Performance Benefits of Rehydration with Intravenous Fluid and Oral Glycerol

SIMON P. VAN ROSENDAL[1], NATALIE A. STROBEL[1], MARK A. OSBORNE[1,2], ROBERT G. FASSETT[1,3], and JEFF S. COOMBES[1]

[1]Human Performance Laboratory, School of Human Movement Studies, The University of Queensland, Brisbane, Queensland, AUSTRALIA; [2]Queensland Academy of Sport, Brisbane, Queensland, AUSTRALIA; and [3]School of Medicine, The University of Queensland, Brisbane, Queensland, AUSTRALIA

ABSTRACT

VAN ROSENDAL, S. P., N. A. STROBEL, M. A. OSBORNE, R. G. FASSETT, and J. S. COOMBES. Performance Benefits of Rehydration with Intravenous Fluid and Oral Glycerol. *Med. Sci. Sports Exerc.*, Vol. 44, No. 9, pp. 1780–1790, 2012. **Purpose**: Intravenous (IV) saline has been used by athletes attempting to accelerate rehydration procedures. The diuresis from IV rehydration may be circumvented through the concomitant use of oral glycerol. We aimed to examine the effects of rehydrating with four different regimens of IV fluid and oral glycerol on subsequent 40-km cycling time trial performance. **Methods**: Nine endurance-trained men were dehydrated by 4% bodyweight via exercise in the heat. They then rehydrated with 150% of the fluid lost via four protocols using a randomized crossover design: 1) oral = sports drink and water; 2) oral glycerol = sports drink, water, and glycerol; 3) IV = half as normal saline, half of sports drink, and water; and 4) IV with oral glycerol = half as normal saline, half as sports drink, water, and glycerol. After this, they completed a 40-km cycling performance test in the heat. **Results**: Compared with oral rehydration, there were significant performance benefits ($P < 0.05$) when rehydrating with oral glycerol (improved time to complete 40 km by 3.7%), IV (3.5%), and IV with oral glycerol (4.1%). Plasma volume restoration was highest in IV with oral glycerol, then IV, then oral glycerol, then oral ($P < 0.01$ for all of these comparisons). There were no differences in HR, tympanic/skin temperatures, sweat rate, blood lactate concentration, thermal stress, or RPE between groups. **Conclusions**: Combining IV fluid with oral glycerol resulted in the greatest fluid retention; however, it did not improve exercise performance compared with either modality alone. **Key Words:** CYCLING, DEHYDRATION, FLUID RETENTION, PLASMA VOLUME

APPLIED SCIENCES

Hydrating with intravenous (IV) fluid remains a popular technique for use by some athletes before, during, and/or after competition. This is despite the fact that the World Anti-Doping Agency (WADA) added IV fluid infusions to Section M2 of their list of prohibited substances and methods in 2005 (38). Indeed, a recent survey found that 75% of National Football League teams report regularly administering 1.5 L of normal saline to up to 20 players, 2 h before a game (10). From a performance perspective, the major ergogenic appeal associated with IV rehydration is a rapid plasma volume expansion. With hypervolemia, the augmented plasma volume is then available to assist with maintaining the balance between skin blood flow to aid in heat dissipation and central blood flow to maintain mean arterial pressure and perfusion of internal organs. With progressive dehydration, this balance tips toward maintaining the perfusion of the essential organs as a priority over skin blood flow (1), which may compromise thermoregulation and reduce the sweat rate ultimately impeding physical, cognitive, and skilled performance and possibly increasing the athlete's risk of exertional heatstroke. Although the use of IV fluids is intuitively beneficial, previous studies evaluating performance after IV rehydration in athletes have found no benefit compared with rehydration with oral fluids (4,5,9,20,21). A factor likely contributing to the lack of benefit seen in these studies is that IV fluid was shown to produce a diuresis so that the increased blood volume was only maintained for a short period (~30 min).

When given orally with a fluid bolus, glycerol acts as an osmotic agent that promotes fluid retention and reduces urine output (37). Most glycerol hydration research has provided glycerol with fluid as a method to hyperhydrate before exercise (37). Beginning exercise in this "overhydrated" position delays the onset and/or progression of the effects of dehydration from reaching a threshold at which performance is compromised. Three studies have also investigated the addition of glycerol to rehydration solutions and all three observed that beverages containing glycerol were associated with significantly more rapid and complete restoration of

Address for correspondence: Jeff S. Coombes, Ph.D., School of Human Movement Studies, The University of Queensland, St Lucia, Queensland 4072, Australia; E-mail: jcoombes@uq.edu.au.
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plasma volume than water alone (18,25,34). Thus, the aim of this study was to assess the effects of IV and oral rehydration regimens, with and without glycerol, on subsequent exercise performance in the heat after acute exercise–induced dehydration. It was hypothesized that glycerol and IV rehydration would enhance exercise performance individually and cumulatively, with the greatest benefit seen in the IV with oral glycerol condition.

METHODS

Ethical Approval

Subjects were informed of all the risks and stresses of the study and gave their written informed consent. The study was approved by the University of Queensland Medical Research Ethics Committee.

Subjects

Nine endurance-trained male cyclists took part in this study. Their mean ± SD physical characteristics were as follows: age = 22.8 ± 3.9 yr, bodyweight = 74.1 ± 4.9 kg, height = 179.2 ± 4.7 cm, $\dot{V}O_{2max}$ = 64.8 ± 5.7 mL·kg^{-1}·min^{-1}. All subjects trained regularly and were nonsmokers. Inclusion criteria for the study were as follows: 1) male age 18–40 yr, 2) experienced cyclist (based on high training volumes and at least one competitive race), 3) high endurance training status ($\dot{V}O_{2max}$ > 55 mL·kg^{-1}·min^{-1}), and 4) consistently high training volumes for at least the preceding 2 months. Based on data collected in a pretrial screening questionnaire, subjects were excluded from participating in the study if they reported: 1) a history of current or previous renal, hepatic, cardiovascular, thermoregulatory, or endocrine disorders; 2) contraindications to exercising in the heat; 3) any current or chronic health problems or injuries; 4) the use of any diuretic during the preceding 4 wk; and 5) having made a blood donation in the preceding 3 months. Subjects had their trial session rescheduled if they 1) presented with an abnormally high temperature (>38°C), 2) reported to the laboratory in a dehydrated state based on their baseline urine osmolality reading (>700 mOsm) (32), or 3) failed to abide by the pretrial conditions detailed in the pretrial preparation section.

Graded Exercise Test

Each subject initially completed a graded cycle ergometer test to volitional exhaustion to determine his/her maximal oxygen uptake ($\dot{V}O_{2peak}$). The test was conducted in a temperate environment (22°C). The cycle ergometer used for the $\dot{V}O_{2peak}$ test and all subsequent trials was their own road bike mounted on a stationary wind trainer (Cyclosimulator CS1000; Cateye Co. Ltd., Osaka, Japan), as described previously (22). Thus, the bike setup was identical for all trials. The test protocol (7) and procedures for recording HR, minute ventilation, FeO_2, and $FeCO_2$ and for calibration of associated equipment have been reported by our group elsewhere (7). The average test duration was 19.8 ± 4.0 min. Ventilatory threshold (VT_1) was calculated as described by Lucia et al. (23).

Familiarization Trial and Performance Test Reliability

At least 1 wk after the $\dot{V}O_{2peak}$ test, subjects completed a familiarization trial of the performance test to be used during the experimental trials (30 min of cycling at a fixed work rate of 85% VT_1 followed by a 40-km time trial). Previous reliability studies have shown that the reproducibility of the 40-km time trial protocol used in the present study is significantly enhanced by a familiarization trial (the coefficient of variation (CV) was 0.9% for two trials after a familiarization trial compared with 3% when the familiarization trial was included in the analysis) (22). The familiarization trial also served to acquaint subjects with the performance test protocol and aimed to reduce any learning effect that may have otherwise occurred in the performance tests.

When the subjects arrived at the laboratory, the protocol was reexplained to them, and their bike was mounted to the wind trainer. For the initial 30-min component, subjects cycled at a self-selected intensity and cadence with HR corresponding to 85% VT_1. During this stage, HR (used to maintain intensity) was the only variable on display to the subjects. They were informed when they had completed 15 min. After 30 min, the subjects were instructed to stop cycling for 5 min and were allowed to dismount before starting the 40-km time trial. This break was included to keep the protocol consistent with that used in the experimental trials, whereby subjects were given the chance to void before starting the time trial. Subjects were also informed when they passed 10, 20, 30, 35, 36, 37, 38, 39, and 40 km. All performance variables including speed, distance, HR, and time were removed from view. During the performance test, subjects were given a small volume of water (0.5 mL·kg^{-1}) at the completion of 15 and 25 min of steady-state exercise and after 5, 15, 25, and 35 km of the time trial, to reduce the discomfort of a dry mouth and excessive thirst. No specific encouragement was given to the subjects at any stage during the performance test. The room temperature and relative humidity for the familiarization trials were 34°C and 60%, respectively.

In addition to the familiarization trials, we included reliability testing of the performance test because 1) we wanted to determine the meaningfulness of any performance benefits in the present study and 2) the 40-km time trial protocol was modified by including the 30-min steady-state (at 85% VT_1) component. The split protocol used in the present study is a variation of those used by others who indicate the benefit from combining a fixed workload component, allowing the ability to measure physiological parameters at a constant workload, with a performance test (15). Five subjects were tested, and CV of 1.24% and 0.66% were calculated for the distance traveled during the 30-min steady-state exercise and time to complete the 40-km time trial, respectively. Three of

these five subjects were a subset of those who completed the main study whereas two additional subjects completed the CV component only. These two additional subjects completed a familiarization trial and two trials used to calculate the CV, separated by 1 wk. Those who also did the major study completed a further two trials to calculate their CV after their experimental trials.

Pretrial Preparation

Subjects kept a food diary for the 3 d preceding each experimental trial and were asked to reproduce this diet as consistently as possible before each subsequent trial. Diet diaries were analyzed for total energy intake and for the intake of protein, fat (total, saturated, polyunsaturated, and monounsaturated), cholesterol, CHO, water, sodium, and potassium (FoodWorks Professional 2007; Xyris Software; Highgate Hill Qld, Australia, Pty Ltd.). Subjects were asked to refrain from strenuous training for 48 h and from alcohol and caffeine for 24 h before each experimental trial. During this preceding 24-h period, subjects were asked to consume at least 2 L of water. On the morning of each experimental trial, subjects were instructed to ensure euhydration by consuming a further 500 mL of plain tap water on waking. They also consumed a standardized breakfast comprising two slices of multigrain toast, two sachets of butter, two sachets of honey, a yogurt-topped muesli bar, and sufficient Sustagen (Nestlé Australia Ltd., Sydney, Australia) to make a total caloric intake of 70 $kJ \cdot kg^{-1}$. These measures were used to minimize variability in preexperimental hydration, hormonal, and metabolic status between subjects and treatments.

Experimental Protocol

At least 1 wk after the familiarization trial, subjects reported to the laboratory between 7:00 and 8:00 a.m. for their first experimental trial. Subsequent trials commenced at the same time for each individual subject to control for circadian variations. They were conducted at least 2 wk apart to allow sufficient time for replenishment of red blood cells between trials and to limit any change in the heat acclimation status of individual subjects. To reduce any training effect, subjects were asked to maintain their normal constant training programs around their experimental trials. Each subject completed four experimental trials that differed only by the rehydration treatments provided. The four rehydration treatments were as follows: 1) 100% oral fluid (of which 64% was CHO–electrolyte sports drink and 36% was distilled water; oral), 2) 100% oral fluid with oral glycerol (of which 64% was CHO–electrolyte sports drink with a total dose of 1.5 $g \cdot kg^{-1}$ glycerol and 36% was distilled water; oral glycerol), 3) 50% oral fluid (of which 88% was CHO–electrolyte sports drink and 12% was distilled water) and 50% IV fluid (0.9% NaCl; IV), and 4) 50% oral fluid (of which 88% was CHO–electrolyte sports drink with a total dose of 1.5 $g \cdot kg^{-1}$ glycerol and 12% was distilled water) and 50% IV fluid (0.9% NaCl; IV with oral glycerol). Differences in the relative amounts of oral fluid given as sports drink between the trials were due to maintaining a constant experimental solution volume for all conditions (although the total volume of oral fluid was halved in the IV trials). The total amount of exogenous CHO was then corrected during the standardized lunch as described in the equilibration section. These rehydration volumes were based on the American College of Sports Medicine's (32) recommendation of 150% of fluid lost during dehydration. The combinations of sports drink/water and IV fluids were based on protocols anecdotally used by professional sporting teams at the time of study design and because subjects reported feeling nauseous during pilot trials when trying to consume the whole rehydration volume as Gatorade (Pepsico, Plano, TX). Trials were run in a randomized order predetermined using a computer-based random number generator. Randomization and allocation were conducted by an individual not involved with the study. Treatments were given in a double-blind manner concerning glycerol ingestion. None of the subjects had consumed glycerol before participating in the study. Figure 1 shows the experimental protocol.

Baseline measurements. Subjects were asked not to urinate in the morning before arriving at the laboratory. Upon arrival, subjects voided to completely empty their bladders

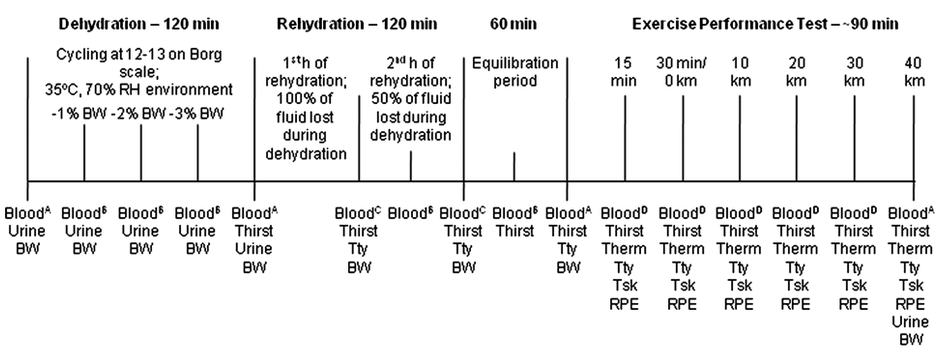

FIGURE 1—Experimental protocol for dehydration, rehydration, and exercise performance. *Vertical lines* indicate time points at which blood samples ([A]16 mL, [B]4 mL, [C]12 mL, [D]6 mL) were taken and outcome measures were assessed. RH, relative humidity; BW, bodyweight; Thirst, thirst sensation; Tty, tympanic temperature; Thermal, thermal sensation; Tsk, skin temperature.

and provided a urine sample for the determination of urine osmolality (Wescor 5500 vapor pressure osmometer; Wescor, Inc., South Logan, UT) to ensure euhydration. Adequate hydration was represented by an osmolality <700 mOsm (32). Tympanic temperature was measured using a tympanic thermometer (FirstTemp Genius Infrared thermometer, model 3000A; Sherwood Medical, St. Louis, MO). We also completed a small validation study comparing this thermometer with intestinal temperature measured by telemetry pills (CorTemp; HTI Technologies, Palmetto, FL) and found it to be highly correlated ($P = 0.93$) with a bias of −0.27°C. The thermometer was set on core temperature, and tympanic temperature was measured as the average of the left and right ears. Subjects then had their bodyweight recorded to the nearest 0.05 kg (Wedderburn Precision Digital Floor Scale; Wedderburn, Brisbane, Australia) while wearing only lycra cycling pants.

Subjects entered the environment chamber and rested for 5 min to equilibrate to the hot environment. A 21-gauge indwelling venous cannula was inserted into a forearm vein for blood extractions throughout the trial. A 10-cm cannula extension and a three-way stop cock were attached to the cannula for blood sampling. Blood was routinely taken with the subject in a seated posture to be consistent with samples taken during exercise. For all blood collections, a Luer lock access device was attached to the three-way stop cock. A serum vacutainer was used to remove the first 3 mL of blood that was discarded. Sample vacutainers were used in order of serum, lithium heparin, and then EDTA. After each sample, the Luer lock was removed, and the stop cock and cannula were flushed with normal saline (0.9% NaCl). Normal saline was also used to keep the cannula patent throughout the course of the trial. An aliquot of 500 μL of whole blood from each blood collection was transferred from the lithium heparin vacutainer to an Eppendorf tube to be used for the determination of hematocrit and hemoglobin. All vacutainers were then centrifuged at 2500*g* at 4°C for 10 min (IEC Centra MP4R Centrifuge, Needham Heights, MA) and the plasma or serum aliquoted and frozen at −80°C for later analysis. An HR monitor was then fitted (Polar T31; Polar Electro Oy, Kempele, Finland).

Dehydration. Subjects then began the dehydration protocol that was divided into 30-min blocks, comprising 23 min of cycling at a moderate intensity, followed by a 7-min rest. During the rest, subjects toweled dry, urinated if needed, and were weighed to monitor fluid loss. This procedure was repeated until subjects had lost 4% of baseline bodyweight. Tympanic temperature was monitored continuously throughout the dehydration protocol, and the session was terminated if it reached 40°C. Urine collected throughout the dehydration session was included as part of the weight loss. At the end of dehydration, subjects were also asked to report their thirst sensation using a 9-point thirst scale ranging from 1 (not thirsty) to 9 (very thirsty) (26).

Rehydration. ***Oral and oral glycerol trials.*** Throughout rehydration, subjects remained seated in a 22°C environment. In the first hour of the oral and oral glycerol trials, subjects consumed 100% of the fluid they lost during dehydration in six separate oral fluid volumes, consumed every 10 min. The first bolus was the first experimental solution comprising a volume of CHO–electrolyte beverage (Gatorade, made from powdered base and with a composition of 63 g of CHO, 470 mg Na^+, and 225 mg of K^+ per liter) equal to 40% of the total first hour rehydration volume, with (oral glycerol) or without (oral) a glycerol dose of 1 $g \cdot kg^{-1}$ bodyweight (Biotech Pharmaceuticals, Laverton North, Victoria, Australia). The remaining 60% of the first hour fluid volume was broken into five boluses of 12% each. The second, fourth, and sixth fluid boluses were distilled water, whereas the third and fifth fluid boluses were a CHO–electrolyte beverage (Gatorade). In the second hour of rehydration, a volume of fluid equal to 50% of that lost during dehydration was consumed so that the total fluid replacement equaled 150% of bodyweight lost. The second hour fluid regimen mirrored that used in the first hour, except that half the volume of fluid was given during each 10-min period. For the oral glycerol trials, the glycerol dose for the second experimental solution was also halved to 0.5 $g \cdot kg^{-1}$ so that the total glycerol dose was 1.5 $g \cdot kg^{-1}$ (before dehydration) bodyweight.

IV and IV with oral glycerol trials. For the IV and IV with oral glycerol trials, half of the total rehydration fluid volume was IV fluid (0.9% NaCl) and half was oral fluid. Again, the total volume of fluid provided in the first hour was 100% of the fluid lost during dehydration, with the remaining 50% provided in the second hour. Therefore, the first-hour IV and oral volumes were each 50% of the total bodyweight loss during dehydration, whereas the second-hour IV and oral volumes were each 25% of the total fluid intake. For the IV fluid, the saline bags were attached to the cannula already in place. The flow was started, and the saline was allowed to run at a rate of approximately 0.8 $mL \cdot kg^{-1} \cdot min^{-1}$ so that the correct volume of fluid was administered by the 50-min mark of the first hour. The IV line was then interrupted for 10 min, allowing the saline to disperse from within the vein before the first-hour rehydration blood sample was withdrawn. The second-hour IV fluid was then attached to the cannula and the line was opened. The flow was adjusted to approximately 0.4 $mL \cdot kg^{-1} \cdot min^{-1}$ so that the fluid was again administered during the first 50 min of the hour. While the IV was being administered, the subject remained seated and consumed the oral component of the rehydration volume. The oral protocol for the IV and IV with oral glycerol trials was the same as that described for the oral and oral glycerol trials, except that the experimental solutions were 80% of the total oral fluid to be consumed that hour and the remaining five drinks were each 4% of the total volume of oral fluid to be consumed that hour. These percentage changes were used to ensure that the experimental solutions were the same volume as in the oral trials. For the IV with oral glycerol trials, the experimental solutions once again comprised glycerol doses of 1 $g \cdot kg^{-1}$ (first hour) and 0.5 $g \cdot kg^{-1}$ bodyweight (second hour) in a CHO–electrolyte beverage (Gatorade).

All experimental solutions were mixed with sports drinks to ensure they had a similar temperature, color, texture, and flavor to mask the taste of glycerol. After consuming each experimental solution, the subjects were asked if they could distinguish whether they were receiving glycerol or not. Only one subject correctly identified the glycerol trials. Subjects were also questioned regarding adverse reactions, and no subjects reported experiencing adverse effects during any trial. All oral and IV fluids were given at 22°C to ensure a similar effect on core temperature between conditions. Other measurements taken during rehydration are displayed in Figure 1.

Postrehydration equilibration period. Subjects remained in a temperate environment (22°C) for the 60-min postrehydration equilibration period. They consumed a standardized lunch comprising two pieces of multigrain toast, two sachets of butter, two sachets of strawberry jam, and a yogurt-topped muesli bar. Subjects then consumed a calculated amount of solid CHO (jellybeans) to correct for the greater CHO consumption in the oral and oral glycerol trials from the larger volume of CHO–electrolyte sports drinks consumed. The total caloric intake of 70 $kJ \cdot kg^{-1}$ aimed to offset the energy used during the dehydration component of the trial. Subjects then reentered the environment chamber (34°C and 60% relative humidity) and were prepared to begin the exercise performance test.

Exercise performance test. Subjects were refitted with an HR monitor and had skin temperature recorded from the four sites to be used for exercise skin temperature (pectoralis, biceps, triceps, and subscapular). Skin temperature was calculated as the mean of the four sites using an infrared thermometer (FirstTemp Genius Infrared thermometer, model 3000A; Sherwood Medical) as used by Cornish et al. (6). Subjects then reported their perceived thermal stress using a 17-point thermal sensation scale with extremes of unbearably cold and unbearably hot (extended symmetrically from Gagge et al. [11]). At this time, subjects remounted their bike and began the 30-min steady-state exercise at 85% VT_1. An electric fan was directed at the subject from front on and delivered a constant wind speed at the subjects for all trials. The performance test was conducted as described in the familiarization trial. In addition to the measurements indicated in Figure 1, speed, distance, HR, and tympanic temperature were recorded every 5 min during the 30-min steady-state exercise. The blood samples collected during the performance test were handled the same way as the other blood samples except that a further 500-μL aliquot was transferred to a vacutainer containing sodium fluoride and potassium oxalate for the determination of plasma lactate and glucose concentrations.

During the 5-min break before starting the 40-km time trial performance test, subjects voided, if needed. With 30 s of the 5-min break remaining, subjects remounted the cycle ergometer and completed the 40-km time trial. In addition to measurements indicated in Figure 1, time, speed, HR, and tympanic temperature were recorded every 5 km. Whole body sweat rate during exercise was calculated from bodyweight changes, corrected for fluid intake and urine output. Sweat rate was not corrected for blood sample volumes, respiratory water losses, or metabolic water production because these were considered to be similar between trials.

Blood, urine, and net fluid balance analyses. All variables were analyzed in duplicate, and third measures were taken if the variation between samples was >3%. Urine was analyzed for osmolality using a vapor pressure osmometer with an overall CV of 0.6%. Hemoglobin was measured from the whole blood using the cyanmethemoglobin method (ATI Unicam 5625 UV/VIS Spectrometer set at 540 nm). Hematocrit was measured from the whole blood using 100 µL of heparinized capillary tubes, which were centrifuged at 14,000*g* for 5 min (Jouan HEMA-C microhematocrit centrifuge, Sussex, England). A Mikro-Hämatokrit chart was used to read the hematocrit reading. Hematocrit was not corrected for trapped plasma. The CV for the hemoglobin and hematocrit analyses were 0.9% and 0.3%, respectively. Percent change in plasma volume was calculated using the equations of Dill and Costill (8). Plasma lactate and glycerol were measured via automated analysis (Cobas Mira; Roche Diagnostic Systems, Basel, Switzerland). The CV for these assays were 2.4% and 2.6%, respectively. Net fluid balance was calculated from the change in bodyweight relative to baseline.

Data Analysis

The change in plasma volume was selected for the sample size calculation because it has the greatest variability compared to the other primary outcome measures (time trial performance, tympanic temperature, and sweat rate). Assuming that the difference in change in plasma volume between two of the trials that would be clinically significant would have an effect size of 0.9, we needed eight individuals ($P < 0.05$, power = 0.8). Because of the expected dropouts and withdrawals, we aimed to recruit 15 subjects. Data were initially tested for normality (Shapiro–Wilk normality test). One-way repeated-measures ANOVA with Tukey *post hoc* tests were used to compare group means. A general linear model with two-way repeated-measures ANOVA with Tukey *post hoc* tests were used to assess time × trial interactions, and Bonferroni corrections were used for multiple comparisons. Mauchly tests were used to examine sphericity for the two-way repeated-measures ANOVA, and datum that was not significant based on the Mauchly test was corrected based on the ε value. If $\varepsilon < 0.75$, then Greenhouse–Geisser corrections were used, whereas Huynh–Feldt corrections were used if ε was >0.75. Significance was then determined from these corrected significance values. One-way repeated-measures ANOVA were analyzed using GraphPad Prism 5 (GraphPad Software, Inc., La Jolla, CA), and two-way repeated-measures ANOVA were analyzed using SPSS for Windows (version 17.0; SPSS, Inc., Chicago, IL). The significance level was set at

TABLE 1. Nutritional assessment from food diaries recorded for 3 d leading up to each experimental trial.

	Oral	Oral Glycerol	IV	IV with Oral Glycerol
Total energy (MJ)	13.3 ± 3.4	14.1 ± 3.1	13.5 ± 3.7	14.1 ± 2.8
Protein (g)	138 ± 35	142 ± 43	132 ± 41	140 ± 42
Total fat (g)	113 ± 36	113 ± 33	111 ± 35	109 ± 36
Saturated fat (g)	43 ± 12	41 ± 16	39 ± 9	41 ± 15
Polyunsaturated fat (g)	18 ± 7	18 ± 6	21 ± 11	18 ± 6
Monounsaturated fat (g)	44 ± 18	44 ± 13	42 ± 17	41 ± 14
Cholesterol (mg)	355 ± 65	380 ± 134	330 ± 140	407 ± 122
CHO (g)	379 ± 102	397 ± 100	389 ± 126	399 ± 93
Na^+ (mg)	3565 ± 1117	3935 ± 1354	3550 ± 976	3873 ± 908
K^+ (mg)	5076 ± 1720	5140 ± 1545	5069 ± 1375	4974 ± 1455
Water (mL)	3499 ± 1773	3857 ± 1612	3561 ± 1927	4109 ± 1884

Values are mean of the 3 d ± SD; $n = 9$.

$P = 0.05$. All values presented are mean ± SD unless otherwise specified.

RESULTS

Fifteen individuals were recruited into the study; however, six withdrew. Of these, three withdrew because of their an inability to tolerate exercise in the hot/humid environment, two withdrew because they moved interstate before completing the experimental trials, and one was unable to participate because he was unable to be cannulated for blood collection. Therefore, data are presented for the nine subjects who completed the experiment.

Pretrial diet. There were no differences in pretrial nutritional dietary intakes between trials (Table 1).

Dehydration. Climate chamber conditions during dehydration were similar between conditions (temperature and relative humidity: oral = 34.9°C ± 0.6°C and 68.6% ± 8.3%, oral glycerol = 34.9°C ± 0.6°C and 68.9% ± 7.4%, IV = 35.2°C ± 0.6°C and 66.1% ± 7.4%, and IV with oral glycerol = 35.3°C ± 0.7°C and 72.2% ± 6.7%). Baseline bodyweight was also similar between conditions, and it decreased significantly ($P < 0.001$), but to a similar extent, in all four trials after dehydration (Table 2). On the basis of the technique to dehydrate, the reduction in bodyweight was attributable to water loss and the change was not different ($P > 0.05$) between conditions. The average time taken for dehydration and sweat rate were also not different ($P > 0.05$) between trials (Table 2).

Rehydration. Bodyweight increased significantly ($P < 0.001$) in all trials after rehydration (Table 2). There were no differences for total rehydration fluid volumes between trials or the volumes of experimental solutions 1 and 2 (Table 2). However, because the total volume of oral fluid was lower in the IV and IV with oral glycerol trials, the total volume of CHO–electrolyte beverage consumed during rehydration was higher ($P < 0.001$) in the oral and oral glycerol conditions (Table 2). To correct for this imbalance, the amount of solid CHO (jellybeans) consumed with the standardized lunch was higher ($P < 0.001$) in the IV and IV with oral

TABLE 2. Changes to hydration-related variables throughout dehydration, rehydration, and the performance test.

	Oral	Oral Glycerol	IV	IV with Oral Glycerol
Baseline				
Bodyweight (kg)	73.67 ± 4.65	74.02 ± 5.09	74.28 ± 5.11	74.41 ± 4.91
Dehydration				
Decrease in bodyweight (%)	4.01 ± 0.86	4.05 ± 0.65	4.02 ± 0.79	3.88 ± 0.82
Time taken for dehydration (min)	106.1 ± 14.4	112.8 ± 11.5	107.8 ± 16.6	106.1 ± 12.2
Sweat rate ($L \cdot h^{-1}$)	1.5 ± 0.4	1.5 ± 0.4	1.5 ± 0.6	1.5 ± 0.4
Rehydration				
Increase in bodyweight (%)	5.24 ± 1.49	5.68 ± 1.27	5.24 ± 1.11	5.79 ± 1.93
Total rehydration fluid volume (L)	4.4 ± 0.9	4.5 ± 0.7	4.5 ± 0.9	4.3 ± 0.9
Volume of experimental solution 1 (L)	1.2 ± 0.3	1.2 ± 0.2	1.2 ± 0.2	1.2 ± 0.2
Volume of experimental solution 2 (L)	0.6 ± 0.1	0.6 ± 0.1	0.6 ± 0.1	0.6 ± 0.1
Total volume of sports drink (L)	2.8 ± 0.6[a]	2.9 ± 0.5[a]	2.0 ± 0.4	1.9 ± 0.4
Solid CHO consumed (g)	10.4 ± 12.6	7.9 ± 13.3	66.2 ± 19.0[b]	68.7 ± 16.7[b]
Total CHO (from sports drink + solid) (g)	189.2 ± 30.1	189.2 ± 31.7	190.4 ± 30.8	188.8 ± 34.0
Total Na^+ intake from rehydration fluids (g)	1.33 ± 0.28	1.35 ± 0.22	8.86 ± 1.80[b]	8.57 ± 1.80[b]
Performance				
Decrease in bodyweight (%)	−3.94 ± 0.62	−3.51 ± 0.95	−3.76 ± 0.80	−3.58 ± 0.63
Net fluid balance (change from baseline)				
After dehydration (L)	−2.96 ± 0.62	−2.99 ± 0.47	−2.99 ± 0.61	−2.89 ± 0.61
After the first hour of rehydration (L)	−0.27 ± 0.17	−0.19 ± 0.14	−0.32 ± 0.42	0.01 ± 0.32
After the second hour of rehydration (L)	0.74 ± 0.43	1.03 ± 0.41	0.73 ± 0.50	1.23 ± 0.79[c]
After equilibration (L)	0.07 ± 0.46	0.44 ± 0.35	0.66 ± 0.38[d]	1.09 ± 0.53[d,e]
After performance (L)	−2.84 ± 0.55	−2.16 ± 0.62[f]	−2.16 ± 0.65[f]	−1.61 ± 0.49[f]

[a] Oral and oral glycerol > IV and IV with oral glycerol ($P < 0.001$).
[b] IV and IV with oral glycerol > oral and oral glycerol ($P < 0.001$).
[c] IV with oral glycerol > oral and IV ($P < 0.05$).
[d] IV and IV with oral glycerol > oral ($P < 0.01$).
[e] IV with oral glycerol > oral glycerol and IV ($P < 0.01$).
[f] Oral glycerol, IV, and IV with oral glycerol > oral ($P < 0.01$).

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glycerol trials so that the total CHO consumed from CHO–electrolyte beverage plus solid CHO was similar between trials (Table 2).

Exercise performance test. The total distance covered during the 30-min steady-state exercise component of the performance test was similar between conditions (oral = 16.66 ± 1.40 km, oral glycerol = 16.78 ± 1.80 km, IV = 16.62 ± 1.66 km, and IV with oral glycerol = 16.69 ± 1.58 km) and between all subjects. There were no significant differences between treatments during steady-state exercise for HR (Table 3) or plasma lactate or glucose concentrations (Table 3).

Figure 2 shows the 10-km splits and the total completion times for the 40-km time trial. There were no differences between trials during the first 20 km. However, time to complete the 20- to 30-km and 30- to 40-km splits was significantly lower in the oral glycerol, IV, and IV with oral glycerol trials compared to oral (Fig. 2). The total 40-km time trial time was also significantly lower in the oral glycerol, IV, and IV with oral glycerol trials compared to oral (difference from oral: oral glycerol = −2.44 min (95% confidence interval (CI) = 0.42–4.64 min, $P < 0.05$), IV = −2.30 min (95% CI = 0.25–4.47 min, $P < 0.05$), and IV with oral glycerol = −2.71 min (95% CI = 0.58–4.79 min, $P < 0.01$); Fig. 2), which equated

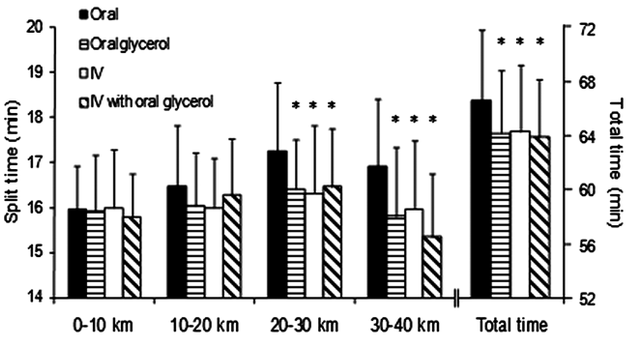

FIGURE 2—Split times for 10-km splits of the 40-km time trial plus the total 40-km time trial time. Data are presented as mean ± SEM ($n = 9$). *Oral glycerol, IV and IV with oral glycerol < oral, $P < 0.01$. SS, steady-state exercise; VT_1, ventilatory threshold.

TABLE 3. Plasma glycerol concentration and metabolic, thermoregulatory, cardiovascular, and perceptual variables measured during the exercise performance test.

	Before Performance	15 min Steady State	30 min Steady State/0 km	10 km	20 km	30 km	40 km
Glycerol (mmol·L^{-1})							
Oral glycerol	14.99 ± 3.03	14.01 ± 3.45	13.47 ± 3.80	12.52 ± 4.03	12.07 ± 4.38	11.51 ± 4.47	10.55 ± 4.62
IV with oral glycerol	14.85 ± 3.52	14.08 ± 3.08	13.28 ± 3.51	13.12 ± 3.37	12.68 ± 3.51	12.52 ± 4.02	10.14 ± 4.64
Lactate (mmol·L^{-1})							
Oral	1.99 ± 0.60	1.92 ± 0.57	1.65 ± 0.51	2.84 ± 1.47	2.65 ± 1.45	2.30 ± 0.96	4.62 ± 1.89
Oral glycerol	2.02 ± 0.39	1.82 ± 0.34	1.63 ± 0.43	2.78 ± 1.33	2.92 ± 1.44	2.72 ± 1.07	6.90 ± 4.07
IV	2.04 ± 0.26	2.07 ± 0.87	1.88 ± 0.91	2.94 ± 1.40	2.68 ± 1.45	3.00 ± 1.42	5.90 ± 2.87
IV with oral glycerol	1.79 ± 0.13	2.01 ± 0.83	1.80 ± 0.46	3.38 ± 1.56	3.26 ± 1.43	3.17 ± 1.91	6.86 ± 4.12
Glucose (mmol·L^{-1})							
Oral	4.96 ± 1.19	3.88 ± 0.91	4.85 ± 0.77	4.03 ± 0.86	4.18 ± 0.59	4.41 ± 0.78	4.68 ± 1.2[a]
Oral glycerol	4.98 ± 0.33	3.65 ± 0.53	4.86 ± 0.59	4.19 ± 0.51	4.58 ± 0.53	4.55 ± 0.57	6.46 ± 0.80
IV	5.28 ± 1.53	4.13 ± 0.89	4.84 ± 0.69	4.38 ± 0.51	4.60 ± 0.48	4.32 ± 0.37	5.11 ± 0.55[b]
IV oral glycerol	5.40 ± 0.76	3.62 ± 0.67	4.63 ± 0.53	4.14 ± 0.62	4.82 ± 0.62	4.80 ± 0.72	5.99 ± 1.11
Tympanic temperature (°C)							
Oral	36.5 ± 0.9	37.3 ± 0.7	37.4 ± 0.9	37.8 ± 0.9	37.9 ± 1.0	38.2 ± 1.0	38.2 ± 0.8
Oral glycerol	36.4 ± 1.5	37.7 ± 0.8	37.8 ± 1.0	37.8 ± 0.9	37.9 ± 1.0	38.1 ± 1.1	38.1 ± 1.3
IV	36.2 ± 1.1	37.4 ± 0.6	37.4 ± 0.7	37.6 ± 0.7	37.8 ± 0.8	38.0 ± 1.0	38.1 ± 1.1
IV with oral glycerol	36.5 ± 0.6	37.2 ± 0.7	37.4 ± 0.5	37.6 ± 0.8	38.1 ± 0.7	38.1 ± 0.7	38.3 ± 1.0
Skin temperature (°C)							
Oral	34.3 ± 2.2	35.6 ± 0.6	35.7 ± 0.4	35.9 ± 0.5	36.3 ± 0.6	36.3 ± 0.4	36.3 ± 0.3
Oral glycerol	35.4 ± 1.6	35.4 ± 0.6	35.7 ± 0.5	35.9 ± 0.8	36.0 ± 0.6	36.3 ± 0.6	35.9 ± 0.9
IV	34.6 ± 2.0	35.7 ± 0.1	36.1 ± 0.3	36.1 ± 0.4	36.4 ± 0.5	36.5 ± 0.3	36.4 ± 0.4
IV with oral glycerol	34.8 ± 2.5	35.7 ± 0.7	35.8 ± 0.6	36.0 ± 0.4	36.5 ± 0.4	36.4 ± 0.5	36.4 ± 0.7
HR (bpm)							
Oral	—	144 ± 7	144 ± 8	164 ± 13	169 ± 10	170 ± 11	184 ± 10
Oral glycerol	—	142 ± 5	143 ± 4	165 ± 10	173 ± 12	174 ± 12	188 ± 11
IV	—	145 ± 8	144 ± 7	163 ± 13	168 ± 12	173 ± 10	186 ± 11
IV with oral glycerol	—	143 ± 7	144 ± 5	161 ± 13	166 ± 12	168 ± 12	186 ± 11
Thirst sensation							
Oral	2 ± 1	3 ± 1	3 ± 1	4 ± 1	5 ± 1	6 ± 1	7 ± 1
Oral glycerol	2 ± 1	2 ± 1	3 ± 1	4 ± 1	5 ± 1	5 ± 1	6 ± 2
IV	2 ± 1	3 ± 1	3 ± 1	3 ± 1	5 ± 1	6 ± 1	7 ± 1
IV with oral glycerol	3 ± 1[c]	3 ± 1	3 ± 1	4 ± 2	5 ± 1	6 ± 1	7 ± 1
Thermal sensation							
Oral	0.8 ± 0.9	1.5 ± 0.8	1.7 ± 0.6	2.1 ± 0.6	2.3 ± 0.5	2.9 ± 0.4	3.3 ± 0.4
Oral glycerol	1.0 ± 0.5	1.5 ± 0.4	1.9 ± 0.4	2.2 ± 0.4	2.8 ± 0.4	2.9 ± 0.5	3.2 ± 0.5
IV	0.7 ± 0.7	1.4 ± 0.5	1.7 ± 0.7	2.1 ± 0.6	2.3 ± 0.6	2.6 ± 0.7	3.2 ± 0.7
IV with oral glycerol	0.3 ± 0.9	1.3 ± 0.5	1.6 ± 0.7	1.8 ± 0.6	2.3 ± 0.5	2.6 ± 0.7	3.2 ± 0.4
RPE							
Oral	—	13 ± 1	13 ± 1	15 ± 1	16 ± 1	16 ± 1	19 ± 1
Oral glycerol	—	13 ± 1	13 ± 1	15 ± 1	15 ± 1	16 ± 1	18 ± 1
IV	—	13 ± 1	13 ± 1	15 ± 1	16 ± 1	17 ± 1	19 ± 2
IV with oral glycerol	—	13 ± 1	13 ± 1	15 ± 1	16 ± 1	16 ± 1	19 ± 1

[a] Oral < oral glycerol and IV with oral glycerol ($P < 0.05$).
[b] IV < oral glycerol ($P < 0.05$).
[c] IV with oral glycerol > oral glycerol ($P < 0.05$).

to performance benefits of 3.7%, 3.5%, and 4.1% for oral glycerol, IV, and IV with oral glycerol, respectively, compared to oral. Plasma glucose concentration was significantly higher in oral glycerol and IV with oral glycerol compared to oral and in oral glycerol compared to IV at the end of the 40-km time trial (Table 3). However, there were no differences between conditions for HR or plasma lactate concentration (Table 3).

Plasma volume and glycerol. Plasma volume decreased during dehydration in all groups ($P < 0.001$) but to a similar extent ($P > 0.05$) between groups (Fig. 3). During rehydration, plasma volume increased in all groups ($P < 0.001$). Overall, both IV trials showed significantly greater increases for plasma volume than the two oral trials. The addition of glycerol to the rehydration solutions also increased plasma volume significantly higher than the corresponding fluid regimen without glycerol. Therefore, plasma volume was highest in IV with oral glycerol, followed by IV, then oral glycerol, and then oral ($P < 0.01$ for all of these comparisons).

Glycerol concentration increased significantly ($P < 0.001$) after the first hour of rehydration in both the oral glycerol (11.46 ± 2.62 mmol·L^{-1}) and IV with oral glycerol (9.91 ± 3.24 mmol·L^{-1}) trials. Peaks were 16.42 ± 1.65 mmol·L^{-1} after the second hour of rehydration in the oral glycerol trial and 16.36 ± 1.93 mmol·L^{-1} at the midequilibration time point in IV with oral glycerol. Glycerol levels then decreased during the performance test (Table 3). There were no differences between oral glycerol and IV with oral glycerol at any stage. Glycerol concentrations were too low to be detected during dehydration in the oral with glycerol and IV with oral glycerol trials and at all time points during the oral and IV conditions.

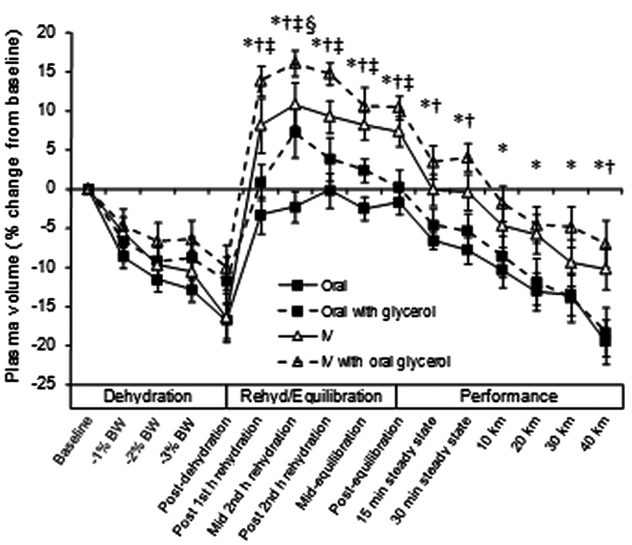

FIGURE 3—Percent change in plasma volume during exercise-induced dehydration (−4% bodyweight), rehydration with 150% of fluid lost, passive equilibration, and an exercise performance test. See Methods section for detail of the experimental procedures. Data are presented as mean ± SEM ($n = 9$); $P < 0.05$. Oral versus IV with oral glycerol. ‡Oral glycerol versus IV with oral glycerol. §Oral versus oral glycerol. #IV versus IV with oral glycerol. $Oral glycerol versus IV. BW, bodyweight; Rehyd, rehydration.

Urine osmolality. Urine osmolality was similar between trials at baseline (oral = 400.8 ± 290.8 mOsm, oral glycerol = 332.6 ± 131.0 mOsm, IV = 317.3 ± 182.5 mOsm, and IV with oral glycerol = 367.7 ± 143.7 mOsm).

Thermoregulatory responses. Both tympanic and skin temperatures were similar between trials at all times during the performance test (Table 3). Sweat rate during the performance test was also similar between trials (oral = 1.6 ± 0.3 L·h^{-1}, oral glycerol = 1.5 ± 0.5 L·h^{-1}, IV = 1.7 ± 0.4 L·h^{-1}, and IV with oral glycerol = 1.7 ± 0.4 L·h^{-1}).

Perceptual measures. Thirst sensation at the end of dehydration (oral = 6 ± 2, oral glycerol = 7 ± 1, IV = 7 ± 1, and IV with oral glycerol = 6 ± 1) and the first hour of rehydration (oral = 2 ± 1, oral glycerol = 2 ± 1, IV = 3 ± 1, and IV with oral glycerol = 3 ± 2) was similar in all conditions. Thirst was higher ($P < 0.05$) in IV with oral glycerol compared to the oral glycerol trial after the second hour of rehydration (oral = 2 ± 1, oral glycerol = 1 ± 1, IV = 2 ± 1, and IV with oral glycerol = 3 ± 1) and after equilibration (oral = 2 ± 1, oral glycerol = 2 ± 1, IV = 2 ± 1, and IV with oral glycerol = 3 ± 1). Thirst was then similar between all conditions during the performance test (Table 3). Thermal sensation and RPE were similar between conditions throughout the performance test (Table 3).

DISCUSSION

The present study explored the simultaneous effects of rehydrating with IV fluid and oral glycerol on exercise performance. Compared with oral rehydration, time trial performance was significantly improved by 3.7%, 3.5%, and 4.1% for oral glycerol, IV, and IV with oral glycerol, respectively. Thus, performance was improved to a similar extent either by providing half of the rehydration volume as IV fluid or by incorporating glycerol with the oral fluid. However, combining IV fluid and oral glycerol augmented the performance improvements only slightly compared with either of the techniques alone. For highly trained athletes, a worthwhile performance improvement is considered to be half of the CV for that measure (16). CV testing on the current protocol yielded a value of 0.66% for the time to complete the 40-km time trial. Thus, the performance improvements in the oral glycerol, IV, and IV with oral glycerol were both statistically significant and practically worthwhile improvements compared to the oral trial. Furthermore, one may even speculate that the differences from oral glycerol (3.7%) and IV (3.5%) to IV with oral glycerol (4.1%) are also above the half CV considered to be practically significant. However, the basis for these performance benefits is somewhat unclear from the mechanistic data collected.

The IV trials of the current experiment are in contrast to previous results showing no performance benefit after IV rehydration (4,5,9,20,21) or hyperhydration (17). Of note, these previous studies also differed from the present findings by showing no sustained hydration benefit from IV fluids. These discrepancies are most likely explained by differences

in study design. No previous IV rehydration studies have investigated the efficacy of using fluid volumes recommended by the American College of Sports Medicine for rapid and complete recovery after exercise (150% of the bodyweight lost) (32). In the previous IV rehydration studies by Castellani et al. (5), Casa et al. (4), and Kenefick et al. (20), subjects were dehydrated by −4% to −5% bodyweight as in the present study, but only rehydrated with ~50% of the fluid lost. In the study of Kenefick et al. (21), the subjects were dehydrated by −2.4% bodyweight and rehydrated with 100% of fluid lost. Furthermore, Castellani et al. (5), Casa et al. (4), and Kenefick et al. (19) all infused 0.45% NaCl, whereas Kenefick et al. (21) had both 0.45% and 0.9% NaCl trials. The $[Na^+]$ (154 $mmol \cdot L^{-1}$) of normal saline is similar to that of the extracellular fluid that effectively limits its distribution to the extracellular compartments. The use of only half normal saline in these previous studies would have enabled the fluid in those trials to disperse within both the extracellular and intracellular compartments. When coupled with the smaller total fluid volumes, the result is a much smaller volume of fluid acting to expand the extracellular compartments (including plasma volume). In our study, the relatively greater sodium concentration in saline compared with sports drinks resulted in the total amount of sodium provided being much higher in the IV compared with the oral trials, therefore contributing to the greater plasma volume expansion in the IV trials.

An enhanced plasma volume could be expected to have numerous beneficial effects. Gonzalez-Alonso et al. (13,14) report that, when presenting together, dehydration (−4% BW) and hyperthermia elicit a synergistic effect and reduce stroke volume by more than double and increase systemic vascular resistance by approximately five times compared with either dehydration or hyperthermia alone (13). The greater circulating blood volume counteracts this and allows the maintenance of central venous pressure and cardiac preload, with concomitant preservation of mean arterial pressure and stroke volume. In addition to this resulting in a decreased exercising HR, it can also be expected to preserve peripheral blood flow to the muscles and skin during exercise, thereby facilitating heat dissipation and enhanced thermoregulation. Unfortunately, our results are not explained by these specific mechanisms. Despite the significantly higher plasma volumes during exercise in the IV trials, we found no associated reduction of HR during exercise. Furthermore, tympanic and skin temperatures were not lower at any time, and sweat rate was not higher during the performance test after IV rehydration.

The mechanisms for the performance benefits seen in the glycerol trials of the current experiment are also difficult to elucidate. Enhanced fluid retention, resulting in the same proposed mechanisms as those discussed above, is the primary mechanism considered responsible for glycerol effectiveness. Similarly to previous trials (18,34), we found that the addition of glycerol significantly augmented the plasma volume increases during the 3-h rehydration/equilibration period and improved the net fluid balance. Although the plasma volume increases were not maintained (relative to the same trial without glycerol) during the performance test, the improved net fluid balance was maintained in both the oral glycerol and the IV with oral glycerol trials. Again, there were no differences in HR, tympanic, or skin temperatures or sweat rate associated with the glycerol ingestion. Thus, it is also difficult to credit improved hydration as the method by which glycerol improved exercise performance in these trials.

Another potential mechanism by which glycerol has been postulated to enhance endurance performance is by maintaining blood glucose via its contribution to liver gluconeogenesis (2,3,28), which may increase plasma glucose and decrease the utilization of muscle and liver glycogen during exercise. Plasma glucose concentration was higher at the end of exercise in the two glycerol trials, which may have partially contributed to the performance benefits seen. However, the IV trial was similar to oral, so once again, it does not explain the performance improvements in the IV trial. Furthermore, although there is evidence that glycerol may contribute a small amount to total CO_2 production and increase blood glucose, thereby providing an energy substrate during exercise (2,3,12), the ingestion of glycerol has proved ineffective for improving endurance performance when used as a supplement without associated fluid ingestion (i.e., in nonhyperhydration trials) (2,12,28). It has been shown that the human liver, although possessing high levels of glycerol kinase (2), does not have the gluconeogenic capacity to rapidly convert glycerol to glucose for metabolism during exercise and therefore provides only a minor energy substrate (12,28). In the present study, the higher blood glucose concentration may have provided sufficient substrate availability to help explain the improved self-paced performance in the glycerol trials in the absence of thermoregulatory benefits. Although there was no statistically significant difference between conditions for plasma lactate concentration, lactate was 28%–49% higher at the end of the time trial in oral glycerol, IV, and IV with oral glycerol trials compared to that in oral trial. These differences likely reflect the increased speed (and therefore greater anaerobic contribution) in these trials over the final 20 km of the time trial.

Overall, the most likely explanation for the performance benefits seen with both glycerol and IV rehydration is some combination of all the factors discussed above. It is also reasonable to conclude that the lack of difference in cardiovascular, thermoregulatory, and metabolic strain, despite the higher work rate throughout at least the final half of the time trial (self-paced exertion), provides evidence that these factors may be playing a role. Similarly, RPE and thermal stress during exercise were comparable in all conditions, indicating that athletes were able to maintain a higher work rate toward the end of the self-paced time trial in the oral glycerol, IV, and IV with oral glycerol trials, without increases to subjective markers of physical stress. Several previous studies investigating glycerol as a hyperhydrating agent before exercise have shown significant (1,15,29) and nonsignificant

(27,39) performance benefits of similar magnitude to those seen here, including improvements in total work (15), mean power output (1,27), time to exhaustion (29), or race time (39). In each of these trials, the subjects also reported similar RPE between conditions, indicating that they were able to maintain a higher work rate without feeling like they were working harder. It should also be noted that the environmental conditions used in the present study may have contributed to the lack of thermoregulatory benefits, even though significant plasma volume benefits were seen. The high-temperature, high-humidity protocol would decrease the gradient for heat dissipation. The studies reporting lower core temperatures after glycerol ingestion (1,24) or IV fluid infusion (21) all used hot/dry (humidity <42%) environmental conditions, rather than the hot/humid conditions used here. Reducing the capacity for evaporative heat loss to the environment can result in extra sweat dripping off the body without producing concomitant reductions in thermoregulatory stress (27).

A further important consideration for athletes who use IV rehydration is the issue of thirst sensation. In a point–counterpoint article, Noakes proposed that thirst may act in a feed-forward manner to involuntarily slow the athlete, as an attempt to prevent dehydration from becoming physiologically significant (33). Furthermore, thirst affects the subjective response to exercise and also influences factors such as the release of fluid-regulating hormones via the act of drinking (e.g., via oropharyngeal stimulation). It may be expected that excessive thirst in the IV trials in previous experiments (where no oral fluid was provided with the IV fluids) is one reason for the lack of benefits seen after IV rehydration. This was the primary reason that only half the rehydration volume was given as IV fluid in the current experiment. Despite the significant improvements in fluid retention in the current IV trials, thirst sensation was significantly higher in the IV with oral glycerol trial compared to oral trial after the second hour of rehydration and compared to oral glycerol trial after equilibration. However, IV trial was not higher than either of the oral trials at any time point.

The present study was designed to mimic a rehydration technique that has previously been used by professional athletes and used a protocol that fulfills the American College of Sports Medicine's guidelines of rehydrating with a volume equal to 150% of the fluid lost during dehydration. Furthermore, to accurately reflect real-life practice, athletes were rehydrated with a combination of IV and oral fluid, rather than giving IV fluid in isolation, because few athletes would typically rehydrate exclusively with IV fluid after moderate exercise–induced dehydration in the heat.

There were, however, several limitations associated with the study that need to be acknowledged. During pilot testing, attempts were made to single blind the administration of IV fluid with respect to the subjects. Unfortunately, this was logistically difficult and ineffective because the subjects were able to feel the fluid being administered because it was cooler than body temperature. Thus, these plans were abandoned for the main study. Importantly, it is very unlikely that the athletes knowing they received IV fluid would have resulted in performance improvements, especially seeing as they were thirstier during rehydration in the IV protocols. The strong negative relationship between thirst and exercise performance indicates that, if anything, we could reasonably expect performance benefits to have been suppressed or negated in the IV trials. It should also be acknowledged that the thermoregulatory methodology used in this study is also relatively insensitive when being used to infer that thermoregulatory control was unaltered.

As with any ergogenic aid, the potential adverse effects also need to be investigated. Postinfusion acidosis is a well-known adverse effect when administering large volumes of IV saline (e.g., during medical procedures) (35,36). Although the volumes of fluid infused into athletes are unlikely to cause any such problems, the severity of the complications justifies further investigation. Similarly, several authors have shown reduced respiratory function after rapid infusion of IV saline in euhydrated individuals (30,31), leading to reduced maximal oxygen uptake, anaerobic threshold, maximal HR, and maximal power output during subsequent exercise (31). Although these potential adverse effects will be less likely when rehydrating with IV fluid from a state of dehydration, they need to be investigated nonetheless.

In conclusion, we examined the combination of IV infusion and oral glycerol as a technique to enhance exercise performance. By using a protocol that more accurately depicts the way athletes use IV fluid compared to previous research and by incorporating the American College of Sports Medicine's guidelines for rehydration, this is the first study to show that IV infusion in athletes provides significant performance benefits. Compared with oral rehydration, the 40-km time trial performance was improved with partial IV rehydration with or without concomitant ingestion of glycerol. In addition, although plasma volume was expanded less in the oral trials, rehydrating orally with inclusion of glycerol led to statistically equivalent ergogenic outcomes as the partial IV rehydration protocols. Finally, although performance was not further enhanced by the combination of glycerol with IV fluid, plasma volume was augmented to the greatest extent in the IV with oral glycerol trial. Thus, athletes who require large volumes of fluid for rehydration in short periods of time will benefit from IV fluid, and the inclusion of oral glycerol will further enhance rehydration. In saying that, it must be noted that IV infusion is now prohibited by WADA in the circumstances tested in this study.

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The authors have no conflicts of interest to disclose.

Results of the present study do not constitute endorsement by the American College of Sports Medicine.

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