Effect of beverage osmolality on intestinal fluid absorption during exercise

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Gisolfi, C. V., R. W. Summers, G. P. Lambert, and T. Xia. Effect of beverage osmolality on intestinal fluid absorption during exercise. J. Appl. Physiol. 85(5): 1941–1948, 1998.—To determine how osmolality of an orally ingested fluid-replacement beverage would alter intestinal fluid absorption from the duodenum and/or jejunum during 85 min of cycle exercise (63.3 ± 0.9% peak O2 uptake) in a cool environment (22°C), seven subjects (5 men, 2 women, peak O2 uptake = 54.5 ± 3.8 ml·kg⁻¹·min⁻¹) participated in four experiments separated by 1 wk in which they ingested a water placebo (WP) or one of three 6% carbohydrate (CHO) beverages formulated to give mean osmolalities of 197, 295, or 414 mosmol/kgH2O. CHO solutions also contained 17–18 meq Na⁺ and 3.2 meq K⁺. Nasogastric and multilumen tubes were fluoroscopically positioned in the gastric antrum and duodenojejunum, respectively. Subjects ingested a total of 23 ml/kg body mass of the test solution, 20% (370 ± 9 ml) of this volume 5 min before exercise and 10% (185 ± 4 ml) every 10 min thereafter. By using the rate of gastric emptying as the rate of intestinal perfusion (G. P. Lambert, R. T. Chang, D. J. Jensen, X. Shi, R. W. Summers, H. P. Schedl, and C. V. Gisolfi. Int. J. Sports Med. 17: 48–55, 1996), intestinal absorption was determined by segmental perfusion from the duodenum (0–25 cm) and jejunum (25–50 cm). There were no differences (P > 0.05) in gastric emptying (mean 18.1 ± 1.3 ml/min) or total fluid absorption (802 ± 109, 650 ± 52, 674 ± 62, and 633 ± 74 ml·50 cm⁻¹·h⁻¹ for WP, hypo-, iso-, and hypertonic solutions, respectively) among beverages; but WP was absorbed faster (P < 0.05) from the duodenum than in the jejunum. Of the total volume of fluid ingested, 82 ± 14, 74 ± 6, 76 ± 5, and 68 ± 7% were absorbed for WP, hypo-, iso-, and hypertonic beverages, respectively. There were no differences in urine production or percent change in plasma volume among solutions. We conclude that total fluid absorption of 6% CHO-electrolyte beverages from the duodenojejunum during exercise, within the osmotic range studied, is not different from WP.

water absorption; duodenum; jejunum; human

THE ROLE OF SOLUTION osmolality in intestinal fluid absorption remains somewhat controversial. Discrepancies in the data can be attributable in part to species differences, the segment of the intestine studied, the composition of the solution employed, and extrapolation of the results from direct perfusion into the intestine to oral ingestion of the same solution (23, 24). In an attempt to resolve many of these issues, we recently designed a technique to evaluate both gastric emptying and intestinal absorption after the oral ingestion of different rehydration beverages (13). In our most recent investigation using this technique (14), we evaluated fluid and solute absorption from the first 75 cm of the proximal small intestine. We assumed that the distance from the pyloric sphincter to the ligament of Treitz (0–25 cm) represented the duodenum and that the next 50 cm beyond the ligament of Treitz represented the jejunum (25–50 and 50–75 cm). Intestinal fluid was sampled just (3–5 cm) beyond the pyloric sphincter and at 25, 50, and 75 cm beyond this site. The results of this study revealed significant differences in water flux in the duodenum and the first 25 cm of the jejunum after the oral ingestion of a water placebo and an isotonic carbohydrate-electrolyte (CHO-E) beverage. There were no differences between these two beverages in the last 25-cm segment (i.e., 50–75 cm). Moreover, when total water flux for the first 50 cm or the entire 75 cm was analyzed, there were no significant differences between the two beverages studied.

In an early investigation (23) to evaluate the effects of osmolality on intestinal fluid absorption, we studied three solutions with the same CHO and electrolyte content, but, by manipulating the form of CHO, solution osmolality varied from 186 to 403 mosmol/kgH2O. This study was performed at rest with a multilumen tube positioned so that the test segment included the last 10–15 cm of duodenum and the first 25–30 cm of jejunum. The results showed no significant difference in fluid homeostasis among beverages as evaluated by changes in plasma volume. However, if fluid movement across the 10-cm mixing segment of the multilumen tube was also included in the analysis, fluid absorption of the hypotonic solution was 17% greater than of the hypertonic solution and produced a more rapid increase in plasma volume. These experiments, conducted at rest, implied that a hypotonic solution would have a marked advantage over a hypertonic solution during exercise, when plasma osmolality rises.

Thus the purpose of this study was to reevaluate these same solutions and water after their oral ingestion during cycle exercise at 65% peak oxygen uptake (V̇O2peak) and to simultaneously measure gastric emptying and intestinal absorption from the duodenum and the first 25 cm of the jejunum independently. This design focuses on fluid replenishment during prolonged exercise and addresses the role of the duodenum independent of the jejunum in fluid absorption. It addresses the following three questions. 1) How important is the intestinal segment studied? 2) How much of an orally ingested beverage can be absorbed in the first 50 cm of the intestine? 3) What is the influence of beverage osmolality on intestinal absorption from these two different intestinal sites during exercise? We hypothesized that the hypotonic beverage would yield the greatest fluid absorption on the basis of its osmotic advantage in the duodenum without sacrificing any absorption decrement in the jejunum because it con-
tained an equal amount of CHO and electrolyte to the other beverages studied.

**METHODS**

Subjects and infusion solutions. Five men and two women (age = 28 ± 4 yr; height = 181 ± 1 cm; body mass = 80 ± 4 kg; VO2peak = 54.5 ± 3.8 ml·kg⁻¹·min⁻¹) served as subjects in this study. They all received a thorough physical examination and provided signed, informed consent before participating. All experiments were performed in accordance with the guidelines for the use of human subjects in research and were approved by the local Human Use Committee. VO2peak was determined by using a graded protocol on an electronically braked cycle ergometer (The Bike, Cybex, Ronkonkoma, NY). A workload corresponding to 60–65% VO2peak was determined by using a graded protocol on a electronically braked cycle ergometer (The Bike, Cybex, Ronkonkoma, NY). All experiments were performed in accordance with the guidelines for the use of human subjects in research and were approved by the local Human Use Committee. VO2peak was determined by using a graded protocol on an electronically braked cycle ergometer (The Bike, Cybex, Ronkonkoma, NY).

Each subject ingested a water placebo and three 6% CHO-E solutions containing two or three forms of CHO (Table 1). All CHO solutions contained glucose and fructose as transportable substrates but in different forms to yield different osmolalities. The hypotonic solution contained fructose as sucrose and glucose in the free form and as maltodextrin in the combined form. The isotonic beverage contained fructose as sucrose and glucose in the free form. The hypertonic solution contained fructose and glucose as free monosaccharides, requiring no digestion before transport. Each of the CHO solutions also contained 17–18 meq Na⁺ and 3 meq K⁺. All beverages also contained 1 mg/ml polyethylene glycol 3350 (PEG), a nonabsorbable marker for determination of water flux. Experiments were performed 1 wk apart after an 8-h fast.

Measurement of gastric emptying and intestinal absorption. The technique employed to simultaneously determine gastric emptying and intestinal absorption has been described in detail (13, 14). Briefly, a nasogastric (NG) tube (50 in., no. 14 Fr, Levin) is attached to a multilumen tube (Arndorfer, Greendale, WI) with a small rubber band and positioned fluoroscopically, so that the NG tube is located in the gastric antrum and the first sampling port of the multilumen tube is located 2–3 cm past the pyloric sphincter. Gastric emptying was determined by using a modified, repeated double-sampling technique (13) in accordance with the methods of George (5) and Beckers et al. (1). The multilumen tube utilized in this study had additional sampling ports located 25 cm and 50 cm from the initial port, just beyond the pyloric sphincter. Thus net fluid and solute fluxes were determined from the duodenum (0- to 25-cm segment) and from the first portion of the jejunum (25- to 50-cm segment).

During each 10-min interval of the experiment, intestinal fluid was collected at a rate of 1 ml/min from the proximal and 25-cm sampling sites and by constant syphonage at the 50-cm sampling site. Net water flux was calculated for each interval according to the following equations (2)

\[
\dot{Q}_E = \text{GER} \cdot \frac{[\text{PEG}]_p}{[\text{PEG}]_d} - \dot{S}_p
\]

\[
\dot{Q}_L = \dot{Q}_E \cdot \frac{[\text{PEG}]_p}{[\text{PEG}]_d}
\]

\[
\dot{Q}_N = \dot{Q}_L - \dot{Q}_E
\]

where GER is the gastric emptying rate; \(\dot{Q}_E\) is the flow rate entering a given segment (ml/min); \(\dot{Q}_L\) is the flow rate leaving a given segment (ml/min); \(\dot{Q}_N\) is the net water movement entering a given segment (ml/min); \(\dot{Q}_L\) is the flow rate leaving a given segment (ml/min); \(\dot{S}_p\) is the total sampling rate from the proximal collecting site of the two segments studied; \([\text{PEG}]_p\), \([\text{PEG}]_d\), and \([\text{PEG}]_s\) are the concentrations of the nonabsorbable marker in the stomach, at the proximal site of each segment, and at the distal site of each segment, respectively. Net water flux from the 25- to 50-cm segment was calculated by subtraction after determination of net flux in the 0- to 25- and 0- to 50-cm segments, respectively. Solute flux was calculated by multiplying the solute concentration at the proximal and distal sampling sites (of the 0- to 25- and 0- to 50-cm segments) by the flow rates entering and leaving the segments. Net movement of solute was determined by subtraction (2). Solute flux in the 25- to 50-cm segment was calculated as described for water flux. Fluxes of Na⁺ and K⁺ were doubled to account for movement of the accompanying anion. All results were calculated after a 35-min equilibration period to allow a steady state to be reached (2, 25). Steady-state PEG values from the 50-cm sampling site for each solution are shown in Fig. 1. Samples were collected during the equilibration period but were not used in data analysis. Analytical recovery of PEG averaged 82 ± 1% from solutions containing 1 mg/ml PEG.

Protocol. After the NG and multilumen tubes were placed and a venous catheter was inserted in a superficial arm vein, the subject sat for 20 min to stabilize plasma volume. At the end of this period, blood and urine samples were collected, rectal temperature was obtained with a clinical thermometer, nude body weight was obtained, and the subject donned his or her cycling clothes. The subject then mounted the stationary bike, a heart rate monitor (Polar Vantage XL, Polar USAF, Stamford, CT) was attached, and stomach contents were aspirated through the NG tube.

After the stomach was aspirated, the subject drank an initial bolus of test solution equal to 20% of the total volume ingested (23 ml/kg body mass). Mean total volume ingested was 1,850 ± 89 ml, and the initial bolus volume averaged 370 ± 18 ml. Five minutes after ingestion of the initial bolus, exercise commenced for 85 min. At 10-min intervals thereafter, additional volumes of test solution were ingested equal to 10% (185 ± 9 ml) of the total volume consumed. Experiments were performed at 22°C with a wind velocity of ~0.6 m/s.

### Table 1. Composition of the ingested beverages

<table>
<thead>
<tr>
<th>Variable</th>
<th>Hypertonic</th>
<th>Isotonic</th>
<th>Hypotonic</th>
<th>Water placebo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glucose, %</td>
<td>3.25 (180 mM)</td>
<td>2 (110 mM)</td>
<td>1 (55 mM)</td>
<td></td>
</tr>
<tr>
<td>Sucrose, %</td>
<td>2.75 (153 mM)</td>
<td>4 (117 mM)</td>
<td>2 (58 mM)</td>
<td></td>
</tr>
<tr>
<td>Fructose, %</td>
<td>17.2 ± 0.9</td>
<td>17.6 ± 0.2</td>
<td>18.2 ± 0.3</td>
<td>0.06 ± 0.03</td>
</tr>
<tr>
<td>Maltodextrin (M-580), %</td>
<td>3 (30 mM)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sodium, meq/l</td>
<td>3.2 ± 0.2</td>
<td>3.3 ± 0.03</td>
<td>3.3 ± 0.1</td>
<td>0.25 ± 0.01</td>
</tr>
<tr>
<td>Potassium, meq/l</td>
<td>414 ± 2</td>
<td>295 ± 6</td>
<td>197 ± 2</td>
<td>1 ± 0.3</td>
</tr>
<tr>
<td>Osmolality, mosmol/kgH₂O</td>
<td>21</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Values are means ± SE; n = 5 subjects for water placebo.
produced by a fan placed in front of the subject. Blood was sampled every 20 min to determine changes in plasma volume, osmolality, Na⁺, K⁺, and glucose. Heart rate was measured every 15 min. Rectal temperature, body mass, and urine volume were recorded postexercise. Sweat rate was calculated from the change in body mass corrected for fluid ingestion, phenol red injection, and stomach, intestinal, urine, and blood sample volumes.

Analytic procedures. Phenol red concentration in the stomach samples was measured spectrophotometrically at 560 nm after dilution (0.3-ml sample to 5 ml deionized water) and alkalization with 1 ml borate buffer (pH 9.2) (5, 22). All samples and standards were analyzed in duplicate with deionized water as a reference blank. PEG in the intestinal samples was determined by the method of Hyden (11) as modified by Malawar and Powell (15). Osmolality was measured by using freezing-point depression (Multi-Osmette, Precision Systems, Natick, MA), Na⁺, and K⁺ concentrations by flame photometry (model IL 943, Instrumentation Laboratory, Lexington MA), and CHO (i.e., glucose and fructose) by high-performance liquid chromatography (Dionex DX-500 System, Sunnyvale, CA). Samples containing sucrose were hydrolyzed with 8.75 N trifluoracetic acid to liberate glucose and fructose before measurement, and samples with maltodextrin were hydrolyzed with α-amylase and amylglucosidase. This provided a more accurate determination of CHO flux in the intestine as flux values of sucrose and maltodextrin would not necessarily represent movement of the solute from the lumen but possibly only digestion to monosaccharides (i.e., glucose and fructose) with subsequent absorption. Hemoglobin and hematocrit were determined in quadruplicate by using the cyanmethemoglobin and microcentrifugation methods, respectively. Percent change in plasma volume was calculated from hemoglobin and hematocrit values by using the formulas of Dill and Costill (4).

Statistical analysis. Data were tested for normality with the Shapiro-Wilk test and were found to be normally distributed, with the exception of the Na⁺ and K⁺ flux data, in which appropriate transformations were made to normalize the data. Repeated-measures analysis using the SAS/STAT MIXED procedure (21) was utilized for all comparisons, except for comparing PEG concentrations within a solution over time, in which a one-way analysis of variance with repeated measures was used. Pairwise comparisons of values between solutions and within solutions at different gastrointestinal sites or time points was performed by using Bonferroni’s method. The level of significance was set at P < 0.05. All data are reported as means ± SE.

RESULTS

Eight subjects began the experiments, but one vomited during the first trial and opted not to continue the study. This person had successfully completed numerous other studies in the past. Another subject was ill during the water placebo experiment and did not complete it but finished all other trials without gastrointestinal distress. There were no differences in thermoregulatory response, heart rate, urine production, fluid absorbed in the whole 50-cm test segment, or fluid retained (from that absorbed in the 50-cm test segment) during the different trials (Table 2). If water absorption values obtained after equilibration are extrapolated to represent the entire 90-min experiment, 75 ± 4% of the fluid presented (ingested minus aspirated) to the intestine (1,396 ± 102 ml) was absorbed in the first 50 cm of the intestine. This absorbed volume (1,021 ± 54 ml) accounts for 73% of the total volume of sweat produced during the 90-min experiment.

Gastric emptying. Figure 2 shows the complete gastric emptying curves for the different beverages. Ingesting water, the isotonic beverage, or the hypotonic beverage resulted in rapid gastric emptying and equilibration at an average gastric volume of ~340 ml. Thus, at an average gastric emptying rate of 17 ml/min or 170 ml every 10 min, subjects basically kept pace with average fluid ingestion of 185 ml every 10 min. In contrast, the hypertonic beverage delayed gastric emptying and resulted in a significantly higher gastric volume compared with the other three beverages. However, after equilibration, average gastric emptying of 19 ml/min or 190 ml every 10 min basically kept pace with ingesting 185 ml every 10 min, and gastric volume equilibrated at ~575 ml. Thus the higher gastric

Table 2. Fluid and thermoregulatory variables

<table>
<thead>
<tr>
<th>Beverage</th>
<th>Sweat Rate, l/h</th>
<th>Final HR, beats/min</th>
<th>Final Core Temperature, °C</th>
<th>Urine Production, ml</th>
<th>Fluid Absorbed, %</th>
<th>Absorbed Fluid Retained, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hypertonic</td>
<td>0.94 ± 0.08</td>
<td>147 ± 3</td>
<td>38.3 ± 0.1</td>
<td>187 ± 48</td>
<td>68 ± 7</td>
<td>80 ± 4</td>
</tr>
<tr>
<td>Isotonic</td>
<td>0.93 ± 0.07</td>
<td>145 ± 4</td>
<td>38.4 ± 0.1</td>
<td>169 ± 52</td>
<td>76 ± 5</td>
<td>83 ± 5</td>
</tr>
<tr>
<td>Hypotonic</td>
<td>0.89 ± 0.06</td>
<td>144 ± 3</td>
<td>38.2 ± 0.1</td>
<td>214 ± 41</td>
<td>74 ± 6</td>
<td>79 ± 4</td>
</tr>
<tr>
<td>Water placebo</td>
<td>0.99 ± 0.07</td>
<td>150 ± 6</td>
<td>38.3 ± 0.1</td>
<td>197 ± 59</td>
<td>82 ± 14</td>
<td>83 ± 4</td>
</tr>
</tbody>
</table>

Values are means ± SE; n = 5 subjects for water placebo. HR, heart rate.
volume compensated for the higher osmolality of this beverage to yield approximately the same gastric emptying rate.

After the 35-min equilibration period, mean gastric volume measured before fluid ingestion every 10 min was significantly greater during ingestion of the hypertonic beverage than of all other beverages (mean values $= 507 \pm 84, 266 \pm 49, 231 \pm 18$, and $264 \pm 42$ ml for hypertonic, isotonic, hypotonic, and WP, respectively), but mean gastric emptying rate was not significantly different among trials (see values in Fig. 2). There were no differences ($P > 0.05$) in gastric volume (Fig. 2) or gastric emptying for any beverage over time after the equilibration period.

Osmolality. Osmolalities among the different solutions were formulated to be significantly different (Table 1) and remained so in the stomach and in the first 25 cm of the duodenum (Fig. 3, Table 3). With regard to osmolality in the 25- to 50-cm segment (jejunum), WP was significantly ($P < 0.05$) lower than that of the hyper-, iso-, and hypotonic beverages, the hypertonic beverage was significantly greater than the isotonic beverage, and the isotonic beverage was significantly greater than the hypotonic beverage. The change in osmolality from the duodenum to the jejunum is attributable to increased electrolyte concentration (Table 3, Fig. 4), CHO digestion, and net water flux (Fig. 5). In the case of the hypertonic beverage, the decrease in osmolality from the stomach to the jejunum is attributable to greater total solute flux than net water flux. The rise in osmolality of the hypotonic beverage from the stomach to the duodenum is attributable to maltodextrin digestion, $Na^+$ secretion, and greater water than solute absorption. Osmolality of the isotonic beverage did not change from stomach to duodenum, but, in the jejunum, it rose significantly above values observed in the stomach and duodenum.
attributable to Na\textsuperscript+ osmolality of the WP from stomach to duodenum is but only by 10 mosmol/kgH\textsubscript{2}O. The significant rise in osmolality of the WP from stomach to duodenum is attributable to Na\textsuperscript+ secretion and greater water absorption than net solute flux.

Water and solute fluxes. Within the duodenum, fluid absorption during ingestion of the WP was significantly greater than absorption during ingestion of the CHO-E beverages. Although not statistically significant, the data were reversed in the jejunum, i.e., fluid absorption was significantly greater from all three CHO-E beverages compared with the WP. There were no differences in fluid absorption among the CHO-E beverages in either intestinal segment, but net fluid absorption of the WP significantly fell in the jejunum compared with the duodenum (Fig. 5). When total fluid absorption from both segments was combined, there were no differences among beverages (802 ± 109, 650 ± 52, 674 ± 62, and 633 ± 74 ml·50 cm\textsuperscript{-1}·h\textsuperscript{-1} for WP, hypotonic, isotonic, and hypertonic solutions, respectively).

Fig. 4. Mean sodium concentrations in stomach and intestinal segments studied. All solutions having the symbols noted at that site. Hypertonic, isotonic, and hypotonic solutions were not different from each other before ingestion or in the stomach but were all significantly different from water placebo at these points. In 0- to 25-cm segment, there were no differences. In 25- to 50-cm segment, water placebo was significantly different from other solutions. Values are means ± SE; n = 5 subjects for water placebo. †Significantly different from solution. *Significantly different from stomach. ‡Significantly different from 0- to 25-cm segment. All P < 0.05.

Fig. 5. Intestinal water absorption in 2 segments studied. Values are means ± SE; n = 5 subjects for water placebo. *Significantly different from 0- to 25-cm segment. All P < 0.05.
In the duodenum, total solute flux for the CHO-E beverages was greater \((P < 0.05)\) than with ingestion of the WP beverage (Fig. 6). As each of the CHO-E beverages moved from the duodenum to the jejunum, total solute flux during ingestion of the hypertonic and isotonic beverages fell significantly, whereas there was no difference in total solute flux from the hypotonic beverage (Fig. 6). The latter observation was associated with a significantly lower CHO flux from the hypotonic beverage compared with the hyper- and isotonic beverages (Table 4). Absolute concentrations of solutes at the various sampling sites are shown in Table 3.

Plasma volume, electrolytes, and osmolality. In support of the observation that there were no differences in total fluid absorption within the first 50 cm of the small intestine among beverages, there were no differences in plasma volume over time among beverages (Fig. 7). Moreover, there were no differences \((P > 0.05)\) in plasma \(\text{Na}^+\) or \(\text{K}^+\) concentrations among beverages, but \(\text{K}^+\) concentration increased significantly above rest after 40 min of exercise. Plasma osmolality before exercise for all trials averaged 285 ± 2.0 mosmol/kg\(\text{H}_2\text{O}\), indicating the subjects were euhydrated before each experiment, and rose significantly to an average value of 291 ± 0.4 mosmol/kg\(\text{H}_2\text{O}\) during exercise. There were no differences \((P > 0.05)\) among beverages at any time point. Plasma glucose concentration was not significantly different among trials but declined during ingestion of the WP.

**DISCUSSION**

On the basis of previous studies, we hypothesized that the oral ingestion of a hypotonic beverage would increase overall intestinal absorption and plasma volume during exercise. However, the results of this study indicate that oral ingestion of a beverage in the osmolality range of virtually 0 (WP) to 414 mosmol/kg\(\text{H}_2\text{O}\) (Table 1) does not significantly affect overall intestinal absorption or fluid homeostasis during 85 min of exercise at 60–65% maximal \(\text{O}_2\) uptake. This conclusion is in contrast with intestinal perfusion studies, primarily of the jejunum conducted at rest (9, 10), but is consistent with other studies that included fluid absorption from both the duodenum and jejunum (19, 23).

**Gastric emptying.** The effect of osmolality on gastric emptying has been reviewed (3, 12, 17). The results of the present study are consistent with recent reports that osmolality has only a modest effect on gastric emptying (14, 16, 18, 19). We did not observe a statistically significant effect of osmolality on gastric emptying when comparing the WP (osmolality virtually 0 mosmol/kg\(\text{H}_2\text{O}\)) with the three 6% CHO beverages ranging in

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**Table 4. Carbohydrate, sodium, and potassium fluxes in the two segments of the intestine studied**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Hypertonic</th>
<th>Isotonic</th>
<th>Hypotonic</th>
<th>Water Placebo</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHO flux, 0–25 cm</td>
<td>7.4 ± 0.9</td>
<td>7.1 ± 1.1</td>
<td>3.8 ± 0.6*</td>
<td></td>
</tr>
<tr>
<td>CHO flux, 25–50 cm</td>
<td>2.8 ± 0.5†</td>
<td>2.7 ± 0.4</td>
<td>2.3 ± 0.5</td>
<td></td>
</tr>
<tr>
<td>(\text{Na}^+) flux, 0–25 cm</td>
<td>-0.3 ± 0.2</td>
<td>-0.1 ± 0.2</td>
<td>-0.2 ± 0.1</td>
<td>-0.2 ± 0.3</td>
</tr>
<tr>
<td>(\text{Na}^+) flux, 25–50 cm</td>
<td>0.4 ± 0.1†</td>
<td>0.3 ± 0.1</td>
<td>0.2 ± 0.2</td>
<td></td>
</tr>
<tr>
<td>(\text{K}^+) flux, 0–25 cm</td>
<td>0.07 ± 0.04</td>
<td>0.06 ± 0.03</td>
<td>0.06 ± 0.02</td>
<td>0.07 ± 0.04</td>
</tr>
<tr>
<td>(\text{K}^+) flux, 25–50 cm</td>
<td>0 ± 0.02</td>
<td>0.01 ± 0.01</td>
<td>0.02 ± 0.01</td>
<td>-0.01 ± 0.01</td>
</tr>
</tbody>
</table>

Values are means ± SE expressed as mmol·cm\(^{-1}·h^{-1}\); \(n = 5\) subjects for water placebo. CHO, carbohydrate. Negative values indicate secretion. \(\text{Na}^+\) and \(\text{K}^+\) fluxes have been doubled to account for movement of accompanying anion (i.e., chloride or bicarbonate). *Significantly different from hyper- and isotonic beverages. †Significantly different from 0- to 25-cm segment. All \(P < 0.05\).
osmolality from 197 ± 2 to 414 ± 2 mosmol/kgH₂O. The lack of a difference in gastric emptying between water and the 6% CHO beverages supports the findings of Mitchell et al. (16) and Costill (3), which showed that the gastric emptying of CHO beverages ranging in concentrations from 5 to 10% were not different from that of water. The significantly larger gastric volume of the hypotonic beverage must have compensated for its high osmolality because it produced a similar gastric emptying rate compared with the other beverages.

Water and solute absorption. The significant differences observed in water and solute absorption in the duodenum (0- to 25-cm segment) and jejunum (25- to 50-cm segment) are attributable to differences in beverage composition, beverage osmolality, and the "leakiness" of the mucosal membrane in the segments studied. In the duodenum (0- to 25-cm segment), significantly more of the WP was absorbed than any of the CHO-E beverages primarily because of the osmotic superiority of the WP beverage. Despite net Na⁺ secretion (Table 4), net water absorption occurred presumably because water was moving down an osmotic gradient. Santangelo and Krejs (20) also observed net water absorption in the presence of Na⁺ secretion. The osmotic gradient that drives water absorption is thought to be the gradient from intestinal lumen to villus tip (6,7). When the small intestine of an anesthetized cat was perfused with water, the villus tips became hypertonic, but the osmotic gradient from lumen to villus tip still promoted water absorption (7). If fluid absorption occurs along the entire length of the villus, the osmotic gradient at the villus base could be as high as 187 mosmol/kgH₂O because the villus base has an osmolality equal to that of the plasma (6). The high rate of water absorption observed in the duodenum, which was also found in two other reports (see Ref. 14), was no doubt facilitated by the leakiness of the duodenum compared with the jejunum and more distal portions of the small intestine.

In the duodenum, mean osmolality values for the CHO-E beverages were all significantly different from each other (333 ± 7, 266 ± 3, and 237 ± 4 mosmol/kgH₂O for hyper-, iso-, and hypotonic beverages, respectively), but there were no significant differences in water flux among these beverages. In terms of osmolality, all of these solutions would be expected to generate an osmotic gradient in the villus that would promote water absorption. Hallback et al. (6) found that, when the lumen of human intestine was exposed to an isotonic glucose-electrolyte solution, an osmotic gradient along the length of the villus was revealed with an osmolality of ~700 mosmol/kgH₂O at the tip and an osmolality that equaled with plasma osmolality at the base. This observation helps to explain fluid movement in the present study down an osmotic gradient from luminal osmolality values that ranged from 300 to 350 mosmol/kgH₂O for the different 6% CHO-E solutions.

In addition to osmotic forces, there were significant differences in total solute flux among these beverages (Fig. 6), which may have been the more important force driving water movement. Another factor that could have attenuated net water absorption of the hypotonic CHO beverage was digestion of the maltodextrins. Although not significantly different, total solute flux for the hypotonic beverage was only 3.5 ± 0.7 mmol·cm⁻¹·h⁻¹ compared with 6.9 ± 1.1 and 6.9 ± 1.3 mmol·cm⁻¹·h⁻¹ for the hyper- and isotonic beverages, respectively. This difference is attributable in part to the larger amount of a second transportable CHO (fructose) in the hyper- (2.75% fructose) and isotonic (2% fructose) beverages compared with the hypotonic (only 1% fructose) beverage (24). The greater osmotic gradient for the hypotonic beverage may have compensated for the greater digestion and lower total solute flux of this beverage compared with the other CHO-E beverages to produce a nonsignificant difference in net water flux among CHO-E beverages. In this segment, water absorption from the WP was 26.7 ± 3.7 ml·cm⁻¹·h⁻¹.

In the jejunum (25- to 50-cm segment), the differences observed in water and solute flux are attributable to differences in beverage composition, osmotic forces, membrane leakiness, and net fluid transport that occurred in the duodenum. As observed in a recent preliminary report (14), the present study shows that fluid absorption during ingestion of the WP fell significantly from a mean value of 26.7 to 3.7 ml·cm⁻¹·h⁻¹ in passage from the duodenum to the jejunum and was also lower than values observed for all three CHO-E beverages. The marked reduction in net fluid flux from duodenum to jejunum is attributable first to a marked increase in luminal osmolality from 100 ± 12 to 175 ± 13 mosmol/kgH₂O, when this beverage passed from the duodenum into the jejunum, thus decreasing the osmotic gradient driving absorption. In addition, the jejunum is a more resistant membrane than the duodenum; and the volume flow of fluid entering the jejunum from the duodenum must have been reduced because 53% of the WP ingested was absorbed in the duodenum. Last, the lower total solute flux from the WP reduced its fluid absorption compared with the three CHO-E beverages (Fig. 6). This difference in solute flux is due to the presence of CHO in the latter beverages and a greater capacity for glucose uptake in the jejunum compared with the duodenum (8). There were no differences in fluid absorption among the three CHO-E beverages. This is attributable to the fact that jejunal luminal osmolality and total solute flux among the beverages were similar.

Fluid balance. Although there were differences in fluid absorption rate in the two intestinal segments studied while subjects were drinking the different beverages, total fluid absorbed in the first 50 cm of the intestine was not different among beverages and there were no significant differences in plasma volume, plasma osmolality, urine volume, or sweat production among beverages during the 85-min exercise sessions. Of the total volume of fluid ingested (1,396 ± 102 ml), 68, 76, 74, and 82% were absorbed in the first 50 cm of the small intestine from the hyper-, iso-, hypotonic, and WP beverages, respectively (Table 2). Thus ingestion of neither the hypotonic CHO-E beverage nor the WP, which was also hypotonic, conferred any advantage in
terms of fluid balance during exercise. This conclusion is further supported by the lack of any difference in plasma electrolyte concentrations or in plasma osmolality among trials.

We conclude that in normal, healthy, euhydrated adults exercising at ~65% \( \dot{\text{V}} \text{O}_2 \text{peak} \), total fluid absorption in the proximal small intestine from 6% CHO-E beverages (within the osmotic range studied) is not different from a WP beverage, despite significant differences in net water and solute fluxes among beverages in the duodenum and the jejunum. The lack of an osmotic effect among 6% CHO-E beverages is attributable to the limited osmotic gradient in the duodenum, driving fluid either from lumen to blood, in the case of the hypertonic beverage, or from blood to lumen, in the case of the hypotonic beverage. On the other hand, the osmotic gradient in the duodenum while the WP was being ingested was fourfold greater than that for the CHO-E beverages and is considered the primary mechanism causing the significantly greater water absorption from the WP in the duodenum. On the basis of the changes in plasma and urine volumes, fluid homeostasis during 85 min of cycle exercise was not different among the beverages studied.

The authors thank the subjects who participated in the experiments, Dr. Bridget Zimmerman for statistical analyses, and the clerical expertise of Joan Seye for preparation of the manuscript. This research was supported by a grant from the Gatorade Sports Science Institute.

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REFERENCES


