Oxidation of Solid versus Liquid CHO Sources during Exercise

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ABSTRACT

PFIEFFER, B., T. STELLINGWERFF, E. ZALTAS, and A. E. JEUKENDRUP. Oxidation of Solid versus Liquid CHO Sources during Exercise. Med. Sci. Sports Exerc., Vol. 42, No. 11, pp. 2030–2037, 2010. The ingestion of CHO solutions has been shown to increase CHO oxidation and improve endurance performance. However, most studies have investigated CHO in solution, and sporting practice includes ingestion of CHO in solid (e.g., energy bars) as well as in liquid form. It remains unknown whether CHO in solid form is as effectively oxidized as CHO in solution. Purpose: To investigate exogenous CHO oxidation from CHO provided in either solid (BAR) or solution (DRINK) form during cycling. Methods: Eight well-trained subjects (age = 31 ± 7 yr, mass = 73 ± 5 kg, height = 1.79 ± 0.05 m, VO2max = 69 ± 6 mL·kg−1·min−1) cycled at 58% ± 4% VO2max for 180 min while receiving one of the following three treatments in randomized order: BAR plus water, DRINK, or water. The BAR and DRINK was delivered glucose + fructose (GLU + FRC) in a ratio of 2:1 at a rate of 1.55 g·min−1, and fluid intake was matched between treatments. Results: During the final 2 h of exercise, overall mean exogenous CHO oxidation rate was −0.11 g·min−1 lower in BAR (95% confidence interval = −0.37 to 0.05 g·min−1, P = 0.19) relative to DRINK, whereas exogenous CHO oxidation rates were 15% lower in BAR (P = 0.05) at 120, 135, and 150 min of exercise. Peak exogenous CHO oxidation rates were high in both conditions (BAR 1.25 ± 0.15 g·min−1 and DRINK 1.34 ± 0.27 g·min−1) but were not significantly different (P = 0.36) between treatments (mean difference = −0.9 g·min−1, 95% confidence interval = −0.32 to 0.13 g·min−1). Conclusions: The present study demonstrates that a GLU + FRC mix administered as a solid BAR during cycling can lead to high mean and peak exogenous CHO oxidation rates (>1 g·min−1). The GLU + FRC mix ingested in the form of a solid BAR resulted in similar mean and peak exogenous CHO oxidation rates and showed similar oxidation efficiencies as a DRINK. These findings suggest that CHO from a solid BAR is effectively oxidized during exercise and can be a practical form of supplementation alongside other forms of CHO.

Key Words: CHO INGESTION, SOLID AND LIQUID CHO, EXOGENOUS CHO OXIDATION, CYCLING

Competitive cyclists and triathletes routinely consume CHO in different forms such as sports drinks, energy bars, and CHO gels. The intake of CHO has been shown to delay the onset of fatigue and improve endurance capacity (4,6,12,23,26,27). However, the effect of different forms of CHO intake (such as solids or solutions) on metabolism and performance is not fully understood.

The efficacy of CHOs in improving endurance performance is due, in part, to their capacity to be oxidized by the working muscle. A mixture of glucose (GLU) and fructose (FRC) has been shown to be oxidized at 20%–50% higher rates than as GLU alone when ingested at high rates (1.5–2.4 g·min−1) (15,16). Recently, it was also demonstrated that a similar GLU + FRC drink (1.8 g·min−1) resulted in superior endurance performance compared with an isocaloric GLU drink (8,39).

However, these high exogenous CHO oxidation rates during exercise only seem to occur with high rates of CHO intake (>1.5 g·min−1) (14). In the studies previously mentioned, this was done by administering CHO solutions >10%. Although available data concerning athletes’ actual CHO intake during competitions are limited, the use of such concentrated drinks seems not to be common practice. Sporting practice includes ingestion of CHO in solid (e.g., energy bar), liquid (e.g., sports drink), and gel forms, and a more varied intake of CHO sources seems to be a more convenient way for athletes to ingest CHO in large amounts. However, whether it is possible to extrapolate the positive exogenous CHO oxidation and performance findings from drinks to other forms of CHO, intake such as the ingestion of a solid food, is not yet clear.

To date, only a few studies have investigated the effect of solid CHO or solid CHO-rich food on metabolism during exercise and endurance performance. Studies have shown increased performance with the ingestion of solid CHO compared with a placebo (3,10,13) and similar performance improvements when the same amount of CHO was ingested in the form of solids compared with liquids (3,9,12,26). In contrast, the study by Rauch et al. (32) reported enhanced fat
metabolism and impaired endurance performance with a CHO bar compared with a drink. However, the CHO bar in this study delivered only ~29 g of CHO per hour compared with a delivery rate of 70 g of CHO per hour with the drink. Whether the same amount of CHO ingested in solid form has the same effect on CHO and fat metabolism and especially exogenous CHO oxidation during exercise is less clear (22,33).

To the best of our knowledge, CHO oxidation rates and efficiency from the ingestion of solid food have never been examined. It is well established that solid food is emptied slower from the stomach compared with liquids while at rest. This delayed gastric emptying with solid food is because of the increased particle size (13,40) as well as fat and fiber (10,11,37,40). Thus, it can be hypothesized that a solid CHO source could be oxidized at lower rates compared with liquid CHO sources. We therefore set out to study the exogenous CHO oxidation of a CHO mixture (GLU/FRC in a ratio of 2:1) given in the form of an energy bar (BAR) combined with plain water or a CHO solution (DRINK).

METHODS

Subjects. Eight well-trained male endurance cyclists/triathletes (age = 31 ± 7 yr, mass = 73 ± 5 kg, height = 1.79 ± 0.05 m, \( \dot{V}O_{2\text{max}} = 69 \pm 6 \text{ mL-kg}^{-1}\text{-min}^{-1} \)) volunteered to participate in this study. Subjects trained at least three times a week for more than 2 h·d\(^{-1}\) and had been involved in endurance training for at least 2 yr. All subjects were healthy as assessed by a general health questionnaire. Exclusion criteria for the study were a diagnosis of metabolic or intestinal disorders, smoking, associated cycling injuries, regular consumption of medication, and donation of blood.

Exclusion criteria for the study were a diagnosis of metabolic or intestinal disorders, smoking, associated cycling injuries, regular consumption of medication, and donation of blood. All participants were confirmed to be above 4 g·kg\(^{-1}\) body weight, which, in combination with light training or activity before giving their written informed consent to participate. The 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 (\( \dot{V}O_{2\text{max}} \)) 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: \( W_{\text{max}} = W_{\text{out}} + [(i/180)35] \), where \( W_{\text{out}} \) is the power output (W) during the last completed stage and \( i \) is the time (s) in the final stage. HR was recorded continuously by a radiotelemetry HR monitor (625X; Polar, Kempele, Finland). \( W_{\text{max}} \) values were used to determine the 50% \( W_{\text{max}} \) which was later used in the experimental trials. Respiratory gas measurements were obtained using the Douglas bag technique. Douglas bags were collected for 1 min during the final stage 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 1.55 g of CHO·min\(^{-1}\) (GLU and FRC in the ratio of 2:1) in the form of a 10.75% maltodextrin plus FRC drink (DRINK), or an isocarbohydrate energy bar plus plain water (BAR), or plain water (WAT). The order of the trials was randomly assigned and separated by at least 5 d.

Experimental treatments. Because the BAR contained not only CHO but also fat and protein, the CHO treatments were not isocaloric (Table 1A). The BAR also consisted of different CHO (Table 1B). CHO consisted of 0.67 of GLU and GLU polymers and 0.33 of FRC (per BAR, 5 g as crystalline FRC and 9 g contained in cane syrup). To quantify exogenous CHO oxidation, corn-derived maltodextrin (GLUCIDEX 19; Roquette, Lestrem, France) and FRC (Krystal 300; AE Stanley Manufacturing Co., Decatur, IL), which have a high natural abundance of \( ^{13} \text{C} \) (\(-11.228\%\) and \(-10.728\%\) vs Pee Dee Belemnite, respectively), were used for the preparation of DRINK. To ensure a similar amount of sodium in the BAR and in the DRINK, sodium in the form of sodium chloride was added to the DRINK (500 mg of sodium per liter). The BAR consisted predominantly of ingredients with a high natural abundance of \( ^{13} \text{C} \) (72%). Enrichment of all CHO sources of the BAR is shown in Table 1B. The \( ^{13} \text{C} \) 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. 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. The instructions also contained advice 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 allow participants to start the trials with adequate muscle glycogen stores. Diet was assessed with 24-h recalls the days before the rest of the trials, and CHO intake of all participants was confirmed to be above 4 g·kg\(^{-1}\) body weight. In addition, subjects were instructed to refrain from strenuous exercise and drinking any alcohol in the 24 h before the exercise trials. Furthermore, subjects were instructed to perform an intense training session ("glycogen-depleting exercise bout") 3–7 d before each experimental trial in an attempt to reduce any \( ^{13} \text{C} \)-enriched glycogen stores.

Subjects were also instructed not to consume products with a high natural abundance of \( ^{13} \text{C} \). CHO derived from C4 plants

<table>
<thead>
<tr>
<th>Table 1A. Nutrition facts for both CHO treatments.</th>
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<tr>
<td>Per Bar (65 g)</td>
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<td>----------------</td>
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<tr>
<td>Energy (kcal)</td>
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<tr>
<td>Protein (g)</td>
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<tr>
<td>CHO (g)</td>
</tr>
<tr>
<td>Fat (g)</td>
</tr>
<tr>
<td>Fiber (g)</td>
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<td>Sodium (mg)</td>
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</table>

CHO OXIDATION FROM SOLID VS LIQUID

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FIGURE 1. Enrichment of different CHO sources of the BAR.

<table>
<thead>
<tr>
<th>CHO Source</th>
<th>Mean δ13C (‰)</th>
<th>4% CHO</th>
</tr>
</thead>
<tbody>
<tr>
<td>High enriched CHO</td>
<td>-11.05</td>
<td>72</td>
</tr>
<tr>
<td>Maltodextrin</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oat bran</td>
<td>-27.15</td>
<td>28*</td>
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<tr>
<td>Low enriched CHO</td>
<td></td>
<td></td>
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<tr>
<td>Flour</td>
<td></td>
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<tr>
<td>Brown rice flour</td>
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* 5% starch.

Protocol. The subjects arrived in the laboratory 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 for repeated blood sampling during exercise. The cannula was kept patent by flushing with 1.0–1.5 mL of isotonic saline (0.9% BD) after each blood sample collection. The subjects then mounted a cycle ergometer, and a resting blood sample was collected in a 10-mL tube (Exetainer; Labco Ltd., Bore Woods, High Wycombe, UK), which was filled directly from a mixing chamber to determine the 13C/12C ratio in the expired air. A resting blood 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% Wmax (58% ± 4%Vo2max). Additional blood samples were drawn at 15-min intervals until the cessation of exercise. At the same 15-min intervals, respiratory 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 (VO2), carbon dioxide production (VCO2), and RER were determined. Within the last 60 s of each 3-min period, Exetainer tubes were filled in duplicate for breath 13C/12C 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 one energy bar (BAR), 400 mL of 10.75% CHO drink (DRINK). Thereafter, a beverage volume of 200 mL and 32.5 g of BAR was provided every 15 min. The total fluid intake during the exercise bout was 2.6 L (867 mL·h−1), whereas the total CHO intake was 280 g (93 g·h−1). 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 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 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 (ABX Diagnostics, Shefford, UK), and free fatty acid (FFA, NEFA-C Kit; Alpha Laboratories, Eastleigh, Hampshire, UK) concentrations on a semiautomatic analyzer (Cobas Mira S-Plus; ABX Diagnostics). Insulin was analyzed by ELISA (DRG Ultrasensitive Insulin ELISA; DRG Instruments GmbH, Marburg, Germany). Breath samples were analyzed for 13C/12C ratio by continuous-flow IRMS (GC, Trace GC Ultra; IRMS, Delta Plus XP; both Thermo Finnigan, Herts, UK). From indirect calorimetry (VO2 and VCO2) and stable isotope measurements (breath 13C/12C ratio), rates of total fat, total CHO, and exogenous CHO oxidation were calculated.

Calculations. From VO2 and VCO2 (L·min−1), CHO and fat oxidation rates (g·min−1) were calculated using stoichiometric equations (19), with the assumption that protein oxidation during exercise was negligible.

CHO oxidation = 4.21 VCO2 + 2.962 VO2
fat oxidation = 1.695 VO2 + 1.701 VCO2

The isotopic enrichment was expressed as δ per mil difference between the 13C/12C ratio of the sample and a known laboratory reference standard according to the formula of Craig (7):
13C-CHO (~5% of total CHO) consists of starch (Table 1B). Because insoluble starch (24% amylose and 76% amylopectin) has been shown to be oxidized at (approximately 30%) lower rates as GLU (36), the small amounts of starch could lead to an overestimation of exogenous CHO oxidation of ~3%. To account for the possible overestimation, a second enrichment value (minimum exogenous CHO oxidation) was used, assuming that starch was not oxidized at all. Both enrichment values were then averaged and used for calculations (enrichment = −15.2).

Endogenous CHO oxidation was calculated by subtracting exogenous CHO oxidation from total CHO oxidation. A methodological consideration when using 13CO2 in expired air to calculate exogenous substrate oxidation is the temporary fixing of 13CO2 in the bicarbonate pool, in which an amount of CO2 arising from CHO and fat oxidation is retained (34). However, during exercise, the turnover of this pool increases several fold so that a physiological steady-state condition will occur relatively rapidly and 13CO2 in the expired air will be equilibrated with the 13CO2/H13CO2 pool, respectively. Recovery of 13CO2 from oxidation will approach 100% after 60 min of exercise when the dilution in the bicarbonate pool becomes negligible (30,34). As a consequence of this, 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 ANOVA (treatment × time) 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. Mean values were calculated without the use of a statistical model that includes all sampling variance. Paired-sample t-tests were applied when two mean values were compared.

Values in text, tables, and figure are presented as mean ± SD. Differences between treatments are presented as mean differences with 95% confidence interval. 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 2. There was no significant difference in VO2 among the three experimental trials. RER was significantly (P < 0.01) lower in the WAT trial compared with the two CHO ingestion trials, but it was not significantly different between the BAR and DRINK trials. Correspondingly, CHO oxidation was not significantly different between the two CHO trials, but it was significantly higher compared with WAT (P < 0.01). The mean total CHO oxidation rates during the last 120 min of exercise were 1.64 ± 0.56, 2.26 ± 0.31, and 2.22 ± 0.43 g·min⁻¹ for WAT, BAR, and DRINK, respectively. Fat oxidation was significantly higher in the WAT trial than after CHO ingestion (P < 0.01). Mean fat oxidation rates during the last 120 min of exercise were 0.89 ± 0.29, 0.58 ± 0.21, and 0.57 ± 0.22 g·min⁻¹ for WAT, BAR, and DRINK, respectively. Fat oxidation did not differ significantly between the BAR and DRINK trials.

**Exogenous CHO oxidation, endogenous CHO oxidation, and oxidation efficiency.** Exogenous CHO oxidation rates gradually increased over time and leveled off after 135 min with the ingestion of the DRINK (Fig. 1). With the BAR, a plateau was reached after 75 min followed by a second significant increase detected after 150 min of exercise. Both treatments lead to high peak exogenous CHO oxidation rates (BAR 1.25 ± 0.15 g·min⁻¹ and DRINK 1.34 ± 0.27 g·min⁻¹), which were not significantly different between treatments (mean difference = −0.9 g·min⁻¹, 95% confidence interval = −0.32 to 0.13 g·min⁻¹). The total amount of the ingested CHO that was oxidized during the entire 180-min exercise was not

<table>
<thead>
<tr>
<th>Trial</th>
<th>Time (min)</th>
<th>VO2 (L·min⁻¹)</th>
<th>RER</th>
<th>CHOtotal (g·min⁻¹)</th>
<th>Fattotal (g·min⁻¹)</th>
<th>Endogenous CHO (g·min⁻¹)</th>
<th>Exogenous CHO (g·min⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WAT</td>
<td>60–60</td>
<td>2.91 ± 0.23</td>
<td>0.83 ± 0.05</td>
<td>1.77 ± 0.53</td>
<td>0.81 ± 0.26</td>
<td>1.77 ± 0.53</td>
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<td></td>
<td>90–120</td>
<td>2.88 ± 0.22</td>
<td>0.82 ± 0.06</td>
<td>1.64 ± 0.62</td>
<td>0.90 ± 0.30</td>
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<td></td>
<td>120–150</td>
<td>3.02 ± 0.24</td>
<td>0.82 ± 0.06</td>
<td>1.61 ± 0.60</td>
<td>0.93 ± 0.30</td>
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<td></td>
<td>150–180</td>
<td>3.00 ± 0.23</td>
<td>0.81 ± 0.06</td>
<td>1.54 ± 0.60</td>
<td>0.95 ± 0.31</td>
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<td>0.82 ± 0.06</td>
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<td>0.89 ± 0.29</td>
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<tr>
<td>BAR</td>
<td>60–60</td>
<td>2.85 ± 0.24</td>
<td>0.82 ± 0.05</td>
<td>2.23 ± 0.25</td>
<td>0.57 ± 0.19</td>
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<td></td>
<td>90–120</td>
<td>2.98 ± 0.24</td>
<td>0.88 ± 0.04</td>
<td>2.24 ± 0.51</td>
<td>0.58 ± 0.19</td>
<td>1.28 ± 0.31</td>
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<td>120–150</td>
<td>2.99 ± 0.25</td>
<td>0.88 ± 0.04</td>
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<td>0.58 ± 0.21</td>
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<td>150–180</td>
<td>3.03 ± 0.23</td>
<td>0.88 ± 0.04</td>
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<td>1.09 ± 0.30</td>
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<td>60–180</td>
<td>2.98 ± 0.24</td>
<td>0.88 ± 0.03</td>
<td>2.26 ± 0.31</td>
<td>0.56 ± 0.21</td>
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<td>1.03 ± 0.11</td>
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<tr>
<td>DRINK</td>
<td>60–60</td>
<td>2.91 ± 0.21</td>
<td>0.89 ± 0.04</td>
<td>2.22 ± 0.48</td>
<td>0.55 ± 0.23</td>
<td>1.28 ± 0.36</td>
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<td>90–120</td>
<td>2.93 ± 0.22</td>
<td>0.89 ± 0.04</td>
<td>2.24 ± 0.41</td>
<td>0.56 ± 0.22</td>
<td>1.14 ± 0.35</td>
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<td>2.23 ± 0.40</td>
<td>0.57 ± 0.21</td>
<td>1.01 ± 0.31</td>
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<td></td>
<td>150–180</td>
<td>2.95 ± 0.24</td>
<td>0.88 ± 0.04</td>
<td>2.19 ± 0.47</td>
<td>0.59 ± 0.22</td>
<td>0.88 ± 0.33</td>
<td>1.30 ± 0.22</td>
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<td></td>
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<td>2.94 ± 0.22</td>
<td>0.88 ± 0.04</td>
<td>2.22 ± 0.43</td>
<td>0.57 ± 0.22</td>
<td>1.12 ± 0.34</td>
<td>1.14 ± 0.16</td>
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</table>

Values are means ± SD.

* Significant difference between CHO treatments.

b Significantly different from WAT.
significantly less with the BAR compared with the DRINK (−16.0 g, 95% confidence interval = −42.4 to 10.2 g, \(P = 0.19\)). Consequently, the difference in oxidation efficiency was not significant between the BAR and DRINK trials (−7.1%, confidence limit ±10.5%, \(P = 0.15\)).

A treatment \times time effect was detected between the CHO trials (\(P = 0.001\)). Significantly higher exogenous CHO oxidation rates from the DRINK compared with the BAR were detected at three intermediate time points (120, 135, and 150 min). However, the mean exogenous CHO oxidation rates during the final 120 min of exercise were high for both treatments (1.03 ± 0.11 and 1.14 ± 0.16 g min^-1 for BAR and DRINK, respectively) and not significantly different (−0.11 g min^-1, 95% confidence interval = −0.27 to 0.05 g min^-1, \(P = 0.19\); Table 2).

Along with higher exogenous CHO oxidation rates between 120 and 150 min, endogenous CHO oxidation rates with the DRINK ingestion were significantly lower during this period as well. However, no statistically significant differences were found in mean endogenous CHO oxidation rates during the last 120 min of exercise between both treatments (19.6 ± 6.8 and 19.6 ± 8.8 mmol L^-1 for BAR and DRINK, respectively) after 30 min, followed by a decline over time. During both CHO trials, insulin concentrations were significantly higher than during the WAT trial at all exercise time points. There was no significant difference in plasma insulin concentrations between the two different forms of CHO intake.

Plasma metabolites. Plasma GLU and insulin concentrations at rest and during 180 min of exercise are shown in Figures 2 and 3, respectively. Resting plasma GLU concentrations before the onset of exercise were not significantly different among trials. During exercise in the WAT trial, plasma GLU concentration gradually declined from 5.12 ± 0.67 to 4.27 ± 0.76 mmol L^-1. However, plasma GLU concentrations were maintained throughout the exercise period in the BAR and DRINK trials and were significantly greater than the WAT trial during the last 1 h of exercise. Significantly greater plasma GLU concentrations during the DRINK trial compared with the BAR trial were found after 45 and 75 min, respectively (\(P = 0.03\) and \(P = 0.004\), respectively).

Resting plasma insulin concentrations were similar between treatments. Plasma insulin concentration increased significantly in both CHO trials, reaching peak values (19.6 ± 6.8 and 19.6 ± 8.8 mmol L^-1 for BAR and DRINK, respectively) after 30 min, followed by a decline over time. During both CHO trials, insulin concentrations were significantly higher than during the WAT trial at all exercise time points. There was no significant difference in plasma insulin concentrations between the two different forms of CHO intake.

Plasma lactate concentrations were not significantly different at rest (1.01 ± 0.33, 0.94 ± 0.17, and 0.98 ± 0.28 mmol L^-1 for WAT, BAR, and DRINK, respectively)
and increased significantly in the first 15 min during all three trials ($P = 0.02$). In the first hour of exercise, plasma lactate concentrations were higher within the CHO trials than with the WAT trial, reaching statistical significance for the DRINK at 45 and 60 min ($P = 0.04$ and $P = 0.02$, respectively) and for the BAR at 45 min of exercise ($P = 0.04$).

Plasma FFA concentrations were not significantly different before the onset of exercise ($244 \pm 118, 256 \pm 169,$ and $234 \pm 168$ mmol·L$^{-1}$ for WAT, BAR, and DRINK, respectively). Concentrations of FFA in plasma increased during the WAT trial and were significantly higher than during the CHO trials at all time points. No significant differences occurred between the CHO trials or over time during exercise.

GI symptoms, perceived fullness, and RPE. No severe GI problems were recorded in any of the trials. Mean perceived stomach fullness (Fig. 4) during each hour was significantly higher with the ingestion of DRINK than with WAT and was significantly higher with the BAR than with both other treatments ($P < 0.05$). RPE during the last half hour of exercise were $13 \pm 2, 12 \pm 2$, and $12 \pm 1$ in the WAT, BAR, and DRINK trials, respectively.

**DISCUSSION**

The present study demonstrates that a GLU + FRC mix administered either as a solid BAR or as DRINK is oxidized efficiently and leads to high peak and mean exogenous CHO oxidation rates during exercise. Previously, it was thought that despite high intake rates (>1.5 g·min$^{-1}$) of single-source CHO drinks, exogenous CHO oxidation during exercise was limited to peak oxidation rates of $\sim 1$ g·min$^{-1}$ (20). In contrast, when drinks containing multiple transportable CHO are administered, 20%-50% higher oxidation rates with peak values of up to 1.75 g·min$^{-1}$ have been reported (15,16). In the present study, administration of both forms of GLU + FRC (BAR and DRINK) resulted in exogenous CHO oxidation rates greater than 1 g·min$^{-1}$ ($1.25 \pm 0.05$ vs $1.34 \pm 0.09$ g·min$^{-1}$, respectively).

To the best of our knowledge, this is the first time that the oxidation of a solid CHO food has been studied during exercise. Technical difficulties are probably the explanation for the lack of studies that measured CHO oxidation from a whole food. Food naturally consists of several CHO and other ingredients with different natural enrichments in $^{13}$C, making the calculation of exogenous CHO oxidation very complex. As described earlier, the BAR used in the current study contained $\sim 5\%$ starch, which has been shown to be oxidized at approximately 30% lower rates as GLU (36) and would have resulted in a possible overestimation of exogenous CHO oxidation rates of $\sim 3\%$. This was avoided by using an average enrichment, which assumed that only 50% starch was oxidized. Furthermore, it has repeatedly been documented that endogenous protein oxidation can account for 1%-6% of the energy yield during endurance exercise (38). Endogenous protein oxidation would have been reduced by CHO and protein feeding. On the other hand, protein from the BAR could have contributed to protein oxidation to a small extent. However, error in total CHO and fat oxidation would have been small and with a minimal amount of protein ingested similar in both conditions. Furthermore, the protein-containing sources in the BAR showed a low $^{13}$C enrichment ($-27.2$), and an overestimation of exogenous CHO oxidation through oxidation of $^{13}$C from protein is therefore not possible.

With the ingestion of CHO in the form of a solid BAR, we expected that peak exogenous CHO oxidation and oxidation efficiency might be lower than the values obtained from a DRINK because of the increased particle size, fat, and fiber content, which cause slower gastric emptying compared with liquids (10,11,13,37,40). Slower gastric emptying rates would lead to decreased oxidation efficiency and lower oxidation rates. However, the difference in oxidation efficiency between BAR and DRINK was only $\sim 7\%$ and was not statistically significant. Differences in peak oxidation rates were also not significantly different between both treatments. These results suggest that gastric emptying rates were not substantially influenced by the form of CHO intake. This might be due to the relatively low fat and fiber content (both 3%) of the BAR. Gastric emptying might also have been supported by the fluid volume administered in the study (867 mL·h$^{-1}$). Gastric volume and moderate-intensity exercise are potent factors to enhance gastric emptying (2,5,25,28,29). Furthermore, the bolus of water administered at the onset of exercise with the BAR could have helped to deliver much CHO to the intestine, which can explain the rapid increase in oxidation rates.

The rapid increase in exogenous CHO oxidation rates with both treatments goes in line with a similarly quick rise in plasma GLU and insulin concentrations with both treatments. This is in agreement with previous studies, which
demonstrated a similar GLU and insulin response from solid versus liquid at the onset of exercise (21,33). A ~15% lower oxidation rate for the BAR compared with the DRINK was detected between 120 and 150 min of exercise. These findings are supported by the study of Robbergs et al. (33), which found significantly lower blood GLU concentrations from a bar at one time point (80 min). Both of these studies show a more phasic time course for CHO oxidation and blood GLU from solids compared with liquids, respectively. In the current study, after lower oxidation rates from the BAR between 2 and 2.5 h, oxidation rates rise to values >1 g·min⁻¹, which were not significantly different compared with the DRINK. This pattern is evident not only in the average data but also in individual oxidation rates from seven of eight participants, a phenomenon that was not seen in data from drinks.

Whether the observed lower exogenous CHO oxidation rates between 2 and 2.5 h could lead to a relevant difference in performance is difficult to answer now. The exact relationship between increased exogenous CHO oxidation and exercise performance is still unclear. Dose-response studies in which the effect of ingestion of different amounts of CHO on performance was investigated have resulted in equivocal findings (for review, see Jeukendrup [17]). Although, in these studies, exogenous CHO oxidation was not measured, it can be assumed that oxidation increased with increasing intake (in the range used in these studies) (17). This increasing intake, however, was not always linked to improved performance (23,24). No studies have directly investigated the link between increasing exogenous CHO oxidation and performance. Because dose responses have not delivered a clear picture, it is likely that substantial increases in exogenous CHO oxidation would be needed to produce a performance benefit. The only (indirect) evidence in this regard is the study by Currell and Jeukendrup (8), which showed an improvement in performance with GLU + FRC versus GLU. From a previous study, it can be assumed that exogenous CHO oxidation rates were ~35% greater with GLU + FRC ingestion (16). In another study, we observed a 13% difference in peak exogenous CHO oxidation during 5 h of exercise at 58% VO₂max (18). Although performance was not measured in the final hour, RPE and self-selected cadence were lower in the trial with the higher exogenous CHO oxidation. Whether this would have translated into a performance benefit is unknown. There is only one study in which exogenous CHO oxidation was measured in combination with a performance measurement (35). In this study, higher exogenous CHO oxidation rates seemed to be linked to better performance.

Despite some evidence for lower oxidation relative to delivery in the form of a DRINK, the present study demonstrates that a GLU + FRC blend administered in a solid BAR is oxidized at a high rate (>1 g·min⁻¹) during prolonged cycling exercise. These findings suggest that CHO from a solid BAR is effectively oxidized during exercise and can be a practical form of supplementation alongside other forms of CHO.

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REFERENCES


