Carbohydrate exerts a mild influence on fluid retention following exercise-induced dehydration

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Submitted 23 September 2008; accepted in final form 19 November 2009

Osterberg KL, Pallardy SE, Johnson RJ, Horswill CA. Carbohydrate exerts a mild influence on fluid retention following exercise-induced dehydration. J Appl Physiol 108: 245–250, 2010. First published November 25, 2009; doi:10.1152/japplphysiol.91275.2008.—Rapid and complete rehydration, or restoration of fluid spaces, is important when acute illness or excessive sweating has compromised hydration status. Many studies have investigated the effects of graded concentrations of sodium and other electrolytes in rehydration solutions; however, no study to date has determined the effect of carbohydrate on fluid retention when electrolyte concentrations are held constant. The purpose of this study was to determine the effect of graded levels of carbohydrate on fluid retention following exercise-induced dehydration. Fifteen heat-acclimatized men exercised in the heat for 90 min with no fluid to induce 2–3% dehydration. After a 30-min equilibration period, they received, over the course of 60 min, one of five test beverages equal to 100% of their sweat loss during exercise. Fluid retention was measured for each beverage, defined as the percentage of the volume ingested to restore body mass loss. There were no differences in percent dehydration, sweat loss, or fluid intake between trials. Fluid retention was significantly greater for all carbohydrate beverages compared with water (66.3 ± 14.4%, P < 0.001; 71.8 ± 9.9% compared with water, 3% (75.4 ± 7.8%) or 6% (75.4 ± 16.4%) but was significantly less than 12% (82.4 ± 9.2%) retention of the ingested fluid. No difference was found between the carbohydrate beverages. Carbohydrate at the levels measured exerts a mild influence on fluid retention in postexercise recovery.

Carbohydrate; fluid retention; rehydration; renin; osmolality

Rapid and complete rehydration, or restoration of fluid spaces, is important when acute illness or excessive sweating has compromised hydration status. Most rehydration research to date has focused on the effects of electrolytes on fluid retention. There is little argument that sodium, particularly sodium chloride, has the greatest impact on fluid retention (16, 21, 25, 35, 38). Sodium is the primary cation in the extracellular fluid and as such serves to regulate plasma osmolality and helps maintain plasma volume. Maughan et al. (22) found that potassium chloride was as effective as sodium chloride in restoring fluid balance; however, this effect was likely due to the chloride contribution and its impact on the extracellular fluid compartment.

Carbohydrate is often included in rehydration solutions to aid in fluid absorption and add taste to increase sensory acceptance. For the treatment of dehydration induced by severe diarrhea, the World Health Organization recommends a standard solution containing 90 mmol/l sodium and 111 mmol/l glucose in oral rehydration solutions (ORS) to assist fluid absorption through the intestinal sodium-glucose cotransporter (7). For exercise and sport, rehydration solutions commonly contain a mixture of glucose and fructose in precise ratios based on absorption (8, 12, 32) and oxidation (1, 19, 20) characteristics. Although multiple carbohydrate substrates facilitate fluid uptake, their role in retention of fluid once inside the body remains unclear. Maughan et al. (22) found that a beverage with glucose alone produced significantly greater urine loss than any of three other beverages that contained electrolytes. However, no study to date has attempted to determine whether there is a dose effect of carbohydrate concentration on fluid retention when electrolyte concentrations are standardized.

Carbohydrate could enhance fluid retention based on several plausible mechanisms. First, progressively increasing the carbohydrate concentration, energy density, and osmolality has been shown to decrease the rate of gastric emptying (5, 24, 37) and absorption (13, 32) of fluid. Slower emptying and absorption may cause a slower movement of fluid into the bloodstream and sustain a higher plasma osmolality that would attenuate urine production by the kidneys. Second, postexercise ingestion of beverages with higher carbohydrate content could stimulate greater intracellular fluid retention related to glycogen storage. Glucose transport into the cell draws water along with the substrate, and glycogen storage has been shown to increase total body water (27, 36). Finally, in some people, the insulin response invoked by hyperglycemia may lead to increased renal tubular resorption of sodium and fluid, which would promote fluid retention (33). Indeed, physiological hyperinsulinemia causes sodium retention in healthy individuals (29).

The purpose of the present study was to determine whether there is a dose relationship between carbohydrate concentration of an oral rehydration solution and the percentage of ingested fluid that is retained to promote rehydration following exercise-induced dehydration. We compared the effects of three concentrations of carbohydrate: 3, 6, and 12 g/100 ml each containing standardized electrolyte concentrations (18 mmol/l Na+, 11 mmol/l Cl−, 3 mmol/l K+) for the control comparison, we used a carbohydrate-free solution with standardized electrolyte concentrations and a carbohydrate-free, electrolyte-free solution (water). We hypothesized that compared with water, fluid retention, defined as the percentage of the volume retained relative to volume ingested to restore body mass loss, would be greater for fluids containing electrolytes and similar
for beverages containing carbohydrate concentrations of 6% or less. Further, we hypothesized that a high-carbohydrate (12%) beverage with electrolytes would result in greater fluid retention compared with beverages with less or no carbohydrate.

**METHODS**

**Participants.** Fifteen trained men volunteered to participate in this study. Participants ranged in age from 19 to 49 (34.4 ± 10.0) yr with an average body mass of 77.8 ± 6.7 kg and an estimated maximal oxygen consumption of 56.2 ± 6.3 ml·kg⁻¹·min⁻¹. The base was estimated in ECG graded exercise stress test that subjects complete before participation in the study (10). All subjects were recreationally competitive runners or triathletes who trained year round and maintained their normal training during the study. The sample size of 15 was chosen to provide statistical power of 80% based on an expected difference for fluid retention as reported for rehydration beverages administered in a repeated-measures design and with similar sodium and carbohydrate types used in the current study (15, 34). Data for each subject were collected over the course of 3 wk, and all subjects were heat acclimated before beginning the trials (11, 18). The experimental protocol was approved by a Human Subjects Review Committee, and all athletes gave written informed consent before participation.

**Study design.** The study was double-blind, and treatment order was randomized so that each participant completed all treatments serving as his own control. Heat-acclimated participants reported to the facility for each trial at 1445 having abstained from food and fluid for 3 h. Each subject provided a urine sample to assess preexercise hydration status via urine specific gravity and was weighed without clothing. A flexible catheter was inserted into the antecubital vein, and participants sat for 30 min while wearing shorts and t-shirt in a warm environment (30°C) while allowing for equilibration of fluid spaces (24). A baseline blood sample was collected at 1530 and subjects commenced exercise. Each trial consisted of 90 min of moderate-intensity exercise at 70–75% maximal heart rate based on the ECG maximal exercise stress test, with no fluid consumed to induce 2–3% loss of body mass. The 90 min exercise session consisted of 30 min each of stationary cycling, running, and elliptical exercise in the same order for each subject for each of the trials. The environmental conditions were 30°C and 50% relative humidity (RH). Following exercise, participants were weighed without clothing to determine the amount of sweat loss incurred and then emptied their bladders. After changing into dry clothing, they were escorted into a thermoneutral environment (23°C, 30% RH) for the 4-h recovery period. After being seated for 30 min postexercise, a second blood sample was collected prior to ingesting any fluids. Beverages were stored at a constant temperature of 2.8°C. Subjects were then given a volume of beverage equivalent to 25% of their total change in body mass, which was determined by subtracting postexercise body mass from preexercise body mass. Another aliquot (25% of losses) was given at 40 min into recovery. At 50, 60, 70, and 80 min, participants consumed aliquots of beverage equivalent to 12.5% of body mass reduction for a total of 100% fluid replacement. At 90 min, a third blood sample was collected. Participants were asked to void and collect all urine at 60, 90, 120, 180, and 240 min into recovery. Blood sampling was repeated at 180 and 240 min into recovery before urine collection and with subjects in a seated position. This rehydration protocol is similar to that used by Maughan and Leiper (21). Surveys for rating of gastrointestinal (GI) comfort were also completed at the times of blood sampling. After the final urine and blood sample, a final nude body mass was obtained.

**Heat acclimation and experimental control.** To ensure that subjects were heat acclimated before the experimental trials, each participant reported to the laboratory for 10 days of exercise in the heat over the course of 14–18 days (11). To do so, they exercised at a moderate intensity for 90 min in 30°C and were permitted to run, cycle, exercise on the elliptical machine, or any combination of the three. They were given ad libitum access to fluids during exercise as well as encouraged to drink fluids during the day to ensure expansion of plasma volume. Experimental trials started within 3 days of finishing the heat acclimation phase.

**Diet and exercise controls.** For the 24-h period before each experimental treatment, participants were given a control diet containing 3,417 kcal and 2,995 mg of sodium. Subjects were not permitted to eat food other than what was provided. If they chose to not eat all of the food that was provided, whatever was eaten before the first trial was repeated for each subsequent trial, i.e., the 24-h diet was kept constant across remaining trials for each subject. Because subjects were not permitted to exercise the day before or the day of the trial, it is reasonable to assume that subjects would not need more than 3,417 kcal to remain in energy balance. Further, diet carbohydrate content was not standardized relative to body mass but the absolute amount was consistent during the preexperiment 24-h period for each subject. Sodium, caffeine, and alcohol intake was restricted due to the potential retention or diuretic effect.

Participants were given 1 liter of water and were told to drink as much additional water as they desired but to stop drinking and eating 3 h before the start of the trial. This was done to ensure that they reported for each trial in a consistent state of euhydration based on urine specific gravity. Participants who arrived at the laboratory with a urine specific gravity >1.020 were rescheduled for another day.

**Beverages.** Subjects replaced 100% of the acute change in body mass with one of five beverages that included placebo (noncaloric and flavored water without electrolytes) or four beverages with the same concentration of electrolytes but that varied by carbohydrate concentration: 0, 3, 6, and 12% carbohydrate for which proportions of sucrose, glucose, and fructose were kept consistent. All beverages were matched for taste and flavor and were given to subjects at a temperature of 3.3°C (see Table 1 for beverage composition).

**Blood analysis.** Blood draws were conducted using sterile aseptic technique. An indwelling 20-gauge venous catheter (BD Insyte Autoguard Shielded IV Catheter, Sandy, UT) and needle-free syringe system was maintained patent using a sterile saline (Bacteriostatic 0.9% sodium chloride injection, USP, Hospira, Lake Forest, IL 60045) lock in between blood draws. After each blood draw, −3 ml of sterile saline was used to flush and lock the catheter until the next blood draw. Before each blood draw, the saline was removed and discarded, and −1.5 ml of blood was withdrawn and discarded before obtaining the sample for analysis.

Two aliquots of blood were taken from each subject at each draw. Blood from a heparinized syringe (∼2 ml) was immediately used to measure blood glucose, hematocrit, and hemoglobin using a blood gas analyzer (GEM Premier 3000, Instrumentation Laboratories, Lexington, MA). Other blood samples were placed in tubes with potassium oxalate sodium fluoride (K2EDTA) and were kept at 4°C in a thermoelectric cooler to maintain optimal conditions for enzyme and hormone analyses. Blood samples were centrifuged at 2500 × g for 10 min at 4°C and the plasma was stored at −20°C until assayed. Alanine, aspartate, and lactate were measured in duplicate using an analyzer (GEM Premier 3000, Instrumentation Laboratories, Lexington, MA) and plasma sodium and potassium were quantified using automated methods.

**Table 1. Composition of beverages**

<table>
<thead>
<tr>
<th>Carbohydrate type</th>
<th>Water Placebo*</th>
<th>Placebo* + Electrolytes</th>
<th>3% + Electrolytes</th>
<th>6% + Electrolytes</th>
<th>12% + Electrolytes</th>
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<tbody>
<tr>
<td>Sodium, mmol/l</td>
<td>18</td>
<td>18</td>
<td>18</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>Potassium, mmol/l</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Osmolarity, mOsm</td>
<td>15</td>
<td>49</td>
<td>187</td>
<td>338</td>
<td>691</td>
</tr>
</tbody>
</table>

*Both placebo beverages contained flavoring (lemon lime) and artificial sweeteners (aspartame). †High fructose corn syrup (HFCS)-42 (58% glucose, 42% fructose). With complete hydrolysis, the ratio of glucose to fructose for all treatments with carbohydrate is 3.25 to 2.75.
MA). Hematocrit and hemoglobin values were used to calculate the change in relative plasma volume using the method of Dill and Costill (9). A second sample (7 ml) was drawn into a nonheparinized vacutainer, allowed to stand for 20 min at room temperature, and centrifuged for 15 min at 3,500 rpm. The serum was aliquoted and stored for measurement of concentrations of sodium and potassium and osmolality (Fiske 2400, Norwood, MA). Aliquots of serum were frozen at -80°C and later assayed for concentrations of insulin (ELISA assay LINCO Research, St. Charles, MO), renin (SensoLyteTM 520, AnaSpec, San Jose, CA), and aldosterone (ELISA, Alpha Diagnostics Intl, San Antonio TX).

Urinary analysis. All urine samples were collected in disposable specimen containers. Within 5 min of the collection, urine volume was determined by mass and urine specific gravity was assessed (A 300 Clinical Refractometer).

Statistical analysis. SPSS version 14.0 was used to analyze the data. ANOVA was used for two-way repeated measures (beverage treatment x time) was used to determine differences in means in weight gain while one-way ANOVA was used for variables measured once time. A backwards regression strategy was used to identify independent variables that were associated with fluid retention including sweat losses, fluid intake, and total carbohydrate. Effect size was calculated using the difference between means for a comparison, divided by the pooled SD for those two means (12). Data are reported as means ± SD. A probability level of 0.05 was selected for statistical significance.

RESULTS

Fluid balance. Preexercise urine specific gravity, dehydration, body mass loss, and total fluid intake did not differ between treatments (see Table 2). A one-way ANOVA for the order of the trials unrelated to treatments showed that there were no differences in the mean sweat loss. This supports the stability of the physiological state of the subjects and the consistency of dehydration responses during the experimental period. The mean of the coefficient of variation for each subject’s preexercise body weight was 0.65%, further suggesting the consistency of the state of the subjects at the start of each experimental trial.

The 12% carbohydrate beverage (P < 0.001) resulted in significantly less absolute urine loss than all other treatments (0.35 ± 0.17 liter). P + E (0.58 ± 0.16 liter) was not different from P (0.64 ± 0.21 liter), 3% (0.49 ± 0.13 liter), or 6% (0.48 ± 0.28 liter) (see Figs. 1 and 2, respectively, for urine specific gravity and urine loss at each time point).

For the primary outcome variable, the mean volume for percent fluid retained was directionally greatest for the 12% beverage but was not statistically different from that of 3% or 6%. Percent retention for P + E was not different from that of P while the retention for both of these trials was less than that for the 12% beverage (P < 0.05). Percent fluid retained was less for P than all carbohydrate beverages (P < 0.001, see Fig. 3). Using the mean and SD, we calculated a statistical power of 84% for this variable and an effect size of 0.43 for the ANOVA results (3). The regression analysis showed that none of the variables considered accounted for significant variance in percent fluid retained. Final body mass was not significantly different between trials.

Blood measures. Blood glucose was not different at baseline or postexercise but was significantly lower at several time points during postexercise recovery (see Fig. 4). Blood sodium was not different pre- or immediately postexercise. At 90 min, blood sodium (P < 0.001) was significantly lower for P and P + E compared with all other treatments. P remained lower than 12% at all time points.

Serum insulin was not different pre- or postexercise. Insulin (P < 0.001) was significantly lower for P and P + E than all other treatments. Insulin (P < 0.001) was significantly higher for 12% at 180 and 240 min compared with all other treatments (see Fig. 5).

For all trials the relative plasma volume decreased on average 7.1 ± 4.8% following exercise and dehydration and was only significantly different at 90 min for 3% (P = 0.034) during the recovery period (see Fig. 6).

Serum osmolality was not different pre- or postexercise for any of the treatments. Osmolality (P < 0.001) was significantly higher for 12% beverage than all other beverages at 90 min but was not significantly different at any other time point.

Serum aldosterone was not different pre- or postexercise or at 90 min postexercise. Aldosterone was significantly lower at 180 min (P = 0.001) and 240 min (P = 0.006) for P and 12% compared with P + E and 3%. The 6% beverage was not different from the others at any time point. However, the pattern of change in mean values for serum aldosterone was similar for all trials.

Table 2. Preexercise urine specific gravity, body mass loss, and postexercise fluid intake

<table>
<thead>
<tr>
<th></th>
<th>Placebo USG</th>
<th>Placebo + Electrolytes</th>
<th>3%</th>
<th>6%</th>
<th>12%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preexercise USG</td>
<td>1.008 ± 0.005</td>
<td>1.007 ± 0.003</td>
<td>1.007 ± 0.004</td>
<td>1.008 ± 0.005</td>
<td>1.006 ± 0.003</td>
</tr>
<tr>
<td>Preexercise body mass, kg</td>
<td>77.76 ± 6.92</td>
<td>77.86 ± 6.85</td>
<td>77.76 ± 6.75</td>
<td>77.84 ± 6.77</td>
<td>77.97 ± 7.01</td>
</tr>
<tr>
<td>Postexercise body mass, kg</td>
<td>75.77 ± 6.85</td>
<td>75.76 ± 6.61</td>
<td>75.71 ± 6.61</td>
<td>75.76 ± 6.60</td>
<td>75.93 ± 6.91</td>
</tr>
<tr>
<td>Change in mass, kg</td>
<td>1.99 ± 0.40</td>
<td>2.10 ± 0.38</td>
<td>2.05 ± 0.43</td>
<td>2.07 ± 0.41</td>
<td>2.04 ± 0.40</td>
</tr>
<tr>
<td>Volume ingested, liters</td>
<td>1.99 ± 0.39</td>
<td>2.10 ± 0.38</td>
<td>2.05 ± 0.43</td>
<td>2.07 ± 0.41</td>
<td>2.04 ± 0.41</td>
</tr>
</tbody>
</table>

Values are means ± SD, USG, urine specific gravity.
Serum renin ($P = 0.02$) was significantly higher for all carbohydrate beverages at 90 min compared with P and P + E. The 12% beverage ($10.17 \pm 9.69$ ng/100 ml) approached significance ($P = 0.06$) at the 240 min time point compared with P ($4.05 \pm 2.99$ ng/100 ml).

GI and sensory ratings. No significant treatment × time interactions were detected in any of the sensory or GI ratings.

DISCUSSION

In this study, beverages containing carbohydrate and electrolytes contributed to greater fluid retention than did water alone in recreational adult male athletes who rehydrated following exercise-induced dehydration. We did not find significant differences in fluid retention between beverages containing 3% and 6% carbohydrate and the placebo with electrolytes. The solution containing 12% carbohydrate and electrolytes was associated with the greatest fluid retention compared with the placebo and placebo with electrolytes. There was no statistical difference between placebo and placebo with electrolytes, although a trend existed for greater fluid retention for the electrolyte beverage (66.3 ± 14.4% vs. 71.8 ± 9.9%). Our data are similar to Nielson et al. (25), Maughan and Leiper (21), and others (30) who have shown that electrolytes influence fluid retention, but our data also show that the greatest fluid retention tended to occur when the electrolytes are combined with a 12% carbohydrate-containing solution.

We proposed several mechanisms by which carbohydrate dose could impact fluid retention. Increasing the carbohydrate content of a beverage raises both the caloric content and osmolality of the beverage. Both characteristics can reduce the rate of gastric emptying (4, 5, 24) and rate of fluid absorption (13, 32). A slow rate of fluid entering the vascular space would sustain the body’s response to the state of dehydration and modulate the bolus of fluid initially presented to the kidney during rehydration. Beverages containing carbohydrate concentrations between 0 and 6% empty from the stomach at similar rates (24, 28, 31) so we did not expect differences between these beverage treatments. Somewhat in contrast to our hypothesis was the difference ($P = 0.034$) in relative plasma volume for the 3% beverage at 90 min (greater relative plasma volume compared with that of other beverage treatments). Because of the lower osmolality of the 3% treatment compared with the other carbohydrate-containing beverages

Mean ± SD percentage of each of the beverage retained following the recovery period.

*Significant difference: *p < 0.05 for P or P + E, or 3% vs. 6% vs. 12%.

Fig. 2. Urine volume (mean ± SD) at each time point during recovery period. $P < 0.05$ at following times: at 90 min, 12% < P, P + E; at 180 min, 12% < P, P + E, 3, 6%; at 240 min, 12% < P, P + E, 6%.

Fig. 3. Percent fluid retained (mean ± SD) during the recovery period. *$P < 0.05$ for P < 3, 6, 12%. **$P = 0.05$ for P and P + E < 12%.

Fig. 4. Blood glucose concentration (mean ± SD) before exercise and during postexercise recovery. $P < 0.05$ at the following times: at 90 min, 12% > P, P + E, 3% at 180 min, 12% > P, P + E, 3%, 6%; at 240 min, 6, 12% < P, P + E.

Fig. 5. Serum insulin concentration (mean ± SD) before exercise and throughout recovery period. $P < 0.05$ the following times: at 90 min, P and P + E < 3% < 6% < 12%; at 180 min and 240 min, P, P + E, 3%, 6%, < 12%.
and by having transportable substrate not found in the carbohydrate-free treatments, the 3% treatment may have provided a stimulus for absorption and an initial restoration of the relative plasma volume measured at the 90-min point. While we are not familiar with other data showing statistically significant differences between 3 and 6%, prior research shows trends for faster fluid absorption and directionally greater relative plasma volume when beverages of lower carbohydrate (2 vs. 6%) (14) or lower osmolality for the same absolute carbohydrate content are ingested (13, 31), respectively. Beverages with 8% carbohydrate and higher appear to empty more slowly and retard intestinal fluid uptake (8, 14, 32). While we did not measure gastric emptying or absorption, the end point of percent of fluid volume retained that we observed is consistent with the hypothesis: we found no difference in fluid retained for the 3% and 6% carbohydrate beverage while the beverage with 12% carbohydrate tended to retain more fluid [effect sizes of 0.8 compared with 3% and 0.4 compared with 6% (6)].

In parallel with the slower appearance of fluid in the vascular space, the appearance of a fluid that provides a great amount of carbohydrate would potentially contribute to a high blood osmolality, which could sustain the response to the state of dehydration and support fluid retention. We did not see differences between the beverages for overall restoration of relative plasma volume at the end of the observation period. This may not be unreasonable because the relative plasma volume can be restored even in the absence of fluid ingestion (17). However, with the increase in plasma glucose during the 12% carbohydrate treatment, we observed an elevation in plasma osmolality that would be expected to stimulate vasopressin (2, 26). The rise in glucose would also stimulate insulin, which has been shown to also increase urinary sodium reabsorption, even in healthy individuals (29). We did observe a higher insulin concentration for the 12% carbohydrate treatment compared with the noncarbohydrate trials. Renin concentrations were also elevated for all carbohydrate trials with a tendency for the elevation to be sustained for the highest carbohydrate treatment. These responses may have contributed to the greater fluid retention for the 12% trial compared with effects of the treatments devoid of carbohydrate.

We also hypothesized that fluid retention could be greater for 12% carbohydrate due to the water associated with the storage of carbohydrate as glycogen. Olsson and Saltin (27) found that total body water increased an average of 2.2 liters with high vs. low glycogen storage. The average amount of carbohydrate consumed was 244 g for 12% compared with 124 g for 6% and 62 g for 3%. It is possible that the 12% carbohydrate beverage resulted in greater glycogen storage compared with beverages containing little or no carbohydrate. Assuming a 3:1 ratio of water to carbohydrate, the mean difference in fluid retention between the 12% and 6% beverage would theoretically be 360 g of water. We found a mean difference of ~100 g of fluid retention between the 6 and 12% beverages but 178 g difference between P and P + E, suggesting that glycogen storage was not a primary mechanism of fluid retention in this study. There were no differences across treatment in final body mass. However, mean body mass for the 12% beverage was 281 g more than the placebo + electrolytes and 254 g greater than 6%. The differences between the other beverages were <30 g, indicating the 12% beverage caused the body to retain more fluid. Nonetheless, without analyzing water content of muscle biopsies or the volume of intracellular fluid space using whole body tracer techniques, we cannot know for sure the compartment in which the fluid was retained.

All efforts were made to minimize intrasubject variability by requiring subjects to become heat acclimatized, report to each study in a well-hydrated state based on urine specific gravity, and control exercise, caloric intake, sodium intake. The order of the trials, we are confident that variability in factors that could affect the results, e.g., plasma volume, muscle glycogen content, were minimized. Because the total dose of carbohydrate for each individual varied dependent on total fluid volume administered for rehydration (100% of body mass change) and that volume was influenced by slight differences in intraindividual sweat rate, we used multiple regression to account for subtle variations in the treatments to examine more precisely the impact of carbohydrate dose on the percentage of fluid retained. Regardless, we were unable to detect a clear association of fluid retention and carbohydrate dose. At the end of each session of exercise after 30 min of rest, it was assumed that subjects had reestablished some degree of homeostasis while remaining in a state of dehydration. We did not measure core temperature or skin blood flow, so that lack of confirmation remains a limitation of the study. However, by design and with the consistency of the responses, we expected this to have little or no impact on the internal validity of the comparisons within the study.

The accuracy of using the change in body mass as a surrogate for hydration status is debatable (23). A certain amount of the change in body mass can be attributed to nonsweat losses (respiratory water) and nonfluid loss (substrate that is oxidized). Some fluid would also be gained as substrate is oxidized and lost, but water is formed in the process. Because each subject performed the same workout and reported to the study in the same nutrition and hydration state, the environment was consistent across trials, and the error in using body mass for

![Fig. 6. Plasma volume (mean ± SD) before exercise and throughout the postexercise recovery period.](http://jap.physiology.org/)}
Influence of carbohydrate on fluid retention

Hydration would be systematic and not invalidate our interpretation of the results. However, a source of error that could influence our results is that the actual volume of water ingested for each treatment would be systematically less as the carbohydrate concentration increased with the treatment. This could potentially favor the impact of carbohydrate on fluid retention because the vascular space and kidneys would receive a smaller volume of fluid and presumably retain a greater amount. This also could have contributed to the difference observed between the 12% carbohydrate treatment and the treatments without carbohydrate. Future work might account for this by first matching the water needed to replace fluid loss, and then add the carbohydrate in graded amounts to the treatment.

In summary, our data suggest the presence of carbohydrate in combination with the electrolytes used in this study promoted fluid retention more so than ingesting water alone for rehydration following exercise-induced dehydration. While we did not observe a clear dose effect for carbohydrate, a trend for the greatest fluid retention occurred when electrolytes were combined with a 12% carbohydrate-containing solution. Lower concentrations of carbohydrates appeared to exert only a mild influence on fluid retention when electrolytes are standardized.

DISCLOSURES
The study was conducted at the Gatorade Sports Science Institute, which is a part of the Gatorade Company (funding source). C. A. Horswell is currently employed by Gatorade.

REFERENCES