervention concurrently with exercise to combine elements of fluid volume, composition, and delivery interval that often work in tandem during fluid recovery. However, antidiuretic hormones increase in response to exercise intensity,[37-39] exercise duration,[40-42] and heat,[37] which can carry over to postexercise recovery periods for 30 to 120 min.[20,41] The present study was done under conditions that represent previously measured ambient temperature[1,2,6] and work intensities[4] on the fireline (33°C environment, 40±5% $VO_{2\ peak}$). Despite differences in fluid composition and delivery interval, there were no differences in total body weight loss (–0.6±0.3 kg) or cumulative (677±440 mL), exercise (442±328 mL), and postexercise (205±147 mL) urine outputs when adequate hourly fluid volume was delivered during exercise.

Fluids in the present study were delivered to accommodate approximately 100% of expected fluid loss, as determined from a pre-experiment familiarization trial (1005±245 mL·h^{-1}). Subjects demonstrated significant body weight loss across each trial (–0.6±0.3 kg), with a percent body weight loss of 0.4±0.2 postexercise that increased to 0.7±0.3% after an additional 60 min of recovery. These percent body weight losses adhere to current recommendations for fluid balance during exercise,[15-17] as do corresponding USG values of 1.006±0.005 and 1.009±0.007. Fluids delivered to avoid dehydration of >2% of body weight are often shown to attenuate unfavorable cardiovascular and T_C responses to exercise.[8-13,43] The MCE trial resulted in, at most, a 70 mL discrepancy in sweat rate. The BCE trial had a higher HR than the MW trial, likely a result of postprandial hyperemia at the stomach.[44] These differences could suggest an altered ability to thermoregulate as a function of fluid delivery interval and composition. However, PSI significantly increased from 60 to 120 min across all trials (3.6±0.7 and 4.5±0.9, respectively), characterized by collective increases in HR (114±16 and 119±19 beats·min^{-1} at 60 and 120 min, respectively) and T_c (37.7±0.4 and 38.1±0.4°C at 60 and 120 min, respectively).

Transient attenuation of T_C and HR increases have been shown in response to identical fluid volumes delivered at various intervals when allowing loss of >2% body weight during exercise.[14] The time-dependent drift in both measures in the present study was not transiently attenuated in response to altered fluid delivery and occurred at a constant workload, despite <1% of fluid loss by body weight. These findings demonstrate that although fluid delivery can be provided in an attempt to optimize fluid balance, it is not solely capable of alleviating accumulated thermal load when exercise persists at the same absolute intensity in the heat.

A case study[45] documented the thermal load, drinking behaviors, and movement patterns of a WLFF who experienced heat exhaustion and medical evacuation from the fireline. Despite aggressive fluid intake at an average rate of 24 doses·h^{-1} and average volume of 840 mL·h^{-1}, heat exhaustion occurred approximately 7 h into the work shift. His self-selected work rates (accelerometry derived) were considerably higher than previously measured in nearly 300 WLFF d on assignment. WLFF on assignment tend to mitigate thermal strain by modulating total energy expenditure, work rates, and/or work:rest ratios.[2,7]

Overemphasizing fluid provision may diminish the safety concerns associated with safe work intensities and work:rest ratios. Hydration advocates must recognize that management of the environmental condition/work intensity interaction necessitates consideration of altered work:rest ratios. The present results clearly demonstrate that varied fluid delivery methods that approximate fluid losses are not differentially advantageous in offloading heat during low- to moderate-intensity extended exercise. Moreover, minimizing body weight loss with aggressive fluid intake cannot singularly halt accumulated thermal load, as demonstrated by the present study's significant drift in HR and T_c from 60 to 120 min.

The present study delivered fluids with a CHO administration rate of 62±15 g·h^{-1} (BCE, MCE). Fluid delivery into the small intestine is influenced by the glucose concentration of the beverage and exercise intensity.[46] The CE solution (Gatorade, PepsiCo) used in this study is formulated with a 6% CHO combination of maltodextrin and fructose, which is generally accepted as a more optimal beverage formula[15] by mitigating sodium-glucose transporter saturation[47] and increasing the peak rate of exogenous CHO oxidation.[27] The exercise intensity of the present study (40±5% VO_2 peak) fell beneath the 70% VO_2 peak threshold at which gastric emptying is altered.[46]

At the 60- and 120-min collection points, total CHO oxidation rates were not different between BCE and MCE trials (1.5±0.3 g·min^{-1}), suggesting similarities in the digestion, absorption, and eventual oxidation of exogenous CHO regardless of the oral delivery frequency. MCE or BCE can effectively maintain CHO oxidation across 120 min of moderate-intensity exercise in the heat and is comparable to commonly used 15 to 30 min CHO delivery intervals.[28,48,49] Supplemental CHO feedings at a rate of 40 g·h^{-1} during wildfire suppression have yielded increased self-selected work output (accelerometry derived) during latter stages of the day, which may translate to improved vigilance on the fireline.[50] The present findings suggest that higher amounts of orally ingested CHO could be reasonably implemented and oxidized during higher intensity segments of a prolonged work shift.

LIMITATIONS

A limitation of laboratory studies is that the field is difficult to mimic. WLFF do not exclusively hike on assignment, and, when they do, it does not typically last >60 min.[4] Subjects in the study were recruited from the surrounding community and, with the exception of one, were not current or former WLFFs. Similarly, females were not incorporated into the subject pool despite being representative members of WLFF crews. Furthermore, the pre-experiment familiarization trial did not account for urinary outputs that may occur in response to ingested fluids, which could explain why body weight significantly decreased postexercise. Some subjects also expressed sensations of low to moderate stomach discomfort during the bolus-dose trials. However, one of our subjects vomited immediately after an MW trial, without any indication of gastrointestinal discomfort during exercise. Thermoregulation is also differentially influenced by the temperature of ingested fluids.[23] Microdosing a fluid colder than an individual's T_c may be more advantageous for mitigating increases in PSI. The present study may have additionally benefitted from other common measures of hydration status (osmolality, plasma volume), renal response (glomerular filtration rate), or gastric aspiration.

Conclusions

These data demonstrate that fluid retention, PSI, and CHO oxidation during continuous work in the heat are unaffected by varied fluid delivery schedules of equal volume. However, administration of fluids to closely match fluid losses do not protect against accumulated thermal load at constant work rates. This key finding suggests that attention to work:rest ratios should be prioritized over aggressive hydration to mitigate thermal stress and heat-related injury risk. This is well understood and practiced by experienced WLFFs.[13] Regardless, individuals participating in extended, moderate work in the heat can rely on widely varied and flexible fluid delivery strategies as long as fluid volume accommodates individual sweat rates.

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