Gastric Emptying and Intestinal Absorption of a Low-Carbohydrate Sport Drink During Exercise

Jennifer Rogers, Robert W. Summers, and G. Patrick Lambert

The purpose of this study was to determine if lowering carbohydrate (CHO) concentration in a sport drink influences gastric emptying, intestinal absorption, or performance during cycle ergometry (85 min, 60% VO₂peak). Five subjects (25 ± 1 y, 61.5 ± 2.1 mL · kg⁻¹ · min⁻¹ VO₂peak) ingested a 3% CHO, 6% CHO, or a water placebo (WP) beverage during exercise. Gastric emptying was determined by repeated double sampling and intestinal absorption by segmental perfusion. Total solute absorption and plasma glucose was greater for 6% CHO; however, neither gastric emptying, intestinal water absorption, or 3-mi time trial performance (7:58 ± 0:33 min, 8:13 ± 0:25 min, and 8:25 ± 0:29 min, respectively, for 6% CHO, 3% CHO, and WP) differed among solutions. These results indicate lowering the CHO concentration of a sport drink from 6% CHO does not enhance gastric emptying, intestinal water absorption, or time trial performance, but reduces CHO and total solute absorption.

Key Words: intestinal water flux, intestinal solute flux, body fluid homeostasis, fluid balance, exercise performance

Prolonged exercise can result in dehydration; decreasing body weight by even 1% is sufficient to impair thermoregulation and subsequently exercise performance (for review, see 13). Many sport drinks have been formulated to replenish fluid losses during exercise as well as to potentially enhance athletic performance. Such a beverage should be readily emptied from the stomach, absorbed quickly from the small intestine, and provide an exogenous form of energy (17, 23).

Carbohydrate (CHO) in sport beverages serves two main functions: the enhancement of intestinal water absorption (12), and the provision of an exogenous source of energy (4, 20). Glucose absorption from the small intestine occurs primarily through a Na⁺-dependent co-transport mechanism, but also via the paracellular pathway when present in high luminal concentrations. Na⁺-dependent co-transport and paracellular absorption also promote intestinal water absorption. Fructose absorption, in contrast, occurs by a separate facilitated diffusion mechanism. Thus, more than one form of CHO (i.e., sucrose, glucose, or fructose) might be included...
in sport beverages to enhance CHO and, subsequently, intestinal water absorption (26). Many sport beverages contain a combination of CHO forms to achieve a total CHO concentration usually in the range of 5 to 9%. CHO concentrations greater than 6% could impede the rate of gastric emptying (21, 27) and intestinal absorption of ingested fluids (22).

Exogenous CHO supplementation has been shown to improve exercise performance (2, 9), an effect attributed to the maintenance of euglycemia during exercise (3, 4, 19, 20). In addition to the beneficial effects with regard to water absorption and the maintenance of plasma glucose concentrations, CHO and Na+ inclusion in sport drink formulation improves palatability and might encourage increased consumption during exercise (17). Anecdotal reports, however, indicate that some individuals might experience abdominal cramping, discomfort, or heaviness after sport drink consumption. For this reason, sport drinks could be diluted prior to ingestion. Sport drink dilution reduces the CHO concentration of the beverage that might influence intestinal CHO and water absorption and therefore performance capacity.

The purpose of this investigation was to determine if lowering the CHO concentration of a sport beverage (from 6% to 3% CHO) influences the rate of gastric emptying, intestinal solute or water absorption, or exercise performance. It was hypothesized that, compared with a 6% CHO solution, ingestion of a 3% CHO solution would 1) not influence the rate of gastric emptying, 2) decrease CHO, total solute, and therefore net water absorption from the small intestine, and 3) increase the time required to complete a 3-mi performance time trial following a prolonged submaximal exercise session.

**Methods**

**Subjects**

Eight healthy volunteers participated in this investigation, five of whom completed all trials (4 male, 1 female; age, 25 ± 1 y; weight, 70.2 ± 3.6 kg; 61.5 ± 2.1 mL·kg⁻¹·min⁻¹ VO₂peak; mean ± standard error). Three subjects had excessive salivation, a very active “gag reflex,” or difficulty drinking with the multilumen tube in position during exercise and were unable to complete the entire exercise protocol; subsequently, their data were omitted from analysis. Prior to participation, all subjects provided signed, written informed consent and underwent a physical examination. The University of Iowa Human Use Committee approved all procedures. One week prior to the first experiment, VO₂peak was determined by an incremental maximal exercise test on an electronically braked cycle ergometer (Cybex, Medway, MA). Ventilation and expired gases were assessed with the Q-Plex I metabolic system (Quinton Instruments, Seattle, WA). A workload corresponding to 60 to 65% VO₂max was subsequently determined.

**Procedures**

Subjects were instructed to refrain from physical activity for 24 h prior to an experiment and to eat similar foods the day prior to each trial. On the day of an experiment, subjects arrived at the University of Iowa Hospital and Clinics at 6 AM for oral passage and positioning of the multilumen and nasogastric tubes, following
an overnight fast. This protocol has been previously described in detail (15, 16).

Briefly, a nasogastric tube (50 cm, 14 French, Levine) was attached with small rubber bands to a multilumen tube (Andover, Greendale, WI; construction described below). The final rubber band was positioned 7 cm proximal to the nasogastric tip, allowing the nasogastric tube to separate from the multilumen tube and remain in the gastric antrum. The multilumen tube passed through the pyloric sphincter and spanned the proximal 50 cm of the small intestine. Contrast medium (Hypaque sodium 50%, a brand of diatrizoate sodium injection, USP) was introduced into the distal sampling port of the multilumen tube to fluoroscopically visualize the tube in the small intestine. An 18-gauge catheter was inserted into a superficial arm vein to obtain blood samples during the exercise protocol.

After positioning the nasogastric and multilumen tubes, subjects returned to the exercise physiology laboratory, voided, attached a heart rate monitor, and then sat upright for 20 min to allow for plasma volume equilibration. Five minutes prior to exercise, a blood sample was obtained and any residual stomach contents were aspirated. The subject ingested an initial bolus of a test solution equal to 20% (327 ± 12 mL) of the total fluid volume to be consumed throughout the exercise protocol. Total fluid consumption was calculated as 23 mL/kg body weight (1647 ± 42 mL). Small serial ingestions (10% of total fluid consumption, 163 ± 24 mL) were provided at 10 min intervals throughout the exercise protocol to maintain relatively constant stomach volumes and gastric emptying rates. Solutions were presented in a clear flask at 10 to 15 °C. The test solutions used in this set of experiments consisted of 3% CHO, 6% CHO, and a water placebo (WP) matched in color and flavor to the other 2 solutions. The 3% CHO and 6% CHO solutions were formulated to contain equivalent concentrations of Na⁺ and K⁺, approximately 17 and 3 mEq/L, respectively. In addition, 1 g/L polyethylene glycol 3350 (PEG) was added to each solution as a nonabsorbable marker for determination of intestinal water flux. Table 1 summarizes beverage composition. Subjects consumed 1 solution throughout each exercise session according to a randomized, double-blinded experimental design. A minimum of 1 wk separated each trial.

Each exercise session consisted of 85 min constant-load cycle ergometry (60 to 65% VO₂peak, 171 ± 19 W) in a thermoneutral environment (22 °C). Gastric and intestinal samples were obtained over 10-min intervals followed by solution ingestion. Immediately following the 85-min constant load work bout, subjects were allowed a 1-min rest period in which the final gastric and intestinal samples were obtained. Subjects then completed a 3-mi cycle ergometer time trial. Subjects were only aware of the total distance completed during this performance test and were encouraged equally among rides to perform maximally. Blood samples were obtained every 20 min during the 85-min exercise bout as well as immediately following time trial completion to determine changes in plasma volume and composition (Na⁺, K⁺, and glucose concentrations; osmolality).

Determination of Stomach Volume
and Gastric Emptying Rate

Stomach volume was determined at 10-min intervals based on a modified version of the repeated double sampling technique (1, 10) as described by Lambert et al. (16). A 70 cc Toomey syringe was used to obtain an initial gastric sample (~ 5 mL).
Table 1  Solution Composition for 3% CHO, 6% CHO, and WP

<table>
<thead>
<tr>
<th></th>
<th>3% CHO</th>
<th>6% CHO</th>
<th>WP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glucose (%)</td>
<td>1</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Sucrose (%)</td>
<td>2</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>Na⁺ (mEg/L)</td>
<td>17.2 ± 0.3</td>
<td>17.6 ± 0.4</td>
<td>0</td>
</tr>
<tr>
<td>K⁺ (mEg/L)</td>
<td>3.10 ± 0.04</td>
<td>3.10 ± 0.05</td>
<td>0</td>
</tr>
<tr>
<td>Osmolality (m osm/kgH₂O)</td>
<td>159 ± 4</td>
<td>280 ± 2</td>
<td>4 ± 0.4</td>
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</tbody>
</table>

Note. Values are means ± standard error; n = 5 for each solution.

A second Toomey syringe was used to inject ~15 mL of phenol red (200 mg/L) through the nasogastric tube into the stomach. The exact amount of phenol red injected was obtained by subtracting pre- and post-injection weights of the second syringe. The first syringe was then used to repeatedly draw and inject the gastric residue to ensure adequate mixing of phenol red, followed by procurement of a second gastric sample. The subject then ingested the given solution for that 10-min time period. Stomach volume was calculated as follows:

\[
\text{Stomach volume (mL)} = PR_{\text{vol}} \times \left( \frac{[PR_{\text{inj}}] - [PR_{\text{post}}]}{[PR_{\text{post}}] - [PR_{\text{pre}}]} \right)
\]

where \(PR_{\text{vol}}\) was the volume of phenol red injected, \([PR_{\text{inj}}]\) was the concentration of phenol red injected, \([PR_{\text{post}}]\) was the concentration of phenol red in the gastric sample after adding and mixing phenol red, and \([PR_{\text{pre}}]\) was the concentration of phenol red in the stomach prior to the addition of phenol red.

The gastric emptying rate (GER) for each 10-min interval was determined by subtracting the current stomach volume from the previous stomach volume after beverage ingestion. The GER was also used as the infusion rate in calculating intestinal water absorption (15).

Determination of Intestinal Absorption by Segmental Perfusion

The multilumen tube consisted of 4 lumens (each approximately 2 mm in diameter) assembled in a semi-rounded configuration. The total length of the multilumen tube was 215 cm. One lumen was used to inflate a latex balloon that was attached with 2-0 silk. A double latex bag of mercury (1 mL) was also enclosed in the balloon. The remaining 3 lumens served as intestinal fluid sampling ports. The proximal sampling port was positioned approximately 5 cm beyond the pyloric sphincter in the duodenum. The second and third sampling sites were 25 cm and 50 cm distal to the first site. This design allowed water and solute flux rates in the duodenum and jejunum to be determined individually. Intestinal samples were drawn through 5 holes spaced 1 cm apart (3 at the top and 2 at the bottom) on each lumen. To reduce obstruction of the holes by the intestinal mucosa, a polyvinyl basket was positioned over the top of the holes.
Intestinal samples were obtained from each sampling site by constant siphonage (1 mL/min) with a 10 cc syringe. Although samples were obtained throughout the 85-min bout of cycle ergometry, only the samples collected following the first 35 min were used for determination of water and solute fluxes. The initial 35-min period served as an equilibration period to allow intestinal fluxes to reach steady-state conditions. This was verified by a lack of significant changes in PEG concentration at the sampling sites after this equilibration period. Net water flux during each 10-min interval was calculated as follows (5):

\[
Q_E = \text{GER} \times ([\text{PEG}]_s / [\text{PEG}]_p) - S_p
\]

\[
Q_L = Q_E \times ([\text{PEG}]_p / [\text{PEG}]_d)
\]

\[
Q_N = Q_L - Q_E
\]

where \(Q_E\) was the flow rate entering a given intestinal segment (mL/min); \(\text{GER}\) was the gastric emptying rate (mL/min); \([\text{PEG}]_s\), \([\text{PEG}]_p\), and \([\text{PEG}]_d\) represent concentrations of the nonabsorbable marker PEG in the stomach, proximal sampling site of a given intestinal segment (0 to 25 cm or 0 to 50 cm), and distal sampling site of a segment, respectively; \(S_p\) was the sampling rate from the proximal collection site for a given intestinal segment; and \(Q_L\) was the flow rate leaving that particular segment. Net water flux (\(Q_N\)) for the 0 to 25 cm and 0 to 50 cm intestinal segments were determined by subtracting \(Q_E\) from \(Q_L\). \(Q_N\) for the 25 to 50 cm segment was determined by subtracting water flux across the 0 to 25 cm segment from water flux across the entire 0 to 50 cm test site.

The solute flux for a given segment of the intestine (0 to 25 cm and 0 to 50 cm) was calculated by multiplying solute concentration at the proximal sampling site for that particular segment by the flow rate entering that segment and then subtracting the product of the solute concentration and flow rate at the distal sampling site. As with water flux, solute flux for the 25 to 50 cm intestinal segment was determined by subtracting solute flux across the 0 to 25 cm segment from solute flux across the 0 to 50 cm segment.

**Analytical Procedures**

Phenol red concentration was determined spectrophotometrically (560 nm) after dilution (0.3 mL sample in 5 mL deionized water) and alkalinization (1 mL borate buffer at pH 9.2) according to the protocols of George (10) and Schedl et al. (24). Intestinal PEG concentrations were determined according to the methods of Hyden (14) as modified by Malawer and Powell (18). Osmolality was determined through freezing-point depression (Multi-Osmette, Precision Systems, Natick, MA). [Na+] and [K+] were assessed via flame photometry (model IL 943, Instrumentation Laboratory, Lexington, MA). Carbohydrate concentration was assayed by high-performance liquid chromatography (Dionex DX-500 system, Sunnyvale, CA). Samples containing sucrose were first hydrolyzed to glucose and fructose with invertase (Sigma-Aldrich, St. Louis, MO). All samples and standards were assessed in duplicate with deionized water used as a reference blank. The percent change in plasma volume for each 20-min interval was determined from changes
in hemoglobin concentration (cyanomethemoglobin method) and hematocrit (microcentrifugation method) (6). Hematocrit and hemoglobin values were determined in quadruplicate.

Statistical Analysis
The data were analyzed using the linear mixed model with terms for solution and time where appropriate. This analysis assumes constant correlation among the repeated measures on the same subject. All post hoc comparisons of means were adjusted with the Tukey method. Level of significance was set at $P < 0.05$.

Results

Gastric Emptying Rate
The inclusion of CHO in a solution (up to 6% CHO) did not influence the rate of gastric emptying, as the mean GER for 3% CHO (15 ± 1 mL/min), 6% CHO (19 ± 3 mL/min) and WP (14 ± 2 mL/min) were not significantly different. The mean rate of gastric emptying for all solutions was 16 ± 2 mL/min. Beverage ingestion occurred every 10 min during the exercise protocol with a mean bolus of 163 ± 24 mL; thus, over a 10 min interval, the GER approximated the rate of ingestion. Complete gastric emptying curves for each solution are found in Figure 1.

Solute Flux
Because of the small volume of gastric and intestinal samples procured from 1 subject, Na$^+$ and K$^+$ flux data were analyzed for 4 subjects only. There were no differences in [Na$^+$] for 3% CHO and 6% CHO at the gastric, proximal (0-cm), 25-cm, or 50-cm intestinal sampling sites. Gastric [Na$^+$] was significantly less for WP (5.2 ± 0.6 mEq/L) compared with 3% CHO (21.0 ± 0.2 mEq/L) and 6% CHO (21.3 ± 2.2 mEq/L), reflecting the differences in solution [Na$^+$]; however, no differences among solutions were found at the proximal or 25-cm intestinal sampling sites. [Na$^+$] at the 50-cm sampling site was significantly greater for WP (83.5 ± 9.4 mEq/L) compared with 6% CHO (60.5 ± 4.1 mEq/L) but not 3% CHO (72.7 ± 3.6 mEq/L).

[K$^+$] was significantly less at each sampling site for WP compared with 3% CHO and 6% CHO. There were no differences in [K$^+$] between 3% CHO and 6% CHO at the gastric, proximal, or 25-cm sampling sites. [K$^+$], however, was significantly greater for 3% CHO (9.2 ± 0.2 mEq/L) than 6% CHO (8.0 ± 0.3 mEq/L) at the 50-cm intestinal sampling site.

Net Na$^+$, K$^+$, CHO, and total solute fluxes are presented in Figure 2. Na$^+$ and K$^+$ flux values were doubled to account for concurrent anion transport. Negative flux values indicate net absorption and positive flux values indicate net secretion. There were no differences in net Na$^+$ or K$^+$ flux in the 0 to 25 cm, 25 to 50 cm, or pooled 0 to 50 cm intestinal segments for 3% CHO, 6% CHO, or WP. Na$^+$ secretion occurred in the duodenum (0 to 25 cm segment) for all solutions followed by Na$^+$ absorption in the proximal jejunum (25 to 50 cm segment). Although net Na$^+$ flux across the entire proximal 50 cm of the small intestine was not significantly different based on the solution ingested, it is interesting to note that 3% CHO
Figure 1 — Complete gastric emptying curves for the 3 solutions studied. Solid lines represent gastric emptying over each 10-min period; dashed lines represent fluid ingestion during the first ~30 sec of every 10-min period. Mean GER values were calculated following the 35-min equilibration period (see text). Values are means (standard error bars removed for clarity); \( n = 5 \) for 3% CHO and 6% CHO solutions; \( n = 4 \) for WP solution.
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and 6% CHO solutions promoted net Na⁺ absorption while WP produced net Na⁺ secretion. Net K⁺ absorption occurred in each intestinal segment with no significant differences among solutions.

CHO flux for WP was zero as this beverage did not contain CHO and CHO is not secreted into the intestinal lumen. There was no difference in CHO absorption in the 0 to 25 cm or 25 to 50 cm intestinal segments for 3% CHO or 6% CHO (\(P = 0.0585\) and \(P = 0.0522\), respectively; Figure 2). When CHO flux was determined

![Graphs](image)

**Figure 2** — Net Na⁺, K⁺, CHO, and total solute fluxes according to intestinal segment (values are means ± standard error; \(n = 4\) for 3% CHO, \(n = 5\) for 6% CHO and WP for Na⁺ flux, K⁺ flux, and total solute flux data). Insufficient sample was collected from one 3% CHO experiment to allow determination of Na⁺, K⁺, and total solute fluxes. Negative values indicate absorption and positive values indicate intestinal secretion. CHO absorption was significantly greater for 6% CHO compared to 3% CHO across the 0 to 50 cm intestinal test segment. Total solute flux across each intestinal segment was greater for 6% CHO compared with WP, and greater than 3% CHO across the 0 to 50 cm intestinal segment. The 3% CHO had significantly greater total solute flux across the 25 to 50 cm segment compared with WP. *indicates a significant difference (< 0.05) from 6% CHO, # indicates a significant difference (\(P < 0.05\)) from 3% CHO.
across the entire 0 to 50 cm intestinal segment, however, CHO absorption was significantly greater ($P < 0.05$) for 6% CHO ($-3.6 \pm 0.7 \text{ mmol} \cdot \text{cm}^{-1} \cdot \text{h}^{-1}$) compared with 3% CHO ($-1.5 \pm 0.1 \text{ mmol} \cdot \text{cm}^{-1} \cdot \text{h}^{-1}$). The GER for 6% CHO and 3% CHO were similar, therefore gastric delivery and subsequent intestinal absorption was greater for 6% CHO, reflecting the greater CHO concentration of this solution.

In the duodenum, jejunum, and across the entire 50-cm test segment, 3% CHO and 6% CHO resulted in net solute absorption. Net solute absorption occurred only in the jejunum (25 to 50 cm segment) for WP, while net solute secretion occurred in the duodenum (0 to 25 cm segment) and across the 0 to 50 cm intestinal segment for this solution. Net solute absorption was greater for 6% CHO than WP for each intestinal segment and greater than 3% CHO from the jejunum as well as for values determined across the 0 to 50 cm intestinal segment.

**Net Water Flux**

Despite significant differences in solute (Na$^+$, CHO, total solute) fluxes and gastrointestinal osmolalities (Figure 3), water flux did not differ for 3% CHO, 6% CHO, or WP in the duodenum ($P = 0.93$), proximal jejunum ($P = 0.19$), or across the entire 0 to 50 cm test segment ($P = 0.54$). Net water absorption occurred in each intestinal segment (Figure 4).

**Changes in Plasma Composition and Volume**

There were no differences in plasma [Na$^+$] or [K$^+$] for 3% CHO, 6% CHO, and WP throughout the experimental protocol. Mean plasma [Na$^+$] ranged from 138 to 142
mEq/L; mean plasma [K+] ranged from 3 to 5 mEq/L. In addition, no differences in plasma osmolality were noted (Figure 5). Plasma glucose concentrations are shown in Figure 6. Mean plasma glucose concentration throughout exercise was greater following 6% CHO ingestion (5.87 ± 0.14 mmol/L) compared with 3% CHO (5.41 ± 0.07 mmol/L) and WP (5.46 ± 0.10 mmol/L) although there were no significant differences in plasma glucose concentration noted at any individual time point.

The percent change in plasma volume throughout exercise is shown in Figure 7. There were no significant differences in percent change in plasma volume among solutions. The overall post-time trial value, however, was different from all other time points ($P < 0.0001$).

**Time Trial Performance**

Mean time to complete a 3-mi cycling time trial following the 85-min exercise bout was 8:13 ± 0:25 min for 3% CHO, 7:58 ± 0:33 min for 6% CHO, and 8:25 ± 0:29 min for WP. Time trial performance was not significantly different among the different trials.

**Discussion**

The main findings of this study were that 1) sport beverage formulation of up to 6% CHO did not delay the rate of gastric emptying, 2) lowering the CHO concentration of a sport beverage from 6% reduced CHO and total solute absorption from the proximal small intestine during exercise but did not influence intestinal water...
Figure 5 — Plasma osmolality throughout 85 min of moderate intensity cycle ergometry followed by a 3-mi time trial (values are means ± standard error; \( n = 5 \) per solution). No significant differences in plasma osmolality were observed according to solution ingested.

Figure 6 — Plasma glucose concentrations throughout 85-min of moderate intensity cycle ergometry followed by a 3 mi time trial (values are means ± standard error; \( n = 5 \) per solution). Although mean plasma glucose concentration was significantly greater throughout exercise following 6% CHO ingestion compared with 3% CHO and WP, there were no significant differences in plasma glucose concentrations at any individual time point during exercise.
Figure 7 — Percent change in plasma volume throughout 85 min of moderate intensity cycle ergometry followed by a 3-mi time trial (values are means ± standard error; n = 5 per solution). The percent change in plasma volume was not significantly different among solutions (P > 0.05). The overall post-time trial value, however, was different from all other time points (P < 0.0001).

Following the 35-min equilibration period (to achieve steady-state conditions for determination of water and solute fluxes), the rate at which a given solution was emptied from the stomach was similar for all 3 solutions (3% CHO, 6% CHO, and WP) tested in this study. The mean GER for all solutions (16 ± 2 mL/min) compares well with similar experimental protocols in which GER ranged from 17 to 20 mL/min (11, 15, 16, 22). The addition of CHO to a sport beverage might delay gastric emptying at high concentrations (21, 27); however, other studies suggest CHO concentrations up to 6% (or up to 4% glucose) do not impede the GER (20, 22). The 3% CHO solution used in this study was formulated with 2% sucrose and 1% glucose, while the 6% CHO was formulated with 4% sucrose and 2% glucose. These CHO concentrations are not expected to alter the rate of gastric emptying. Furthermore, GER follows an exponential time course based largely on stomach volume. Maintenance of slightly higher stomach volumes observed in the 3% CHO and 6% CHO trials (Figure 1) likely enhanced emptying of these solutions and did not appear to affect stomach comfort or performance.

Water and solute absorption occur primarily in the proximal segment of the small intestine (duodenum and jejunum). The primary factors influencing water absorption from the duodenojejunal are intestinal osmolality and net solute absorption. CHO concentrations in the intestinal lumen influence solute and therefore water fluxes, in that the incorporation of more than 1 form of CHO activates additional
noncompetitive transport mechanisms that could increase water absorption (26). In addition, the rate of gastric emptying determines the volume of fluid and solute delivered to the proximal small intestine and therefore also influences water and solute fluxes. In this study, no differences in luminal [Na⁺] throughout the proximal small intestine were noted for 3% and 6% CHO ingestion, as both solutions were formulated to contain equivalent Na⁺ and K⁺ concentrations. Gastric [Na⁺], however, was lower, and [Na⁺] at the 50-cm intestinal sampling site was greater, for WP compared with 3% CHO and 6% CHO. As net water absorption was similar for all test solutions, this suggests that net Na⁺ secretion occurred in the duodenum to decrease the existing osmotic gradient after WP ingestion (7, 16).

Total solute flux was greater for 6% CHO compared to 3% CHO and WP because of enhanced CHO absorption. We did not, however, observe any differences in net water flux in the duodenum or jejunum with regard to the specific solution ingested. Perhaps this can be attributed to differences in solution osmolalities and the resulting osmotic gradients in each intestinal segment. At the distal intestinal sampling site (~55 cm past the pyloric sphincter), the mean osmolality for 3% CHO was 243 ± 8 mosm/kg H₂O and for WP was 189 ± 16 mosm/kg H₂O, compared to 289 ± 7 mosm/kg H₂O for 6% CHO. The relative hypotonicity of 3% CHO and WP might compensate for the reduced rates of solute absorption to sustain an osmotic gradient favoring water absorption from the proximal small intestine. Shi and colleagues (25) studied the effects of solution osmolality and intestinal water flux using a duodenojejunum perfusion technique in humans at rest. In that study, three different 6% CHO solutions were studied, each differing in CHO type to produce differences in osmolality (hypotonic, isotonic, and hypertonic). The authors found that net solute and water fluxes did not differ across the proximal 40 cm of the small intestine despite significant differences in solution osmolalities. Solute flux (and specifically CHO and Na⁺ fluxes) had a greater effect on water absorption than did osmolality but no differences in fluid homeostasis (hypotonic, isotonic, and hypertonic). The authors concluded that, across the proximal small intestine, water absorption through pathways related to solute flux (primarily CHO absorption pathways) were able to sustain water absorption despite differences in solution osmolalities that could be expected to alter net water flux. Similar results were found in a subsequent study, as oral ingestion of a hypotonic, isotonic, or hypertonic 6% CHO or a water placebo at regular intervals throughout a moderate-intensity bout of cycle ergometry did not influence water absorption or fluid homeostasis (11). The experimental design of the present study differed from those of Shi et al. (25) and Gisolfi et al. (11), in that the concurrent effects of reduced CHO composition and the resulting reduction in solution osmolality were examined. The results of the current study, however, concur with those previously reported as reductions in solution osmolality did not alter net water flux during prolonged cycling despite the finding that CHO absorption (and total solute flux) was greater for 6% CHO.

One limitation to the protocol utilized in the present study is that the independent effects of reduced solution CHO concentration and reduced osmolality were not assessed. Furthermore, CHO solutions were formulated to contain equivalent concentrations of Na⁺ and K⁺ to isolate the effects of reduced CHO concentration. True sport beverage dilution reduces Na⁺ and K⁺ concentrations, which might alter solute and water flux responses from those noted in the present study.
The percent change in plasma volume, osmolality, or glucose concentration did not differ with respect to the solution ingested at any individual time point throughout the exercise protocol. The final plasma volume change (post-time trial) was, however, greater than all other time points during each trial. This likely reflects loss of plasma from the vascular compartment during the time trial as vascular hydrostatic pressure was increased because of more forceful muscular contractions compared to the submaximal phase of the trials. In addition, the mean plasma glucose concentration throughout exercise was greater during 6% CHO ingestion compared to 3% CHO and WP ingestion.

Plasma glucose concentrations have been correlated with exercise performance from the standpoint that hypoglycemia could contribute to muscular fatigue (3, 4). Despite maintaining greater mean plasma glucose concentrations over the duration of the exercise bout, ingestion of 6% CHO did not significantly enhance cycle time trial performance compared to 3% CHO and WP. This is in contrast to numerous other studies in which CHO supplementation during exercise delayed time to fatigue (4), improved time trial performance (9), or enhanced total work output (2, 8, 20).

In the present study, all subjects maintained euglycemia which might account for the apparent lack of performance enhancement following 6% CHO ingestion. Another possibility is that CHO availability did not limit exercise performance for the given performance test. Specifically, the length of exercise time, at the intensity ridden, might not have stressed the glycogen reserves. The 3-mi cycling time trial was completed within 7 to 10 min for all subjects. CHO oxidation from intramuscular glycogen stores is expected to contribute to the energy requirements for this high-intensity exercise bout. As exogenous CHO supplementation is not always associated with a glycogen-sparing effect (3, 4, 20), however, this performance test may not be influenced by CHO supplementation. We did not obtain measures of endogenous or exogenous CHO oxidation during exercise; these processes might be differentially influenced by the CHO concentration in a sport beverage. In addition, a separate reliability study was not completed for this performance measure. This particular performance measure was chosen, in part, to mimic race conditions in which athletes perform maximally at the end of a race. Although the subjects who participated in the present study were trained road cyclists accustomed to performing maximally following a prolonged bout of exercise, it remains possible that significant differences in performance were undetected by the 3-mi time trial used in the current study or that there might have been insufficient power because of the low number of subjects to detect possible differences among the trials.

In summary, the results of our study show that CHO concentration (up to 6%) did not influence the rate of gastric emptying following sport beverage consumption, but that reducing the CHO concentration from 6% limited CHO absorption from the proximal small intestine. Because of a greater osmotic gradient present between the intestinal lumen and plasma, however, water absorption of the 3% CHO and WP solutions were similar to that of the 6% solution. Despite greater plasma glucose concentration after ingestion of 6% CHO, 3-mi time trial performance was not significantly improved. These results indicate that during prolonged cycling, lowering the CHO concentration of a sport drink from 6% CHO does not enhance intestinal water absorption or subsequent 3-mi time trial performance, and results in reduced CHO and total solute absorption.
Acknowledgments

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