CHO Oxidation from a CHO Gel Compared with a Drink during Exercise

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ABSTRACT

PFEIFFER, B., T. STELLINGWERFF, E. ZALTAS, and A. E. JEUKENDRUP. CHO Oxidation from a CHO Gel Compared with a Drink during Exercise. Med. Sci. Sports Exerc., Vol. 42, No. 11, pp. 2038–2045, 2010. Recently, it has been shown that ingestion of solutions with glucose (GLU) and fructose (FRC) leads to 20%–50% higher CHO oxidation rates compared with GLU alone. Although most laboratory studies used solutions to deliver CHO, in practice, athletes often ingest CHO in the form of gels (semisolid). It is currently not known if CHO ingested in the form of a gel is oxidized as effectively as a drink. Purpose: To investigate exogenous CHO oxidation from CHO provided in semisolid (GEL) or solution (DRINK) form during cycling. Methods: Eight well-trained cyclists (age = 34 ± 7 yr, mass = 76 ± 9 kg, \(\text{VO}_{2\text{max}} = 61 ± 7 \text{ mL-kg}^{-1}\text{-min}^{-1}\)) performed three exercise trials in random order. The trials consisted of cycling at 59% ± 4% \(\text{VO}_{2\text{max}}\) for 180 min while receiving one of the following three treatments: GEL plus plain water, DRINK, or plain water. Both CHO treatments delivered GLU plus FRC in a ratio of 2:1 at a rate of 1.8 g·min⁻¹ (108 g·h⁻¹). Fluid intake was matched between treatments at 867 mL·h⁻¹. Results: Exogenous CHO oxidation from GEL and DRINK showed a similar time course, with peak exogenous CHO oxidation rates being reached at the end of the 180-min exercise. Peak exogenous CHO oxidation rates were not significantly different (\(P = 0.40\) between GEL and DRINK (1.44 ± 0.29 vs 1.42 ± 0.23 g·min⁻¹, respectively). Furthermore, oxidation efficiency was not significantly different (\(P = 0.56\) between GEL and DRINK (71% ± 15% vs 69% ± 13%, respectively). Conclusions: This study demonstrates that a GLU + FRC mixture is oxidized to the same degree when administered as either semisolid GEL or liquid DRINK, leading to similarly high peak oxidation rates and oxidation efficiencies. Key Words: CHO INGESTION, CYCLING, EXOGENOUS CHO OXIDATION, CHO FORM

The intake of CHO during exercise is a common strategy of athletes competing in endurance events. Indeed, it is generally accepted that this strategy is beneficial, and the intake of CHO can delay fatigue and enhance both endurance capacity (6,7) and endurance performance (11,12,14). The ergogenic effect of CHO ingestion during prolonged exercise has largely been attributed to several mechanisms, including the maintenance of plasma glucose (GLU) concentrations (8), and potentially to some exercise situations contributing to either a glycogen-sparing effect (35,37) or a central cognitive effect (5,6).

Another mechanism to explain the beneficial role of CHO during exercise might be the maintenance of high CHO oxidation rates, particularly late in exercise when glycogen stores become limited (7,8). A series of studies using stable (\(^{13}\)C) and radioactive (\(^{14}\)C) isotopes have investigated CHO oxidation from the ingestion of different sources of CHO and CHO mixtures. Particularly interesting was the consistent finding that, when ingested at high intake rates (1.5–2.4 g·min⁻¹), mixtures of GLU + FRC produce 20%–50% higher exogenous CHO oxidation rates late in exercise compared with an isocaloric amount of GLU-only solutions (15,16,19,39). Accordingly, Currell and Jeukendrup (11) demonstrated that a GLU + FRC mixture, which has been associated with high exogenous CHO oxidation rates, coincided with a significant 8% improvement in endurance performance (40-km time trial (TT) preceded by 2 h of moderate-intensity cycling) when compared with GLU alone.

However, to show the ergogenic benefit of GLU + FRC solutions, large fluid volumes (800–1000 mL·h⁻¹) and high CHO concentrations (>10% CHO solution; >100 g of CHO·h⁻¹) have been implemented in laboratory settings. Currently, common sports drinks are generally less concentrated (4%–8% CHO), and to achieve CHO intake rates of >1.5 g·min⁻¹ would require very large fluid intake rates (~1–2.5 L·h⁻¹), which likely exceed sweat rates of most athletes in cool weather conditions (31). In reality, athletes, especially runners, have been reported to take in rather low voluntary fluid volumes (21,29) (unpublished observation). An alternative to sports drink consumption for athletes in the field is the ingestion of concentrated CHO gels that offer
the possibility to take in much CHO with an ad libitum amount of fluid, thus dissociating fluid and CHO intakes. Indeed, it seems to be common practice for endurance athletes to take in CHO in the form of gels (13).

However, whether the intake of a semisolid CHO gel has the same effect on metabolism and exogenous CHO oxidation as a CHO solution is not clear. Rate-limiting steps for the oxidation of ingested CHO are most likely at the entrance of the systemic circulation via intestinal transit and absorption (17). The rate of gastric emptying has been reported to depend mainly on gastric volume and the energy content of the ingested food (22,26). However, it has also been suggested that other factors such as viscosity of an ingested meal can influence the rate of gastric emptying (24). For example, the addition of gel-forming fibers such as guar gum to CHO solutions has been reported to slow down gastric emptying in some studies (25,34). In contrast, a study by Leiper et al. (23) reported faster gastric emptying rates from a gel-forming CHO compared with an isocaloric low-viscosity CHO solution. However, no consequences on plasma GLU or insulin concentrations were reported in that study.

Furthermore, it is theoretically possible that the simultaneously ingested gel and water are not entirely mixed together when leaving the stomach because it has been described that the stomach empties in layers, holding back solid and more concentrated foods in the sinus of the stomach (for review, see Schulze [33]). This could result in differences in CHO concentrations in the gut between a readily dissolved drink compared with a semisolid gel and, therefore, lead to different rates of intestinal absorption and subsequent oxidation. Therefore, the purpose of the present study was to clarify whether there is a difference in oxidation rates from GLU + FRC delivered as a gel plus plain water compared with a CHO solution during prolonged cycling. Considering that endurance athletes consume ~35% of their CHO intake in the form of gels when competing (unpublished observation), this is very relevant to athletes, and to the best of our knowledge, the oxidation of CHO delivered in the form of gel has never been studied.

We hypothesized that possible differences in gastric emptying rates would not substantially influence exogenous CHO oxidation rates and that mixing of the gel with water in the stomach would occur rapidly, and no differences between a gel and a drink would exist.

METHODS

Subjects. Eight well-trained male endurance cyclists/triathletes (age = 34 ± 7 yr, mass = 76 ± 9 kg, height = 1.78 ± 0.06 m, \( \dot{V}O_{2\text{max}} = 61 ± 3 \text{ mL kg}^{-1}\text{min}^{-1} \)) volunteered to participate in this study. Subjects trained at least three times a week for more than 2 h per session and had been involved in endurance training for at least 2 yr. All subjects were healthy as assessed by a general health questionnaire and were informed of the purpose, practical details, and risks associated with the procedures before giving their written informed consent to participate. This study was approved by the School of Sport and Exercise Sciences ethics subcommittee, University of Birmingham, Birmingham, UK.

Preliminary testing. At least 1 wk before the start of the experimental trials, an incremental cycle test to volitional exhaustion was performed to determine maximal power output (\( W_{\text{max}} \)) and maximal oxygen consumption (\( \dot{V}O_{2\text{max}} \)). This test was performed on an electromagnetically braked cycle ergometer (Lode Excalibur Sport, Groningen, The Netherlands). On arrival at the laboratory, body mass (Seca Alpha, Hamburg, Germany) and height were recorded. Subjects then started cycling for 3 min at 95 W, followed by incremental steps of 35 W every 3 min until exhaustion. \( W_{\text{max}} \) was determined by the following formula: \( W_{\text{max}} = W_{\text{out}} + [(t/180)35] \), where \( W_{\text{out}} \) is the power output (W) during the last completed stage and \( t \) is the time (s) in the final stage. HR was recorded continuously by a radiotelemetry HR monitor (625X; Polar, Kempele, Finland). The calculated \( W_{\text{max}} \) value was used to determine the 50% \( W_{\text{max}} \), which was later used in the experimental trials. Respiratory gas measurements were collected for the last minute during each stage using the Douglas bag technique and were analyzed using a gas analyzer (1400; Servomex, Crowborough, Sussex, England).

Experimental design. Each subject completed three exercise trials that consisted of 180 min of cycling at 50% \( W_{\text{max}} \) while ingesting 1.8 g of CHO-min\(^{-1}\) (GLU/FRC in the ratio of 2:1) in the form of a 12.5% maltodextrin plus FRC drink (DRINK), an isocaloric/isocarbohydrate gel (GEL), or plain water (WAT). The order of the trials was randomly assigned and was separated by at least 5 d.

Experimental treatments. To quantify exogenous CHO oxidation, corn-derived maltodextrin (GLUCIDEX 19; Roquette, Lestrem, France) and FRC (Krystar 300 Crystalline Fructose; Tate & Lyle, Decatur, IL) were used for the preparation of the DRINK, which have a high natural abundance of \(^{13}\)C (−11.228‰ and −11.008‰ vs Pee Dee Belleminiella (PDB), respectively). Correspondingly, the GEL consisted of maltodextrin (M150 Maltodextrin; Grain Processing Corporation, Muscatine, IA) and FRC (Krystar 300 Crystalline Fructose; Tate & Lyle) with an enrichment of −10.148‰ and −10.488‰ versus PDB, respectively. The \(^{13}\)C enrichment of the ingested CHO was determined by elemental analyzer–isotope ratio mass spectrometry (EA-IRMS; Europa Scientific GEO 20-20, Crewe, UK).

Diet and activity before testing. Before the first trial, advice was given to follow a diet rich in CHO. It was made sure that CHO intake was ≥4 g kg\(^{-1}\) body weight, which, in combination with light training or rest, would prevent participants to start the trials with depleted muscle glycogen stores. Subjects were asked to record their food intake and activity patterns for 24 h before the first exercise trial and were then instructed to follow the same diet and activities before the next two trials. Compliance was assessed with 24-h recalls the days before the rest of the trials. In addition,
Subjects were instructed to refrain from strenuous exercise and drinking any alcohol in the 24 h before the exercise trials. Furthermore, 3–7 d before each experimental trial, the subjects were instructed to perform an intense training session (“glycogen-depleting exercise bout”) in an attempt to reduce any endogenous $^{13}$C-enriched glycogen stores. Subjects were also instructed not to consume products with a high natural abundance of $^{13}$C (CHO derived from C4 plants such as maize and sugarcane) at least 1 wk before each experimental trial to reduce the background shift (change in $^{13}$C) from endogenous substrate stores.

**Protocol.** Each subject arrived in the laboratory at the same time in the morning (between 6:00 and 9:00 a.m.) after an overnight fast (10–12 h). All experimental trials were performed at the same time of the day to avoid circadian variance. On arrival, subjects were weighed before a 20-gauge Teflon catheter (Venflon; BD, Plymouth, UK) was inserted into an antecubital vein of an arm and attached to a three-way stopcock (Sims Portex, Kingsmead, UK) to allow insertion into an antecubital vein of an arm and attached to a three-way stopcock (Sims Portex, Kingsmead, UK) to allow.

Subjects then mounted a cycle ergometer, and a resting breath sample was collected into 10-mL Exetainer tube (Labco Ltd., Brow Works, High Wycombe, UK), which was filled directly from a mixing chamber to determine the $^{13}$C/$^{12}$C ratio in the expired air. A resting breath sample (10 mL) was collected and stored on ice until centrifugation. Subjects then started a 180-min exercise bout at a work rate equivalent to 50% $W_{max}$ (59 ± 4% $V_{O2max}$). Additional blood samples were drawn at 15-min intervals until the cessation of exercise. At the same 15-min intervals, expiratory breath samples were also collected. During the first 2 min, expired air was sampled into Douglas bags. Douglas bag samples were analyzed as described above, and oxygen consumption ($V_{O2}$), carbon dioxide production ($V_{CO2}$), and RER were determined. Within the last 60 s of each 3-min period, Exetainer tubes were filled in duplicate for breath $^{13}$C/$^{12}$C ratio as described above.

During the first 2–3 min of exercise, subjects ingested an initial bolus of one of the three experimental treatments: 400 mL of water (WAT), 400 mL of water plus 50 g of CHO in the form of gel (GEL), or 400 mL of a 12.5% CHO drink (DRINK). Thereafter, a beverage volume of 200 mL of WAT, 200 mL of water plus 25 g of CHO in the form of GEL, or 200 mL of a 12.5% CHO DRINK was provided every 15 min. The total fluid intake during the exercise bout was 2.6 L (867 mL·h$^{-1}$) and was matched among all three trials, whereas the total CHO intake was 325 g (108 g·h$^{-1}$) and matched between the two CHO trials. All exercise tests were performed under normal and standard environmental conditions (16°C–24°C dry bulb temperature and 50%–60% relative humidity). During the exercise trials, subjects were cooled with standing floor fans to minimize thermal stress.

**Questionnaires.** Every 30 min during the exercise bout, subjects were requested to verbally answer a short questionnaire to directly assess gastrointestinal (GI) tolerance. GI symptoms were scored on a 10-point scale (0 = no problem at all and 9 = the worst it has ever been). A score $>$4 was registered as serious. RPE were collected using a 6- to 20-point Borg scale (1).

**Analyses.** All blood samples were collected into prechilled test tubes containing EDTA and were centrifuged at 2300g for 10 min at 4°C. Aliquots of the plasma were frozen and stored at −25°C until further analysis. Plasma samples were analyzed enzymatically for GLU (Glucose HK; ABX Diagnostics, UK), lactate (Lactic Acid; ABX Diagnostics, Shefford, UK), and free fatty acid (FFA, NEFA-C KIt; Alpha Laboratories, Eastleigh, Hampshire, UK) concentration on a semiautomatic analyzer (Cobas Mira S-Plus; ABX Diagnostics). Breath samples were analyzed for $^{13}$C/$^{12}$C ratio by continuous-flow IRMS (GC, Trace GC Ultra; IRMS, Delta Plus XP; both Thermo Finnigan, Herts, UK). From indirect calorimetry ($V_{O2}$ and $V_{CO2}$) and stable isotope measurements (breath $^{13}$C/$^{12}$C ratio), rates of total fat, total CHO, and exogenous CHO oxidation were calculated.

**Calculations.** From $V_{O2}$ and $V_{CO2}$ (L·min$^{-1}$), CHO and fat oxidation rates (g·min$^{-1}$) were calculated using stoichiometric equations (20), with the assumption that protein oxidation during exercise was negligible.

\[
\text{CHO oxidation} = 4.21 \times \frac{V_{CO2}}{2} + 2.962 \times \frac{V_{O2}}{2}
\]

\[
\text{fat oxidation} = 1.659 \times \frac{V_{O2}}{2} + 1.701 \times \frac{V_{CO2}}{2}
\]

The isotopic enrichment was expressed as δ per mil difference between the $^{13}$C/$^{12}$C ratio of the sample and a known laboratory reference standard according to the formula of Craig (10):

\[
\delta^{13}C = \left( \frac{^{13}C/^{12}C_{\text{sample}}}{^{13}C/^{12}C_{\text{standard}}} - 1 \right) \times 10^3 \text{ per mil}
\]

The $\delta^{13}C$ was then related to an international standard (PDB).

In the CHO trials, the rate of exogenous CHO oxidation was calculated using the following formula (30):

\[
\text{exogenous CHO oxidation} = V_{CO2} \left( \frac{\delta\text{Exp} - \delta\text{Exp baseline}}{\delta\text{ing} - \delta\text{Exp baseline}} \right) \left( \frac{1}{k} \right)
\]

in which $\delta$ Exp is the $^{13}$C enrichment of expired air during exercise at different time points, $\delta$ ing is the $^{13}$C enrichment of the ingested CHO solution, $\delta$ Exp baseline is the $^{13}$C enrichment of expired air in the WAT trial (background) at different time points, and $k$ is the amount of CO$_2$ (L) produced by the oxidation of 1 g of GLU ($k = 0.7467$ L of CO$_2$·g$^{-1}$ of GLU). Endogenous CHO oxidation was calculated by subtracting exogenous CHO oxidation from total CHO oxidation.

A methodological consideration when using $^{13}$CO$_2$ in expired air to calculate exogenous substrate oxidation is the temporary fixing of $^{13}$CO$_2$ in the bicarbonate pool, in which an amount of CO$_2$ arising from CHO and fat oxidation is retained (32). However, during exercise, the turnover of this pool increases several fold so that a physiological steady-state condition will occur relatively rapidly and
Significantly higher in the WAT trial than after CHO ingestion GEL, and DRINK, respectively. Fat oxidation was significant (27,32). As a consequence, all calculations on substrate oxidation were performed during the last 120 min of exercise (60-180 min). The oxidation efficiency was determined as the percentage of the ingested CHO that was oxidized and was calculated by dividing exogenous CHO oxidation rate by the CHO ingestion rate and then multiplying it by 100.

Statistical analyses. A two-way (trial x time) ANOVA for repeated measures was used to compare differences in substrate utilization and in blood metabolites among the three trials. A Tukey post hoc test was applied where a significant F-ratio was detected. Paired-sample t-tests were applied when two mean values were compared. All values are presented as mean ± SD. Statistical significance was set at P < 0.05. All statistical analyses were performed using SPSS 15 for Windows (SPSS, Inc., Chicago, IL).

RESULTS

VO₂, RER, total CHO, and fat oxidation. VO₂, RER, total CHO, and fat oxidation rates during the 60- to 180-min exercise period are shown in Table 1. The rate of oxygen uptake (VO₂) was not significantly different among the three experimental trials. A significantly lower RER (P < 0.01) was measured in the WAT trial compared with the two CHO ingestion trials, but RER was not different between the GEL and DRINK trials. Correspondingly, CHO oxidation was not different between the two CHO trials, but it was significantly higher compared with the WAT trial (P < 0.01). Mean total CHO oxidation rates during the last 120 min of exercise were 1.35 ± 0.17, 2.03 ± 0.34, and 1.90 ± 0.25 g·min⁻¹ for WAT, GEL, and DRINK, respectively. Fat oxidation was significantly higher in the WAT trial than after CHO ingestion (P < 0.01), but this did not differ significantly between the CHO trials. Mean fat oxidation rates during the last 120 min of exercise were 0.84 ± 0.20, 0.53 ± 0.16, and 0.59 ± 0.16 g·min⁻¹ for WAT, GEL, and DRINK trials, respectively.

Exogenous CHO oxidation, endogenous CHO oxidation, and oxidation efficiency. Exogenous CHO oxidation rates increased over time (Fig. 1) with both CHO

<table>
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<tr>
<th>Trial</th>
<th>Time (min)</th>
<th>VO₂ (L·min⁻¹)</th>
<th>RER</th>
<th>CHO(tot) (g·min⁻¹)</th>
<th>Fat(tot) (g·min⁻¹)</th>
<th>CHO endogenous (g·min⁻¹)</th>
<th>CHO exogenous (g·min⁻¹)</th>
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<tr>
<td>WAT</td>
<td>60-90</td>
<td>2.70 ± 0.36</td>
<td>0.88 ± 0.02</td>
<td>1.44 ± 0.13</td>
<td>0.76 ± 0.19</td>
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<td>90-120</td>
<td>2.76 ± 0.37</td>
<td>0.82 ± 0.02</td>
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<td>120-150</td>
<td>2.76 ± 0.38</td>
<td>0.82 ± 0.02</td>
<td>1.31 ± 0.19</td>
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<td>0.84 ± 0.20</td>
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<td>1.44 ± 0.24</td>
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Values are means ± SD. There were no statistical differences found between GEL and DRINK.

*Significantly different from WAT (P < 0.05).
treatments. Peak exogenous CHO oxidation rates were reached at the end of the 180-min exercise and were not significantly different between the GEL and DRINK trials (1.44 ± 0.29 vs 1.42 ± 0.23 g·min⁻¹, respectively, P = 0.40). Mean exogenous CHO oxidation rates during the final 120 min of exercise were not significantly different between CHO treatments (1.28 ± 0.26 and 1.24 ± 0.23 g·min⁻¹ for GEL and DRINK, respectively, P = 0.19; Table 1). Correspondingly, the oxidation efficiency was not different between the GEL and DRINK trials (71% ± 15% vs 69% ± 13%, respectively, P = 0.35).

The contribution of exogenous CHO to total energy expenditure was 39% and 38% for GEL and DRINK, respectively. Endogenous CHO oxidation contributed to total energy expenditure with 41%, 23%, and 25% for WAT, GEL, and DRINK, respectively. Compared with the WAT trial, endogenous CHO oxidation was significantly lower with both forms of CHO ingestion during the last 120 min of exercise (P < 0.05; Table 1).

Plasma metabolites. Plasma GLU, lactate, and FFA concentrations at rest and during 180 min of exercise are shown in Figures 3, 4, and 5, respectively. Resting plasma GLU, lactate, and FFA concentrations before the onset of exercise were similar among all three trials. Throughout exercise in the WAT trial, plasma GLU concentrations stayed relatively stable and greater than ~5 mmol·L⁻¹. Plasma GLU concentrations significantly (P < 0.05) increased with the ingestion of both CHO treatments to peak values of ~7.9 mmol·L⁻¹ at 30 min of exercise. In both trials, plasma GLU concentrations were significantly higher (P < 0.05) during the whole period except the 45-min time point, with both treatments and the 90-min measure in the GEL trial. Plasma GLU concentrations from both CHO treatments were not significantly different (P > 0.05).

Plasma lactate increased significantly in the first 15 min during all three trials (P < 0.05). Within the first 135 min of exercise, plasma lactate concentrations were higher within the CHO trials than with the WAT trial, reaching statistical significance between 15–75 and 120–135 min during the GEL trial and at 30, 60, and 120 min during the DRINK trial (P < 0.05). Concentrations of FFA in plasma increased during the WAT trial and were significantly higher than during the CHO trials after 30 min until the end of the exercise. No significant differences occurred between the CHO trials.

GI symptoms, perceived fullness, and RPE. No severe GI symptoms (>4) were recorded in any of the trials. Mean upper abdominal problems were 0.0 ± 0.0, 0.1 ± 0.1, and 0.2 ± 0.4 in the WAT, GEL, and DRINK trials, respectively. Mean lower abdominal problem was 0.0 ± 0.0 in all three trials. No significant differences were detected among trials. Furthermore, no difference in perceived
stomach fullness was detected. RPE during the last half hour of exercise were 13 ± 2, 12 ± 1, and 12 ± 1 in the WAT, GEL, and DRINK trials, respectively.

**DISCUSSION**

The most important finding of this study was that the delivery and oxidation of CHO in the form of a GLU + FRC blend during exercise is as effective when ingested as a semisolid GEL compared with a DRINK. Recently, intake recommendations for CHO blends (e.g., GLU + FRC) have been published with the advice to ingest CHO at a rate of ~1.5 g·min⁻¹ during endurance exercise (18). This high CHO intake rate may be difficult to achieve with CHO solutions only because of the associated and large fluid intake volumes. Therefore, it is of practical relevance to know whether CHO delivered in the form of a semisolid GEL is used and oxidized as effectively as CHO in a liquid form.

The findings of this study showed that both forms of CHO administration resulted in similar mean and peak exogenous CHO oxidation rates at the end of 3 h of steady-state cycling (1.44 ± 0.29 and 1.42 ± 0.23 g·min⁻¹ for GEL and DRINK, respectively).

From previous studies, it was generally accepted that exogenous CHO oxidation rates peak at ~1.0 g·min⁻¹ with the ingestion of single CHO (such as GLU alone), even with high intake rates (>1.5 g·CHO·min⁻¹; for review, see Jeukendrup [18]). In contrast, the delivery of CHO in the form of GLU + FRC at similarly high ingestion rates (>1.5 g·min⁻¹) can result in peak exogenous CHO oxidation rates significantly exceeding 1.0 g·min⁻¹ (15,16,39). In agreement with these findings, the present study reported peak oxidation rates for both GLU + FRC treatments of ~1.4 g·min⁻¹.

It has been suggested that exogenous CHO oxidation is potentially limited by gastric emptying, intestinal absorption, liver GLU extraction, muscle GLU uptake, or a combination of these factors (17). As mentioned earlier, the rate-limiting steps for exogenous CHO oxidation are thought to be the entrance into the systemic circulation via absorption in the small intestines rather than the intramuscular factors (17). A potential of high CHO concentrations to limit gastric emptying rates of a solution has repeatedly been documented (9,38). For example, Vist and Maughan (38) reported significantly slower gastric emptying rates, with an 18% compared with a 4% CHO solution. However, CHO delivery to the small intestines was still significantly higher with the 18% compared with the 4% solution. In the current study, fluid volume and energy density, the most potent influencers of gastric emptying rates (22,26), were similar between CHO trials, and from this point of view, no difference between treatments was expected. The focus of the present study was to purely evaluate the effect of CHO intake form on exogenous CHO oxidation rates. Previous studies have reported altered gastric emptying rates, with changes in viscosity of ingested drinks: The addition of gel-forming fibers such as guar gum to CHO solutions has been reported to slow down gastric emptying in some studies (25,34). In contrast, a study by Leiper et al. (23) reported faster gastric emptying rates from a gel-forming GLU polymer (78% amylopectin and 22% amylose) compared with an isocaloric, low-viscosity GLU solution (GLU and GLU oligomers). Interestingly, this study did not detect differences in plasma GLU and insulin concentrations, and it could be speculated that faster gastric emptying rates of the GLU polymer were “neutralized” by slower digestion and absorption of the GLU polymer (especially amylose) compared with the GLU solution. It has indeed been suggested earlier that α-amylase susceptibility rather than viscosity determines the plasma responses after ingestion of starch-containing meals (2).

Furthermore, it has been proposed that intestinal absorption is the more important driver for exogenous CHO oxidation rates compared with gastric emptying rates (17). To date, there is no evidence whether CHO from gel or solution is absorbed in a similar extent in the GI tract. As discussed earlier, there would have been the possibility that the simultaneously ingested semisolid GEL and water are not entirely mixed together when leaving the stomach. The stomach empties in layers (for review, see Schulze [33]), holding back solid and more concentrated foods in the sinus of the stomach. This could result in differences in CHO concentrations in the small intestine between a readily dissolved drink and a gel and, therefore, lead to a different time course of rates of intestinal absorption. Consequently, the similarly high exogenous CHO oxidation rates of the present study give indirect evidence that both CHO treatments (GEL vs DRINK) are absorbed at similar rates.

In reality, it is very likely that CHO gels are ingested with much lower fluid volumes as applied in the current study. Fluid intake rates, especially of runners under cool conditions, are reported to be small (~325 mL·h⁻¹) (29). It is well known that gastric volume is one of the most potent drivers of gastric emptying, and the intake of CHO gel combined with low fluid volumes could therefore lead to a
slower delivery of liquid to the small intestine. Theoretically and based on previous research (38), it is not expected that CHO delivery to the small intestines is substantially different with varying fluid volume. Furthermore, intestinal absorption, which is most likely the major determinant of exogenous CHO oxidation rates, is unlikely to be affected by the ingested fluid volume. Hence, the influence of associated fluid volume on exogenous oxidation rates is expected to be minimal.

The similar oxidation rates in the present study fit with the results of the study of Campbell et al. (4), which demonstrated a similar effect on performance when a CHO gel was compared with a drink. The beneficial effects of CHO on endurance exercise performance are generally well accepted. However, the mechanisms to explain the positive performance findings are not entirely clear, but they have been partly attributed to the maintenance of euglycemia, a sparing of endogenous CHO stores, a central stimulatory CNS effect, or the maintenance of high CHO oxidation rates late in exercise. Correspondingly, a recent study using GLU + FRC mixtures, which have been previously shown to increase exogenous CHO oxidation by 20%-50%, resulted in an 8% significant increase in TT performance (18). In this study, 2 h of moderate-intensity steady-state cycling was undertaken with a CHO ingestion rate of 1.8 g-min⁻¹ in the form of GLU or GLU + FRC and was followed by a 40-km cycling TT. The ingestion of a GLU + FRC drink resulted in an 8% improvement in TT performance compared with GLU and 17% compared with the water placebo (11). In the present study, both forms of CHO intake raised blood GLU above concentrations during the WAT trial and, therefore, effectively maintained euglycemia. Accordingly, total CHO oxidation rates also remained ~50% higher (P < 0.001) with both forms of CHO intake compared with the WAT trial at the end of the exercise. Furthermore, ingestion of GEL and DRINK resulted in similar and high exogenous CHO oxidation rates and a substantial suppression of estimated endogenous CHO oxidation (Fig. 2). These current findings help explain the similar ergogenic effects on endurance performance found with gels versus sports drinks (4).

However, a potential negative effect of high CHO intake rates on endurance performance is the development of GI distress. The intake of CHO has been reported to correlate with altered GI distress (3,28) during exercise, which can ultimately reduce performance (3,36). A recent set of studies, however, has reported generally good GI tolerance of high CHO intake rates (1.4 g·min⁻¹; 90 g·h⁻¹) in the form of gels during a 16-km outdoor running competition (29). Accordingly, in the present study, we reported no serious GI problems in any of the trials and no significant difference between treatments. Hence, this study is adding evidence that high CHO intake rates are well tolerated in the form of GEL or DRINK.

In summary, this study demonstrated that a GLU + FRC mixture is oxidized to the same degree when administered as a semisolid GEL or liquid DRINK. In practical terms, these findings suggest that intake of semisolid CHO along with CHO beverages or water is an effective way to deliver high intake rates of CHO, with limited GI tolerance problems, during prolonged endurance exercise.

This study was supported by a research grant from Nestle Nutrition, Vevey, Switzerland.

The authors thank all athletes who participated in the trials for their enthusiasm and the time they dedicated to the study. Results from the present study do not constitute endorsement by the American College of Sports Medicine.

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