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Purpose: This study sought to determine the effect of rapid intravenous (IV) versus oral (ORAL) rehydration immediately after dehydration, on cardiovascular, thermoregulatory, and perceptual responses during subsequent exercise in the heat. Methods: Eight males (21.4 ± 0.7 yr; 176.2 ±1.6 cm; 75.2 ± 3.7 kg; 63.7 ± 3.6 mLokg-1omin-1 VO2max, 9.0 ± 1.7% fat) participated in three randomized trials. Each trial consisted of a 75-min dehydration phase (36-C; 42.5% rh, 47 ± 0.9% VO2max) where subjects lost 1.7 L (IV and no-fluid (NF) trials) to 1.8 L of fluid (ORAL trial). In the heat, fluid lost was matched with 0.45% saline in 20 min by either IV or ORAL rehydration; no fluid was given in the NF trial. Subjects then performed a heat-tolerance test (HTT; 37.0°C, 45% rh, treadmill speed of 2.4 mos-1, 2.3% grade) for 75 min or until exhaustion (Tre of 39.5°C). During the HTT, thermal and thirst sensations, RPE, rectal temperature (Tre), heart rate (HR), and mean weighted skin temperature (Tsk) were measured. Results: Plasma volume in the IV treatment was greater (P<0.05) after rehydration compared with ORAL and NF. However, during the HTT there were no overall differences (P > 0.05) in HR, Tre, Tsk, RPE, thermal sensations, or HTT time (ORAL, 71 ± 8 min; IV, 73 T 5 min; NF, 39 ± 29 min) between the ORAL and IV treatments. Sensations of thirst were lower (P G 0.05) in ORAL compared with IV and NF, likely because of oropharyngeal stimuli. Conclusions: Despite a more rapid restoration of plasma volume, IV rehydration was not advantageous over ORAL rehydration in regards to physiological strain, heat tolerance, RPE, or thermal sensations.

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Rapid IV versus Oral Rehydration: Responses to Subsequent Exercise Heat Stress

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ABSTRACT

KENEFICK, R. W., K. M. O'MOORE, N. V. MAHOOD, and J. W. CASTELLANI. Rapid IV versus Oral Rehydration: Responses to Subsequent Exercise Heat Stress. *Med. Sci. Sports Exerc.*, Vol. 38, No. 12, pp. 2125–2131, 2006. **Purpose:** This study sought to determine the effect of rapid intravenous (IV) versus oral (ORAL) rehydration immediately after dehydration, on cardiovascular, thermoregulatory, and perceptual responses during subsequent exercise in the heat. **Methods:** Eight males (21.4 ± 0.7 yr; 176.2 ± 1.6 cm; 75.2 ± 3.7 kg; 63.7 ± 3.6 $mL \cdot kg^{-1} \cdot min^{-1}$ $\dot{V}O_{2max}$, 9.0 ± 1.7% fat) participated in three randomized trials. Each trial consisted of a 75-min dehydration phase (36°C; 42.5% rh, 47 ± 0.9% $\dot{V}O_{2max}$) where subjects lost 1.7 L (IV and no-fluid (NF) trials) to 1.8 L of fluid (ORAL trial). In the heat, fluid lost was matched with 0.45% saline in 20 min by either IV or ORAL rehydration; no fluid was given in the NF trial. Subjects then performed a heat-tolerance test (HTT; 37.0°C, 45% rh, treadmill speed of 2.4 $m \cdot s^{-1}$, 2.3% grade) for 75 min or until exhaustion (T_{re} of 39.5°C). During the HTT, thermal and thirst sensations, RPE, rectal temperature (T_{re}), heart rate (HR), and mean weighted skin temperature (T_{sk}) were measured. **Results:** Plasma volume in the IV treatment was greater ($P < 0.05$) after rehydration compared with ORAL and NF. However, during the HTT there were no overall differences ($P > 0.05$) in HR, T_{re}, T_{sk}, RPE, thermal sensations, or HTT time (ORAL, 71 ± 8 min; IV, 73 ± 5 min; NF, 39 ± 29 min) between the ORAL and IV treatments. Sensations of thirst were lower ($P < 0.05$) in ORAL compared with IV and NF, likely because of oropharyngeal stimuli. **Conclusions:** Despite a more rapid restoration of plasma volume, IV rehydration was not advantageous over ORAL rehydration in regards to physiological strain, heat tolerance, RPE, or thermal sensations. **Key Words:** THERMOREGULATION, HYDRATION, EXERCISE-INDUCED DEHYDRATION, FLUID REPLACEMENT

Dehydration resulting from physical exercise in the heat, followed by a brief period of rehydration and the continuation of activity or competition, is a common scenario for athletes, laborers, and military personnel. Restoration of body fluids through the use of rapid intravenous (IV) rehydration is typical in clinical settings to restore body fluid losses. More recently, the use of rapid IV rehydration has been used in these work–rehydration–work scenarios to quickly restore body fluid loss from thermoregulatory sweating. In the latter scenario, it is assumed IV rehydration provides a more rapid restoration of body fluid by circumventing factors such as gastric emptying and intestinal absorption associated with oral rehydration. However, to our knowledge, no investigation has studied rapid IV rehydration in a work–rehydration–subsequent work scenario comparable with those commonly employed in athletic or occupational situations.

Studies specifically comparing IV with oral rehydration have reported similar attenuation of cardiovascular and thermoregulatory strain and RPE during subsequent exercise in the heat, with a similar effect on exercise performance (2,3,12,17). However, these studies have either employed exercise in the heat to induce hypohydration on the day before experimental testing (2,12), have used rehydration protocols lasting more than 100 min (3,12,17), have not matched oral and IV fluid temperatures (2), or have not matched volume restoration with sweat losses incurred during exercise (2,3,11,12,17). To date, no study has employed a protocol that would represent a true event scenario where an individual would work, exercise or compete in the heat and become hypohydrated, rehydrate over a short period of time, and again exercise in a hot environment.

The purpose of this study was to determine the effects of rapid (< 30 min) IV versus oral rehydration immediately after dehydration, on cardiovascular, thermoregulatory, and perceptual responses during subsequent exercise in the heat. We hypothesized that IV rehydration would result in a more rapid restoration of plasma volume and body fluid compartments than would oral rehydration, thus allowing for greater heat tolerance and reduced physiological and perceptual strain (Table 1).

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METHODS

Subjects

Eight non–heat-acclimated men volunteered to participate in this investigation. Physical characteristics (mean ± SEM) were age, 21.4 ± 0.7 yr; height, 176.2 ± 1.6 cm; weight, 75.2 ± 3.7 kg; $\dot{V}O_{2max}$, 63.7 ± 3.6 mL·kg^{-1}·min^{-1}; % body fat, 9.0 ± 1.7%; and BMI, 24.3 ± 0.9 kg·m^{-2}. Subjects completed a written informed consent document and a medical history questionnaire after being informed of the purpose of the experiment and possible risks. The committee on the use of human subjects in research at the university approved all procedures.

Preliminary Testing

Height was measured using a stadiometer (Detecto, Webb City, MO), and body mass was determined using an electronic scale (General GE510, Cape Coral, FL). A modified Costill–Fox (5) treadmill test was used to determine $\dot{V}O_{2max}$ (mL·kg^{-1}·min^{-1}). Body density was estimated using skinfold calipers (Harpenden, Ann Arbor, MI) and procedures and equations as described by Jackson et al. (9). Percent body fat was then calculated using the Siri equation (21).

Experimental Testing

Experimental design. The subjects performed three experimental trials in a randomized order, separated by at least 1 wk. Experimental testing involved two experimental treatments and a control trial, each consisting of three stages: a dehydration phase (Dh), a rehydration phase (Rh), and a heat-tolerance test (HTT). Only the rehydration phase differed among trials. Rh treatments were randomly assigned and consisted of intravenous rehydration (IV; 0.45% saline), oral rehydration (ORAL; 0.45% saline), and no fluid (NF). We chose 0.45% saline because it can safely be administered as an IV fluid and is commonly used as an IV fluid in clinical, athletic, and occupational settings. Subjects were given detailed instructions on the recording of food and fluid intake and were then asked to maintain a 3-d dietary record during the 3 d before each experimental trial. These food diaries were then analyzed for energy, carbohydrate, fat, protein, sodium, and potassium content (Food Processor II, ESHA Research, Salem, OR). There were no differences ($P > 0.05$) among the experimental treatments in total kilocalories, carbohydrate, protein, fat, sodium, and potassium intake. Subjects were asked to refrain from any recreational or exercise training for 24 h before experimental testing. They were also instructed to drink 450 mL of water the night before testing, to drink 450 mL of water the morning of testing, and to abstain from eating for 12 h before each experimental treatment.

TABLE 1. Selected Dh variables (N = 8; mean ± SE).

	Oral	IV	NF
Pre-Dh P_{OSM} (mOsm·kg^{-1} H_2O)	286 ± 4*	290 ± 3	289 ± 3
Post-Dh P_{OSM} (mOsm·kg^{-1} H_2O)	300 ± 3^{+}	304 ± 2^{+}	298 ± 3^{+}
Dh %$\dot{V}O_{2max}$ (mL·kg^{-1}·min^{-1})	48.1 ± 2.4	46.8 ± 4.4	48.9 ± 4.6
Post-Dh % weight loss	2.4 ± 0.5	2.3 ± 0.5	2.3 ± 0.5

* Statistically different ($P < 0.05$) from corresponding IV value; $^{+}$ statistically different ($P < 0.05$) from corresponding pre-Dh value.

On arrival at the laboratory (0700–0800 h), subjects provided a urine sample for determination of urine specific gravity (USG; Spartan Refractometer, model A 300 CL, Japan). A USG of 1.023 ± 0.006 (1) was used to verify that the subject was adequately hydrated prior to each trial.

Subjects were then fitted with a monitor (UNIQ heartwatch, Computer Instrument Corp., Hempstead, NY) to measure heart rate (HR), and a flexible thermistor (Yellow Springs Instruments, series 401, Yellow Springs, OH) was inserted 10 cm beyond the external anal sphincter to monitor rectal temperature (T_{re}). A Teflon catheter was then inserted into a superficial forearm vein, and a male luer adapter (model 5877, Abbott Hospital, Inc., Chicago, IL) was inserted into the catheter port for acquisition of subsequent blood samples. The catheter port and male luer adapter were kept patent with heparin lock flush solution. In the IV trials only, a second cannula was placed in the opposite arm to administer the IV fluid during the Rh phase. The subject then entered the environmental chamber (Harris Environmental Systems, Andover, MA), which was set at 36.9 ± 0.1°C and 42.2 ± 1.5% rh, and stood quietly for a 20-min equilibration period. A 10-mL blood sample (baseline) was taken, and subjects then consumed a standard breakfast of one bagel, one banana, and 240–350 mL (depending on body weight) of fruit juice. This meal was served approximately 45–60 min before the start of the dehydration phase of the experiment and contained a total of 426 kcal, 1.7 g of fat, 98.5 g of carbohydrate, 9.7 g of protein, 395 mg of sodium, and 1180 mg of potassium.

Dehydration

Subjects were weighed immediately before the start of exercise in the Dh phase. During the Dh phase, the subjects walked or ran for 75 min at 50% $\dot{V}O_{2max}$ (mean treadmill speed of 2.4 m·s^{-1}, 2.3% grade) in the environmental chamber. Airflow (6.1 m·s^{-1}), generated by two fans, was directed at the subject to enhance evaporative sweat loss. Oxygen consumption ($\dot{V}O_2$) was measured every 8 min via a pnuemotach (Hans Rudolph, Kansas City, MO) attached to a metabolic cart (SensorMedics, Inc., Yorba Linda, CA) to ensure the proper exercise intensity. The mean %$\dot{V}O_{2max}$ for the three dehydration trials ranged from 47.0 to 49.1%. In addition, every 8 min, T_{re} and HR were monitored for safety. HR that exceeded 180 bpm for 5 min resulted in termination of testing, as did a rectal temperature of more than 39.5°C. Body weight was measured every 25 min. At the end of the Dh period, a 10-mL blood sample was drawn and analyzed.

Rehydration

After the Dh phase, subjects remained in the environmental chamber standing for the 30-min rehydration period

at 37°C. The first 5 min of the rehydration period consisted of taking a 10-mL blood sample and measuring body weight. This body weight was subtracted from the body weight measured immediately before starting exercise in the Dh phase, to determine the amount of fluid lost. Because subjects did not urinate during the Dh phase of the experiment, there was no need to correct weight loss for urine volume. During the next 20 min of rehydration, the entire amount of fluid lost during dehydration was matched with 0.45% saline (15°C) either by IV Rh (1710.0 ± 0.1 mL) or by ORAL Rh (1790.0 ± 0.2 mL), or, alternately, no fluid was given (NF). For the ORAL trial, the saline solution was mixed with a nonnutritive sweetener (1 g·225 mL^{-1} of 0.45% saline; Kool Aid) to improve palatability. Servings were administered in equal amounts every 4 min during the 20-min period. The composition of ORAL was 79.0 ± 1.0 mEq $Na^{+}\cdot L^{-1}$, 1.00 ± 0.01 mEq $K^{+}\cdot L^{-1}$, 2.5 ± 0.1 mEq $Ca^{++}\cdot L^{-1}$, and 146.0 ± 1.0 $mOsm\cdot kg^{-1}$ of water. During IV, Rh constant pressure was maintained on the saline bag to ensure a rapid flow rate (~85.5 $mL\cdot min^{-1}$). During the last 5 min of the rehydration period, body weight was again measured, and after rehydration (pre-HTT), 10-mL blood samples were drawn, skin thermistors were placed on each subject, and subjects urinated if needed. Skin thermistors (Yellow Springs Instruments, series 401, Yellow Springs, OH) were placed on the upper arm, chest, upper thigh, and calf of each subject's left side for measurement of mean weighted skin temperatures (T_{sk}) (16).

HTT

Immediately after the 30-min rehydration period, the subjects performed a 75-min HTT at the same workload (50% $\dot{V}O_{2max}$) of the Dh phase of the trial. Environmental conditions in the chamber were 37.0 ± 0.1°C, 42.2 ± 1.5% rh. Measures of T_{sk}, thirst (thirst) (7), and thermal (thermal) (8) sensations, ratings of perceived exertion (RPE), $\dot{V}O_2$, hemoglobin (Hb), hematocrit (Hct), and P_{osm} were measured at pre-HTT, minute 25, and post-HTT. As in the Dh phase, HR and T_{re} were monitored every 8 min for safety. HR exceeding 180 bpm for 5 min, T_{re} of more than 39.5°C, signs or symptoms of heat intolerance, or volitional exhaustion resulted in termination of the HTT.

Analysis of blood samples. Ten-milliliter blood measures were analyzed at five time points: pre-Dh, post-Dh, pre-HTT, 25 min, and post-HTT. Blood was transferred to tubes containing lithium heparin, and samples of whole blood were taken for analysis of Hb and Hct. Hct was determined in triplicate by the microcapillary technique after centrifugation for 4 min. Values were not corrected for trapped plasma. Hb was determined in triplicate by the cyanomethemoglobin method (Kit 525, Sigma Chemical, Inc. St. Louis, MO). Percent change in plasma volume (%ΔPV) was calculated using the equation of Dill and Costill (6) from appropriate Hct and Hb values. All %ΔPV values were calculated using postdehydration as the initial time point. Plasma volume was calculated using pre-Dh body mass (18), and changes in plasma volume were calculated using %ΔPV values. After centrifugation, plasma was separated and analyzed for P_{osm}. P_{osm} ($mOsm\cdot kg^{-1}$ H_2O) was measured in triplicate, via freezing-point depression (MicroOsmometer model 3MO, Advanced Instruments, Needham Heights, MA).

Statistical analysis. An analysis of variance (time × condition) with repeated measures was used to compare differences among the trials. A Newman–Keuls *post hoc* analysis was used to determine significant differences within and between conditions. A power analysis selecting conventional alpha ($P < 0.05$) and beta (0.20) values determined that eight subjects would be sufficient to detect a 10% improvement in physical performance during the HTT. All data are presented as means ± SE.

RESULTS

Dehydration

Pre-Dh USG were not different ($P > 0.05$) among treatments and the NF trial, averaging 1.010 ± 0.002. During IV treatment, pre-Dh P_{osm} was greater ($P < 0.05$) than during the ORAL treatment. However, by post-Dh (pre-HTT), P_{osm} values were elevated ($P < 0.05$) above pre-Dh values but were not different ($P > 0.05$) among the treatments and the NF trial. There were no differences ($P > 0.05$) in exercise intensity (%$\dot{V}O_{2max}$) during the Dh phase among the treatments and the NF trial. The percent of pre-Dh body weight lost in the Dh protocol was similar ($P > 0.05$) among the treatments and the NF trial.

Rehydration

There were no differences ($P > 0.05$) in the Rh time, total time post-Dh to pre-HTT, or volume of fluid given in the IV and ORAL trials. Urine volume was greater ($P < 0.05$) post-Rh in the IV treatment (505 ± 36 mL) compared with the NF (385 ± 35 mL) and ORAL (312 ± 48 mL) treatments. Post-Rh percent weight loss (compared with the pre-Dh body weight) was similar between the ORAL (0.4 ± 0.3%) and IV (0.26 ± 0.2%) treatments but was lower ($P < 0.05$) than NF (2.8 ± 0.5%).

HTT

Exercise time and intensity. The mean exercise time for the HTT was greater ($P < 0.05$) in the ORAL (70.6 ± 8.2 min) and IV (72.6 ± 4.7 min) treatments compared with NF (38.7 ± 28.9 min). Exercise intensity (relative or %$\dot{V}O_{2max}$) throughout the HTT was not different ($P > 0.05$) among the three treatments. The average oxygen uptake and average %$\dot{V}O_{2max}$ during the HTT for all three treatments was 31.5 ± 6.0 $mL\cdot kg^{-1}\cdot min^{-1}$ and 49.2 ± 4.3%, respectively. Percent body weight lost during the HTT was 2.28 ± 0.4% in the ORAL trial, 2.55 ± 0.6% in the IV trial, and 1.3 ± 0.7% in the NF trial. During the NF trial, one subject was unable to start the HTT because of syncope and symptoms of heat exhaustion. This subject's data are included in the analysis of the Dh and Rh phases of the

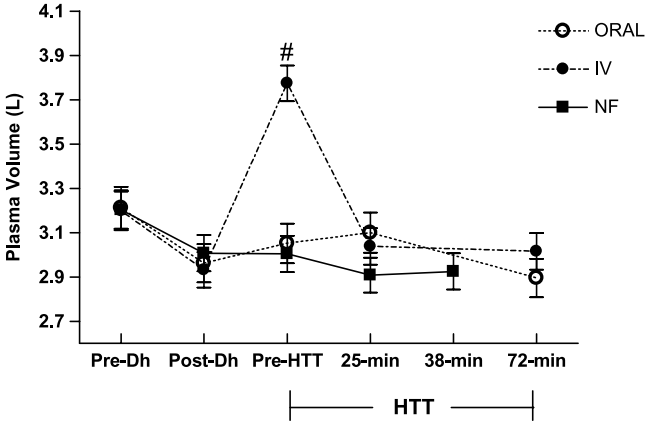

FIGURE 1—Plasma volume as a function of time after rehydration and during the HTT. Values are means ± SE; ORAL and IV, $N = 8$; NF, $N = 7$. Pre-Dh is considered the reference point. # Significant difference ($P < 0.05$) from corresponding ORAL and NF values. Mean exercise time for the HTT was 38.7 ± 28.9 min in the NF, 70.6 ± 8.2 min in the ORAL, and 72.6 ± 4.7 min in the IV trials.

experiment; however, in the analysis of the HTT, $N = 7$ for the NF trial, compared with $N = 8$ for the ORAL and IV treatments. During the NF trial, three subjects were able to complete the 75-min HTT, and four completed 50 min of the HTT. Of the four subjects who stopped at 50 min of the HTT during the NF trial, one was stopped because of a core temperature of 39.5°C, and the other three stopped because of volitional exhaustion. Only one subject stopped at 50 min of the HTT in the ORAL and IV treatments because of volitional exhaustion.

Osmolality and hemodynamic responses. Pre-HTT (post-Dh) P_{osm} values were significantly ($P < 0.05$) elevated from pre-Dh values but were not different ($P > 0.05$) among treatments and the NF trial, averaging 302.7 ± 2.3 mOsm·kg^{-1} H_2O. In addition, at 25 min and post-HTT, P_{osm} were not different ($P > 0.05$) among the treatments and the NF trial. The mean of the NF trial and treatments at 25 min was 302.0 ± 1.7 mOsm·kg^{-1} H_2O and 306.7 ± 1.7 mOsm·kg^{-1} H_2O post-HTT. Pre-HTT plasma volume in the IV treatment was greater ($P < 0.05$) compared with the corresponding plasma-volume value in the ORAL treatment and the NF trial. At 25 min of the HTT and post-HTT, plasma volume was not different ($P > 0.05$) among the NF trial and the treatments (Fig. 1).

Cardiovascular and thermoregulatory responses. In the NF trial, measures of HR at the pre-HTT and 25-min time points were greater ($P < 0.05$) than corresponding ORAL and IV values. HR was not different ($P > 0.05$) among the treatments and the NF trial at the post-HTT time point (Fig. 2A). T_{re} was lower ($P < 0.05$) pre-HTT in the IV treatment compared with the ORAL and NF trials. However, T_{re} was not different ($P > 0.05$) among the treatments or in the NF trial at the 25-min and post-HTT time points (Fig. 2B). T_{sk} was not different ($P > 0.05$) among the treatments or in the NF trial at the pre-HTT and 25-min time points. However, T_{sk} in the NF trial was greater ($P < 0.05$) post-HTT compared with the ORAL and IV treatments (Fig. 2C).

Perceptual responses. The NF trial pre-HTT and 25-min thermal sensations were greater ($P < 0.05$) compared with ORAL and IV. However, thermal sensations were not different ($P > 0.05$) among the treatments and the NF trial at the 25-min and post-HTT time points (Fig. 3A). RPE was not different ($P > 0.05$) among the treatments and the NF trial at the pre-HTT, 25-min, and post-HTT time points (Fig. 3B). Sensations of thirst were different ($P < 0.05$) among the treatments and in the NF trial at the pre-HTT and 25-min time points. However, both

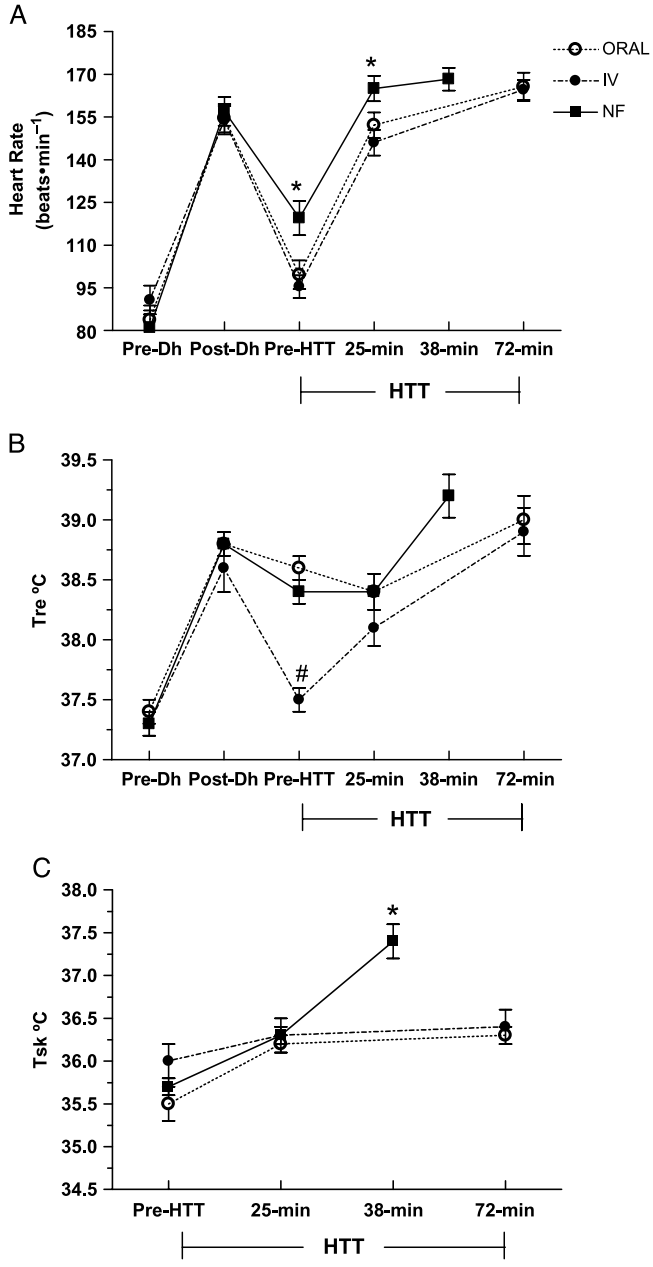

FIGURE 2—Heart rate (*A*), T_{re} (*B*), and T_{sk} (*C*) as functions of time after rehydration and during the HTT. Values are means ± SE; ORAL and IV, $N = 8$; NF, $N = 7$. * Significant difference ($P < 0.05$) from corresponding ORAL and IV values; # significant difference ($P < 0.05$) from corresponding ORAL and NF values. Mean exercise time for the HTT was 38.7 ± 28.9 min in the NF, 70.6 ± 8.2 min in the ORAL, and 72.6 ± 4.7 min in the IV trials.

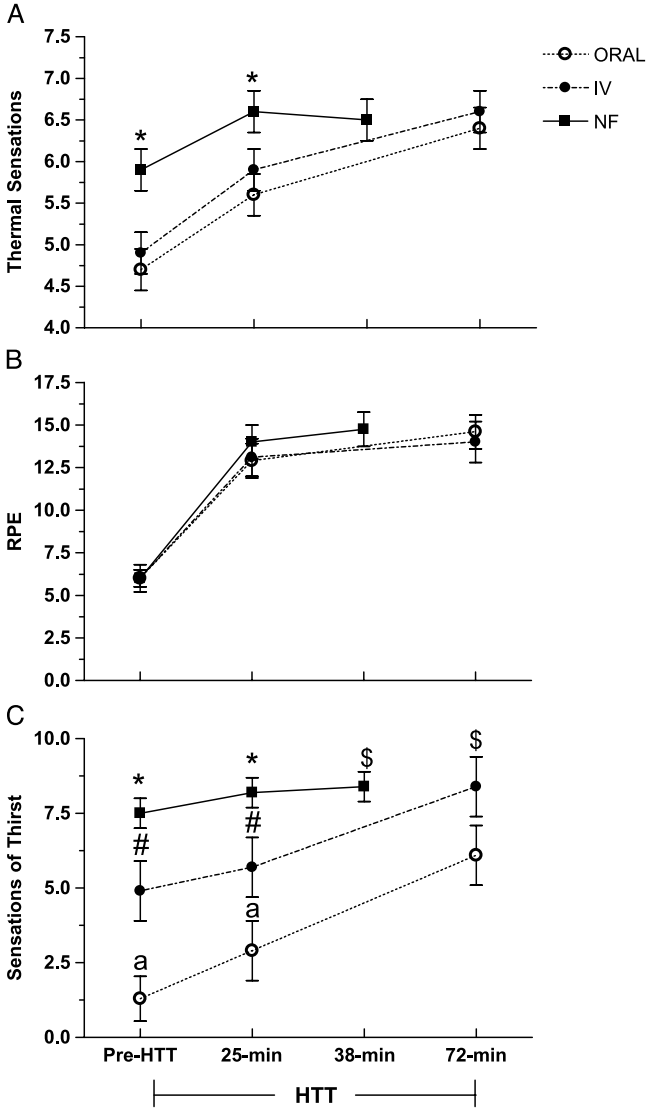

FIGURE 3—Thermal sensations (*A*), RPE (*B*), and sensations of thirst (*C*) as functions of time after rehydration and during the HTT. Values are means ± SE; ORAL and IV, *N* = 8; NF, *N* = 7. * Significant difference ($P < 0.05$) from corresponding ORAL and IV values; # significant difference ($P < 0.05$) from corresponding ORAL and NF values; a significant difference ($P < 0.05$) from corresponding IV and NF values; $ significant difference ($P < 0.05$) from corresponding ORAL values. Mean exercise time for the HTT was 38.7 ± 28.9 min in the NF, 70.6 ± 8.2 min in the ORAL, and 72.6 ± 4.7 min in the IV trials.

the IV and NF post-HTT sensations of thirst were greater ($P < 0.05$) compared with ORAL (Fig. 3C).

DISCUSSION

The purpose of this study was to determine the effects of rapid IV versus oral rehydration immediately after a dehydration-exercise bout on heat tolerance and cardiovascular, thermoregulatory, and perceptual responses during subsequent exercise in the heat. This is the first study we are aware of that has attempted to match fluid loss with fluid restoration and fluid temperature within a limited period of time (~20 min) for rehydration. Theoretically, IV rehydration should cause a more rapid plasma-volume restoration compared with oral rehydration. Thus, we hypothesized that the more readily available fluid after IV rehydration would allow for better thermoregulation, less cardiovascular and perceptual strain, and greater heat tolerance. The findings of the present study demonstrate that plasma volume was restored more rapidly and that T_{re} was significantly reduced immediately after IV rehydration. Despite this response, there were no significant improvements in exercise duration or reductions in cardiovascular and thermoregulatory strain, thermal sensations, and ratings of perceived exertion between oral and IV rehydration during subsequent exercise in the heat. Sensations of thirst, however, were significantly lower in the ORAL treatment compared with the IV and NF treatments.

The dehydration protocol used in the present study induced a modest (2.8%) decrease in body mass and resulted in a significant decrease in plasma volume. We chose this work–rehydration–work scenario because it would represent an exercise duration and intensity similar to a variety of actual sporting events or work settings. Despite the modest fluid losses seen here, we believe that the results of this study would be similar if a larger fluid loss occurred from any combination of greater exercise duration, intensity, or environmental heat stress, provided that the fluid loss was matched with fluid intake during rehydration.

Although rehydration duration and fluid volume were not different between the IV and ORAL treatments, plasma volume in the IV treatment was restored above pre-Dh values and was higher at the beginning of subsequent exercise. Studies that have used IV versus oral saline rehydration after a dehydration protocol have reported varied changes in plasma volume. Castellani et al. (3) reported no difference in the percent change in plasma volume between oral and IV rehydration with 0.45% saline after a 75-min rest period and during exercise in the heat. Differences between the present study and that of Castellani et al. (3) are likely attributable to their measurement of the percent change in plasma volume after 75 min of rest. We previously (11) reported a more rapid plasma-volume restoration with 0.9 and 0.45% IV rehydration compared with 0.45% oral rehydration. In that study, by 35 min of rest after rehydration, there were no differences in plasma-volume restoration between the IV and oral treatments. Maresh et al. (12) and Casa et al. (2), using 0.45% IV rehydration, reported plasma-volume restoration rates similar to those seen the present study, despite using a protocol that induced dehydration on the day before experimental testing and rehydration back to −2% of initial body weight. By 5 min of exercise in the heat in those studies (2,12), and by 25 min of exercise in the present study, there were no differences in the changes in plasma volume between the IV or oral treatments.

It is likely that the fluid that directly enters the vasculature with IV rehydration is distributed to all body fluid compartments and does not stay in the vasculature

specifically. Hypohydration induced by exercise heat stress has been shown to cause a loss of fluid not only from plasma but also from interstitial and intracellular fluid volumes (4,20). General calculations predict that the administration of 1.8 L of 0.45% saline, as in the present study, could be expected to increase plasma volume after equilibration by approximately 144 mL, extracellular fluid by 1056 mL, and intracellular fluid by 600 mL (13). Based on previous findings (2,11) and those of the present study, equilibration of IV fluid occurs by 35 min of rest and within 5–25 min of exercise. Thus, rapidly infusing intravenous saline for 20 min is no more advantageous in plasma-volume restoration than drinking the same solution by 25 min of exercise.

Both IV and ORAL rehydration occurred in a 37°C environment; however, immediately after rehydration, T_{re} was 1.0°C lower in the IV treatment compared with ORAL and NF. This difference in T_{re} after IV rehydration may be attributed to a number of possible causes. First, it is possible that the large volume of 15°C fluid rapidly entering the vasculature may have contributed to the lower T_{re} observed. Using predictive equations by Kay and Marino (10), the addition of 1.7 L of fluid at 15°C would theoretically lower body core temperature by 0.7°C. It is also possible that during the rehydration period, the more rapid restoration of plasma volume may have reestablished skin blood flow and sweating responses, permitting greater thermoregulation. Either of these factors individually, or in combination, may account for the 1°C decrease in T_{re} immediately after IV rehydration. However, it is important to note that by 25 min of exercise during the HTT, T_{re} levels were not different among any of the treatments.

During the HTT, skin temperatures were not different between the two rehydration treatments, and they were significantly lower than for NF at the end of the HTT (Fig. 2C). In addition, the percent body-weight loss between the ORAL and IV treatments was not different, indicating that during exercise, total sweat losses were not different. Castellani et al. (3) also did not observe differences in sweat rate, T_{re}, or T_{sk} between oral and IV rehydration during exercise in a hot environment. However, Casa et al. (2) observed lower T_{re} and T_{sk} during exercise in the heat after oral rehydration compared with IV rehydration. Differences in T_{re} and T_{sk} between our study and that of Casa et al. (2) may be attributable to the different temperatures of the oral and IV fluids administered. In their study, the oral fluid and IV fluid were 10°C and 22°, respectively. Accumulation of approximately 1.35 L at 10°C in the stomach could create a heat sink where a large volume of cooler fluid would pull heat from the body. Theoretical calculations using their mean data at time point zero predict a 0.6°C change in core temperature, which is the approximate difference between actual control and drink rectal temperatures at that time point (10).

One especially unique finding in the present study is that regarding sensations of thirst. A strong relationship between P_{osm} and thirst sensation has been well defined (15,22). However, gargling with tap water has been shown to reduce sensations of thirst despite elevated P_{osm} (19). In the present study, P_{osm} was significantly elevated after dehydration and was not different among the rehydration and NF treatments throughout the HTT. Despite this lack of difference in P_{osm}, sensations of thirst remained lower in the ORAL trial compared with the IV and NF treatments throughout the HTT. Maresh et al. (12) also did not observe differences in P_{osm} with oral and IV rehydration using half-normal saline, reporting lower sensations of thirst with oral rehydration. Riebe et al. (17) reported greater P_{osm} with no rehydration compared with IV and oral rehydration with 0.45% saline. They also reported significantly lower sensations of thirst with oral rehydration compared with IV, and they attributed this finding to stimulating oropharyngeal receptors. The findings of these previous studies (12,17,19) and those of the present study suggest that thirst sensation might be influenced to a greater extent by reflexive oropharyngeal mechanisms than P_{osm}.

There is the possibility that a learned response regarding thirst sensation could exist, such as feeling thirsty after exercising in a hot environment, which could have altered the reports of thirst perception. However, in order not to influence reports of thirst sensation, subjects in the present study were only informed of the general purpose of study, and not of the specific research question regarding thirst perception. Further, while a learned response might have contributed to subjects' reports of thirst sensation, within each experimental treatment and the NF trial, subjects' reports were consistent (Fig. 3C). In the present study, neither thermal sensations nor RPE were different between the rehydration treatments throughout the HTT (Fig. 3A and B). Maresh et al. (12) suggest that thermal sensations are an important cue to perception of exertion during exercise in the heat. They reported lower thermal sensations and ratings of perceived exertion at 15 min of exercise in the heat with oral rehydration. In addition, they reported a strong correlation ($r = 0.83$) between T_{sk} and thermal sensations with oral rehydration. In particular, T_{sk} has been reported to account for much of the variance in RPE in a hot environment (14). However, in the present study there was a weak correlation ($r = 0.33$) between T_{sk} and thermal sensations for all of the treatments. Differences between the findings of Maresh et al. (12) and those of the present study may be attributable to the different temperatures of fluids used in oral (10°C) and IV (22°C) rehydration. Because we did not observe any overall differences in T_{re} and T_{sk} between the rehydration treatments, it stands to reason that IV and oral rehydration equally attenuated thermal sensations and perceived exertion compared with NF. Our findings are in agreement with Riebe et al. (17), who, despite reporting strong correlations between T_{sk} and overall RPE, did not observe significant differences in T_{sk} or RPE between oral and IV rehydration treatments.

We had hypothesized that the greater plasma-volume restoration associated with IV rehydration would allow for a greater ability to thermoregulate, less cardiovascular and perceptual strain, and a greater ability to perform exercise in the heat. Similar to core and skin temperature, there were no differences in cardiovascular strain between the

ORAL and IV rehydration treatments, as HR during the HTT were not different (Fig. 2A). Casa et al. (2) also did not report differences in HR with rehydration back to −2% body weight using either 0.45% oral and IV rehydration during exercise at 74% $\dot{V}O_{2peak}$, in 37°C. Given that we did not observe differences in thermoregulatory, cardiovascular, or perceptual strain between the two rehydration treatments, it is not surprising that exercise time in the heat was not different. Studies that have examined the effect of IV versus oral rehydration on exercise time (2,3,11,12) have also not reported any significant differences. Thus, the initial increase in plasma volume after IV rehydration does not seem to offer any cardiovascular, thermoregulatory, or perceptual benefit that would ultimately contribute to a greater ability to exercise in a hot environment. These data suggest that preexercise plasma-volume values are not important, as long as fluid is resorted and available during subsequent exercise.

CONCLUSION

The findings of the present study demonstrate that although plasma volume was restored more rapidly by IV rehydration, there were no overall differences in heat tolerance, cardiovascular and thermoregulatory responses, thermal sensations, or ratings of perceived exertion between oral and IV rehydration. IV rehydration was responsible for a 1°C lower core temperature immediately after rehydration. However, by 25 min of exercise, there was no difference in core temperature among any of the treatments. Compared with IV and NF, sensations of thirst were significantly lower during oral rehydration, likely because of oropharyngeal stimuli. Despite a more rapid restoration ofplasma volume, IV rehydration did not offer any performance advantage over drinking or in relieving cardiovascular, thermoregulatory, or perceptual strain during moderate exercise in the heat.

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