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Oxidation of combined ingestion of glucose and sucrose during exercise ☆

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Abstract

The first purpose of the study was to examine whether combined ingestion of glucose and sucrose at an intake rate of 1.2 g/min would lead to higher oxidation rates compared with the ingestion of an isocaloric amount of glucose or sucrose alone. The second aim of the study was to investigate whether a mixture of glucose and sucrose when ingested at a high rate (2.4 g/min) would result in exogenous CHO oxidation rates higher than 1.2 to 1.3 g/min.

Eight trained cyclists (maximal oxygen consumption: 64 ± 2 mL · kg^{-1} · min^{-1}, mean ± SE) performed 5 exercise trials in random order. Each trial consisted of 120 minutes of cycling at 50% maximum power output (63% ± 2% maximal oxygen consumption), whereas subjects received a solution providing either 1.2 g/min of glucose (GLU), 1.2 g/min of sucrose (SUC), 0.6 g/min of glucose + 0.6 g/min of sucrose (M–GLU+SUC), 1.2 g/min of glucose + 1.2 g/min of sucrose (H–GLU+SUC), or water (WAT).

Peak exogenous CHO oxidation rates in the H–GLU+SUC trial (1.20 ± 0.07 g/min) were significantly higher ($P < .01$) compared with the GLU, M–GLU+SUC, and SUC trials (0.77 ± 0.04, 0.90 ± 0.07, 0.98 ± 0.04 g/min, respectively). Furthermore, peak exogenous CHO rates in M–GLU+SUC and SUC trials were significantly higher ($P < .05$) compared with the GLU trial.

In conclusion, combined ingestion of moderate amounts of glucose and sucrose (144 g) during cycling exercise resulted in approximately 21% higher exogenous CHO oxidation rates compared with the ingestion of an isocaloric amount of glucose. Furthermore, when a mixture of glucose and sucrose was ingested at high rates (2.4 g/min), exogenous CHO oxidation rates reached peak values of approximately 1.20 g/min.

1. Introduction

The importance of carbohydrate (CHO) availability for endurance exercise performance has been recognized since the 1920s [1]. It is now generally accepted that CHO ingestion during prolonged exercise increases endurance capacity (ie, time to exhaustion). The increase in exercise time to fatigue is most likely caused by maintenance of high rates of CHO oxidation late in exercise as a result of higher blood glucose availability compared with no CHO ingestion [2,3].

Several studies have shown that when a single type CHO is consumed during cycling exercise, the rate of exogenous CHO oxidation approaches peak values of 1.0 to 1.1 g/min (for reviews, see references [4,5]). Interestingly, recent studies from our laboratory have demonstrated that ingesting a mixture of glucose and sucrose [6] or glucose and fructose [7] during prolonged cycling exercise (120 to 150 minutes) can result in approximately 20% to 55% higher exogenous CHO oxidation rates compared with the intake of an isocaloric amount of glucose. It has been suggested that intestinal glucose transporters (SGLT1) may become saturated when large amounts of glucose or glucose polymers are ingested (>1.2 g/min), and hence, the rate of intestinal CHO absorption may be a limiting factor for exogenous CHO oxidation [6-8]. Free fructose and most probably fructose released during sucrose hydrolysis use a different intestinal transporter (GLUT-5) than glucose (SGLT1) [9-12]. Although speculative, the high exogenous CHO

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oxidation rates observed when large amounts of multiple transportable CHOs are ingested during exercise may have been caused by an enhanced intestinal CHO absorption capacity which may have increased the availability of exogenous CHO for oxidation. This hypothesis is now supported by data of 3 studies from our laboratory, which have consistently shown that ingestion of large amounts of multiple transportable CHOs (average ingestion rate ranging from 1.8 to 2.4 g/min) results in high exogenous CHO oxidation rates (>1.1 g/min), and this does not occur when an isocaloric amount of glucose alone is ingested [6-8]. However, the effect on exogenous CHO oxidation is less clear when mixtures of multiple transportable CHOs are consumed at lower intake rates, and CHO transporters may not become saturated.

To our knowledge, only 2 studies have examined the rate of exogenous CHO oxidation of a mixture of glucose and fructose when ingested at a moderate rate (approximately 0.8 g/min). In a study by Adopo et al [13], combined ingestion of glucose and fructose resulted in higher exogenous CHO oxidation rates compared with the ingestion of an isocaloric amount of glucose or fructose. Riddell et al [14], however, found no difference in exogenous CHO oxidation rate in boys between 10 and 14 years when a mixture of glucose + fructose or an isocaloric amount of glucose alone was consumed. The reason for the contradictory findings between the study of Adopo et al [13] and the experiment of Riddell et al [14] is largely unknown but may be related to differences in subject selection (ie, children vs trained athletes) or experimental study design (ie, exercise protocol and CHO feeding protocol).

Although the exact transport mechanism for sucrose is not firmly established, intestinal transport of sucrose seems to be, at least in part, different from that of glucose or fructose [9-12]. Combined ingestion of glucose and sucrose might increase the rate of intestinal CHO absorption, and this could lead to higher exogenous CHO oxidation rates. At present, no studies have investigated the effect of moderate amounts of glucose + sucrose ingestion on exogenous CHO oxidation. The first purpose of the study was to examine the rate of exogenous CHO oxidation after combined ingestion of glucose and sucrose at an intake rate of 1.2 g/min compared with the ingestion of an isocaloric amount of glucose or sucrose alone. We hypothesized that ingestion of a mixture of glucose + sucrose would lead to higher exogenous CHO oxidation rates compared with ingestion of an isocaloric amount glucose. The absorption of glucose and fructose released from sucrose most likely occurs via the same intestinal CHO transporters as free glucose (SLGT1) and free fructose (GLUT-5) [10,12]. Thus, both intestinal CHO transport systems will be used when moderate amounts of glucose + sucrose or sucrose are ingested. We hypothesized that the oxidation rates of ingested glucose + sucrose and an isocaloric amount of sucrose are similar. The ingested sucrose was labeled with [U-^{13}C]-sucrose, and the ingested glucose was labeled with [U-^{14}C]-glucose, which enabled us to measure the rate of exogenous glucose and sucrose oxidation when glucose and sucrose were ingested simultaneously. The second aim of the study was to investigate whether a mixture of glucose and sucrose when ingested at a high rate (2.4 g/min) would result in exogenous CHO oxidation rates higher than previously observed (>1.2-1.3 g/min) [6].

2. Methods

2.1. Subjects

Eight trained male cyclists or triathletes aged 26.8 ± 2.7 years and with a body mass of 72.1 ± 2.9 kg participated in this study. Before participation, each of the subjects was fully informed of the purpose and risks associated with the procedures, and a written informed consent was obtained. All subjects were healthy as assessed by a general health questionnaire. The study was approved by the South Birmingham Local Research Ethics Committee and the UK Administration of Radioactive Substance Advisory Committee.

2.2. Preliminary testing

At least 1 week before the start of the experimental trials, an incremental cycle exercise test to volitional exhaustion was performed to determine the individual maximum power output (Wmax) and maximal oxygen consumption ($V\dot{o}_2max$). This test was performed on an electromagnetically braked cycle ergometer (Lode Excalibur Sport, Groningen, The Netherlands), modified to the configuration of a racing bicycle with adjustable saddle height and handlebar position. After reporting to the laboratory, body mass (Seca Alpha, Hamburg, Germany) and height were recorded. Subjects then started cycling at 95 W for 3 minutes, followed by incremental steps of 35 W every 3 minutes until exhaustion. Heart rate (HR) was recorded continuously by a radiotelemetry HR monitor (Polar Vantage NV, Kempele, Finland). Wmax was calculated from the last completed work rate, plus the fraction of time spent in the final noncompleted work rate multiplied by the work rate increment. The results were used to determine the work rate corresponding to 50% Wmax, which was later used in the experimental exercise trials. Breath-by-breath measurements were performed throughout exercise using an online automated gas analysis system (Oxycon Pro, Jaeger, Hoechberg, Germany). The volume sensor was calibrated using a 3-L calibration syringe, and the gas analyzers were calibrated using a 5.03% CO_2: 94.97% N_2 gas mixture. Oxygen consumption ($V\dot{O}_2$) was considered to be maximal ($V\dot{o}_2max$) when at least 2 of the 3 following criteria were met: (1) a leveling off of $V\dot{O}_2$ with increasing workload (increase of no more than 2 mL · kg^{-1} · min^{-1}), (2) a HR within 10 beats per minute of predicted maximum (HR 220 minus age), (3) a respiratory exchange ratio (RER) >1.05. $V\dot{o}_2max$ was calculated as the average oxygen uptake over

the last 60 seconds of the test. The $V\dot{o}_2max$ and Wmax achieved during the incremental exercise test were 64 ± 2 mL · kg^{-1} · min^{-1} and 364 ± 12 W, respectively (Table 1).

2.3. Experimental design

Each subject performed 5 exercise trials, which consisted of 120 minutes of cycling at 50% Wmax, whereas ingesting an 8.7% glucose drink (GLU), an 8.7% sucrose drink (SUC), an isocaloric sucrose + glucose drink (M–GLU+SUC) (the ingested sucrose/glucose ratio was 1:1), a 17.5% sucrose + glucose drink (H–GLU+SUC) (the ingested sucrose/glucose ratio was 1:1), or plain water (WAT). To quantify exogenous glucose oxidation, the ingested fructose was enriched with [U-^{13}C]-sucrose, and the ingested glucose was labeled with [U-^{14}C]-glucose. The order of the 4 experimental CHO drinks was randomly assigned in a crossover design. The experimental CHO trials were separated by at least 7 days.

2.4. Diet and activity before testing

Subjects were asked to record their food intake and activity pattern 2 days before the first exercise trial and were then instructed to follow the same diet and exercise activities before the other 3 trials. In addition, 5 to 7 days before each experimental testing day, they were asked to perform an intense training session ("glycogen-depleting" exercise bout) in an attempt to empty any ^{13}C-enriched glycogen stores. Subjects were further instructed not to consume any food products with a high natural abundance of ^{13}C (CHO derived from C_4 plants: corn, cane sugar) at least 1 week before and during the entire experimental period to reduce the background shift (change in $^{13}CO_2$) from endogenous substrate stores.

2.5. Protocol

Subjects reported to the Human Performance Laboratory in the morning (between 7:00 and 9:00 AM) after an overnight fast (10-12 hours) and having refrained from any strenuous activity or drinking any alcohol in the previous 24 hours. For a given subject, all trials were conducted at the same time of the day to avoid any influence of circadian variance. On arrival in the laboratory, a flexible 21-gauge Teflon catheter (Quickcath, Baxter BV, Norfolk, United Kingdom) was inserted in an antecubital vein of an arm and attached to a 3-way stopcock (Sims Portex, Kingsmead, United Kingdom) to allow for repeated blood sampling during exercise. The catheter was kept patent by flushing with 1.0 to 1.5 mL of isotonic saline (0.9% Baxter) after each blood sample collection.

Table 1
Subject characteristics

Age (y)	26.8 ± 2.7
Height (cm)	179.2 ± 3.2
Body mass (kg)	72.1 ± 2.9
$V\dot{o}_2max$ (mL · kg^{-1} · min^{-1})	64 ± 2
Wmax (W)	364 ± 12
HRmax (beats/min)	189 ± 3

Values are means ± SEM, n = 8 subjects. $V\dot{o}_2max$ is expressed per kilogram of body mass. HRmax indicates maximal heart rate.

The subjects then mounted a cycle ergometer, and a resting breath sample was collected in 10-mL Exetainer tubes (Labco Ltd Brow Works, High Wycombe, United Kingdom), which were filled in duplicate directly from a mixing chamber to determine the $^{13}C/^{12}C$ ratio in the expired air. A second resting breath sample was collected for later determination of $^{14}CO_2$ specific activity. The expired air of each second breath sample was collected in a 6-L anesthetic gas bag using a 2-way Hans Rudolph valve and subsequently passed through a CO_2 trapping solution, containing 1 mL of hyamine hydroxide in 1 mol/L methanol (Zinsser analytic, Berkshire, United Kingdom), 3 mL of 96% ethanol (BDH Laboratory Supplies, Poole, United Kingdom) and 1 to 2 drops of phenolphthalein (Riedel-de Haën, Seeize, Germany). The expired air was bubbled for 2 to 3 minutes through the pink CO_2 trapping mixture until the solution became clear, at which point exactly 1 mmol of CO_2 was trapped [15]. Seventeen milliliters of liquid scintillation cocktail (Ready Gel, Beckman Coulter, High Wycombe, United Kingdom) was then added to the solution, and $^{14}CO_2$ radioactivity in disintegrations per minute (dpm, later converted to dpm/mmol) was subsequently counted in a liquid scintillation counter (Beckman, LS 1800, USA).

Next, a resting blood sample (10 mL) was taken and stored on ice until centrifugation. Subjects then started a 120-minute exercise bout at a work rate equivalent to 50% Wmax (63% ± 2% $V\dot{o}_2max$). Additional blood samples were drawn at 15-minute intervals during exercise. Expired breath samples were collected every 15 minutes until the end of exercise. V_{O_2}, V_{CO_2} (carbon dioxide production), and RER were measured every 15 minutes for periods of 4 minutes using an online automated gas analysis system, as previously described.

During the first 3 minutes of exercise, subjects drank an initial bolus (600 mL) of 1 of the 5 experimental drinks. Thereafter, every 15 minutes, a beverage volume of 150 mL was provided. The total fluid provided during the 120-minute exercise bout was 1.65 L. The average rate of glucose intake in the M–GLU+SUC, H–GLU+SUC, and GLU trial was 0.6, 1.2, and 1.2 g/min, respectively. The average rate of sucrose intake in M–GLU+SUC, H–GLU+SUC, and SUC trial was 0.6, 1.2, and 1.2 g/min, respectively. Thus, the total average CHO intake rate in the M–GLU+SUC and H–GLU+SUC trial was 1.2 and 2.4 g/min, respectively.

Subjects were asked to rate their perceived exertion (RPE) for whole body and legs every 30 minutes on a scale from 6 to 20 using the Borg category scale [16]. In addition, subjects were asked every 30 minutes to fill in a questionnaire to rate (possible) gastrointestinal (GI) problems. All exercise tests were performed under normal and standard environmental conditions (20°C-22°C dry bulb

temperature and 50%-60% relative humidity). During the exercise trials, subjects were cooled with standing floor fans to minimize thermal stress.

2.6. Experimental drinks

The sucrose used in the SUC, M–GLU+SUC, and H–GLU+SUC trials was a cane-derived sucrose (Tate and Lyle Europe, London, UK), which has a high natural abundance of ^{13}C (−11.2 δ‰ vs Pee Dee Bellemnitella [PDB]). To increase the ^{13}C content of the sucrose even further, a trace amount of uniformly labeled ^{13}C-sucrose was added (approximately 0.556 mg [U-^{13}C]-sucrose [≥99%; Cambridge Isotope Laboratories, USA] per gram of sucrose). The sucrose provided to the subjects in the SUC, M–GLU+SUC, and H–GLU+SUC trials had a ^{13}C enrichment of 36.1 δ‰ versus PDB. The ^{13}C enrichment of the cane-derived sucrose and the sucrose in the experimental sucrose (+glucose) solutions was determined by elemental analyzer/isotope ratio mass spectrometry (IRMS; Europa Scientific GEO 20-20, Crewe, UK).

In the GLU, M–GLU+SUC, and H–GLU+SUC, a wheat-derived glucose (Amylum, London, United Kingdom) was used which has a ^{13}C enrichment of −27.0 δ‰ vs PDB (IRMS; Europa Scientific GEO 20-20). The glucose in the GLU and GLU+SUC beverages was labeled with a trace amount of 0.46 MBq [U-^{14}C]-glucose per liter (Amersham Pharmacia Biotech, Little Chalfont, United Kingdom) leading to a dose rate of 0.38 MBq/h. Furthermore, to all drinks, 20 mmol/L of sodium chloride was added.

2.7. Questionnaires

Subjects were asked to fill out a questionnaire every 30 minutes during the exercise trials. The questionnaire contained questions regarding the presence of GI problems at that moment and addressed the following complaints: stomach problems, GI cramping, bloated feeling, diarrhea, nausea, dizziness, headache, belching, vomiting, and urge to urinate/defecate. While subjects were on the cycle ergometer and continued their exercise, each question was answered by simply ticking a box on the questionnaire that corresponded to the severity of the GI problem addressed. The items were scored on a 10-point scale (1 = not at all, 10 = very, very much). The severity of the GI symptoms was divided into 2 categories: severe and nonsevere symptoms, as was previously described by Jeukendrup et al [17]. Severe complaints included nausea, stomach problems, bloated feeling, diarrhea, urge to vomit, and stomach and intestinal cramps, because these are symptoms that commonly impair performance and may bring with them health risks. The above symptoms were only registered as severe symptoms when a score of 5 or higher out of 10 was reported. When a score below 5 was given, they were registered as nonsevere. All other symptoms were registered as nonsevere regardless of the score reported.

2.8. Analyses

Blood samples were collected into prechilled tubes containing potassium oxalate and sodium fluoride (Beckton Dickinson, Plymouth, United Kingdom) and were centrifuged at 2300 g and 4°C for 10 minutes. Aliquots of plasma were immediately frozen in liquid nitrogen and stored at −25°C until analyses of glucose and lactate. Glucose (Glucose HK kit, Sigma-Aldrich, Dorset, United Kingdom) and lactate (Lactate kit, Sigma-Aldrich) were analyzed on a COBAS BIO semiautomatic analyzer (La Roche, Basel, Switzerland).

Breath samples were analyzed for $^{13}C/^{12}C$ ratio by gas chromatography (GC) continuous-flow IRMS (Europa Scientific). Furthermore, a second series of breath samples was analyzed for $^{14}CO_2$ radioactivity. These breath samples were counted for 10 minutes in a liquid scintillation counter, and all counts were corrected for differences in quench and background. From indirect calorimetry (V_{O_2} and V_{CO_2}), stable isotope measurements (breath $^{13}CO_2/^{12}CO_2$ ratio) and radioactive-isotope measurements (breath $^{14}CO_2$ activity), oxidation rates of total fat, total CHO, endogenous CHO, and exogenous glucose and fructose were calculated.

2.9. Calculations

From V_{CO_2} and V_{O_2} (L/min), total CHO and fat oxidation rates (grams per minute) were calculated using stoichiometric equations of Frayn [18], with the assumption that protein oxidation during exercise was negligible;

$$\text{CHO oxidation} = 4.55\ V_{CO_2} - 3.21\ V_{O_2} \quad (1)$$

$$\text{Fat oxidation} = 1.67\ V_{O_2} - 1.67\ V_{CO_2} \quad (2)$$

In the GLU trial, the rate of exogenous glucose oxidation was calculated from the following equation:

$$\text{Exogenous glucose oxidation} = V_{CO_2} \cdot \left(\frac{^{14}CO_2 \cdot 6}{\text{SA Glu}}\right)\left(\frac{1}{k}\right) \quad (3)$$

in which $^{14}CO_2$ is the radioactivity of 1 mmol of expired CO_2 (dpm/mmol) multiplied by 6, because there are 6 carbon atoms per molecule of [U-^{14}C]-glucose; SA Glu is the specific activity of the ingested glucose (dpm/mmol); and k is the amount of CO_2 (in liters) produced by the oxidation of 1 g of glucose (k = 0.7467 L of CO_2 per gram of glucose).

The total exogenous CHO oxidation in the GLU+SUC trials was determined as the sum of exogenous glucose oxidation derived from ingested glucose and exogenous glucose oxidation derived from ingested sucrose. Exogenous glucose oxidation in GLU+SUC trials was calculated using Eq (3), and exogenous sucrose oxidation was calculated from stable isotope measurements [see Eqs (4,5)]. In the SUC trial, exogenous sucrose oxidation was calculated using Eqs. (4,5).

The isotopic enrichment was expressed as δ‰ difference between the $^{13}C/^{12}C$ ratio of the sample and a known laboratory reference standard according to the formula of Craig [19]:

$$\delta^{13}C = \left(\left(\frac{^{13}C/^{12}C \text{ sample}}{^{13}C/^{12}C \text{ standard}}\right) - 1\right) \cdot 10^3 \text{ per mil} \quad (4)$$

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

Exogenous sucrose oxidation was calculated using the following formula [20]:

$$\text{Exogenous sucrose oxidation} = VCO_2 \cdot \left(\frac{\delta \text{ Exp} - \delta \text{ Exp}_{bkg}}{\delta \text{ Ing} - \delta \text{ Exp}_{bkg}}\right)\left(\frac{1}{k}\right) \quad (5)$$

in which δExp is the ^{13}C enrichment of expired air during exercise with SUC or GLU+SUC ingestion at different time points; δIng is the ^{13}C enrichment of the sucrose in the SUC and GLU+SUC solutions; and δExp_{bkg} is the ^{13}C enrichment of expired air in the GLU trial (background) at different time points.

Endogenous CHO oxidation was calculated by subtracting exogenous CHO oxidation from total CHO oxidation.

A methodological consideration when using $^{13}CO_2$ and/or $^{14}CO_2$ in expired air to calculate exogenous substrate oxidation is the trapping of $^{13}CO_2$ and/or $^{14}CO_2$ in the bicarbonate pool, in which an amount of CO_2 arising from decarboxylation of energy substrates is temporarily trapped [21]. However, during exercise, the CO_2 production increases several folds so that a physiological steady-state condition will occur relatively rapidly, and $^{13}CO_2$ and $^{14}CO_2$ in the expired air will be equilibrated with the $^{13}CO_2/H^{13}CO_3$ pool and $^{14}CO_2/H^{14}CO_3$ pool, respectively. Recovery of $^{13}CO_2$ (and $^{14}CO_2$) from oxidation will approach 100% after 60 minutes of exercise when dilution in the bicarbonate pool becomes negligible [21,22]. As a consequence of this, all calculations on substrate oxidation were performed over the last 60 minutes of exercise (60-120 minutes).

2.10. Statistical analyses

A 2-factor (time × treatment) analysis of variance for repeated measures was used to compare differences in substrate utilization and in blood-related parameters over time between trials. A Tukey post hoc test was applied to locate differences when analysis of variance revealed a significant interaction. Data evaluation was performed using SPSS for Windows version 10.0 software package (Chicago, USA). All data are reported as means ± SE. Statistical significance was set at $P < .05$.

3. Results

3.1. Exogenous and endogenous CHO oxidation

Peak exogenous CHO oxidation rates in H–GLU+SUC (1.20 ± 0.07 g/min) were significantly higher ($P < .01$) compared with GLU (0.77 ± 0.04 g/min), M–GLU+SUC (0.90 ± 0.07 g/min), and SUC (0.98 ± 0.04), respectively (Fig. 1). Furthermore, peak exogenous CHO rates in M–GLU+SUC and SUC trials were significantly higher ($P < .05$) compared with the GLU trial. During the second hour of exercise, exogenous CHO oxidation rates in the M–GLU+SUC, H–GLU+SUC and SUC trials were significantly higher ($P < .05$) compared with the GLU trial (Table 2). Furthermore, exogenous CHO oxidation rates in H–GLU+SUC were significantly higher ($P < .05$) during the last 60 minutes of exercise when compared with SUC and M–GLU+SUC, respectively.

Endogenous CHO oxidation was lower ($P < .05$) in the H–GLU+SUC and SUC trials compared with the WAT trial (Table 2). It should be noted that there was a trend toward a lower endogenous CHO oxidation in M–GLU+SUC compared with WAT (6 of 8 subjects), but this failed to reach statistical significance ($P > .05$). There were no significant differences in endogenous CHO oxidation rates among the 4 CHO trials.

3.2. VO_2, RER, total CHO, and fat oxidation

Data for VO_2, RER, total CHO, and fat oxidation over the 60- to 120-minute exercise period are shown in Table 2. VO_2 during the last 60 minutes of exercise was similar for the 5 experimental trials. RER in the WAT trial was significantly lower ($P < .05$) compared with the 3 CHO trials (Table 2). CHO oxidation was significantly higher ($P < .01$) after CHO ingestion compared with WAT ingestion. No significant differences in total CHO oxidation were found among the 4 CHO trials. Total fat oxidation was higher in the WAT trial than in the CHO trials ($P < .05$)

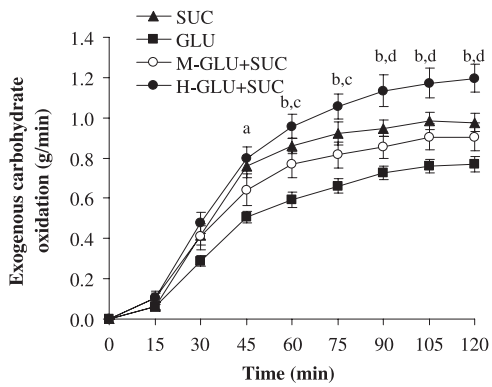

Fig. 1. Values are means ± SE, n = 8. Exogenous CHO oxidation during exercise with ingestion of sucrose (SUC), with ingestion of glucose (GLU), with ingestion of moderate amounts of glucose and sucrose (M–GLU+SUC), or with ingestion of large amounts of glucose and sucrose (H–GLU+SUC); a denotes H–GLU+SUC and SUC significantly different from GLU ($P < .05$); b, H–GLU+SUC, M–GLU+SUC, and SUC significantly different from GLU ($P < .05$); c, H–GLU+SUC significantly different from M–GLU+SUC ($P < .05$); d, significantly different from H–GLU+SUC ($P < .05$).

Table 2
Mean V_{O_2}, RER, total carbohydrate oxidation (CHOtot), total fat oxidation (FATtot), endogenous CHO oxidation, and exogenous glucose oxidation from ingested glucose and ingested sucrose calculated over the 60- to 120-minute exercise period

	V_{O_2} (L/min)	RER	CHOtot (g/min)	FATtot (g/min)	Endogenous CHO oxidation (g/min)	Exogenous CHO oxidation (g/min)	
						Glucose	Sucrose
WAT	2.83 ± 0.07	0.838 ± 0.010	1.69 ± 0.10	0.77 ± 0.06	1.69 ± 0.10		
SUC	2.94 ± 0.10	0.875 ± 0.009[a]	2.25 ± 0.09[a]	0.62 ± 0.06[b]	1.31 ± 0.11[b]		0.94 ± 0.04[c]
GLU	2.84 ± 0.08	0.878 ± 0.008[a]	2.23 ± 0.11[a]	0.58 ± 0.05[a]	1.53 ± 0.08	0.70 ± 0.03[d]	
M–GLU+SUC	2.93 ± 0.11	0.877 ± 0.009[b]	2.28 ± 0.13[a]	0.61 ± 0.05[b]	1.43 ± 0.12	0.41 ± 0.02	0.44 ± 0.04[c]
H–GLU+SUC	2.87 ± 0.09	0.893 ± 0.007[a]	2.43 ± 0.11[a]	0.52 ± 0.04[a]	1.33 ± 0.07[b]	0.53 ± 0.02	0.58 ± 0.04

Data are presented as means ± SE; n = 8. WAT indicates ingestion of water only; SUC, ingestion of sucrose; GLU, ingestion of glucose; M–GLU+SUC, ingestion of moderate amounts of glucose and sucrose; H–GLU+SUC, ingestion of large amounts of glucose and sucrose.

[a] Denotes significantly different from WAT ($P < .01$).

[b] Denotes significantly different from WAT ($P < .05$).

[c] Denotes total exogenous CHO oxidation significantly different from H–GLU+SUC ($P < .05$).

[d] Denotes total exogenous CHO oxidation in H–GLU+SUC, M–GLU+SUC, and SUC significantly different from GLU ($P < .05$).

(Table 2). No significant differences in total fat oxidation were found among the 4 CHO trials.

3.3. Stable and radioactive-isotope measurements

Changes in isotopic composition of expired CO_2 in response to exercise with ingestion of CHO are shown in Fig. 2A. During the GLU trial, there was a small but significant increase in ^{13}C enrichment of the expired air ($P < .01$). The changes in background $^{13}CO_2$ enrichment during exercise in the GLU trial were approximately 4% to 10% compared with the rise in breath $^{13}CO_2$ enrichment observed in other CHO trials. Although the background shift was relatively small in the present study, a background correction was made for the calculation of exogenous sucrose oxidation in the M–GLU+SUC, H–GLU+SUC and SUC trial by using the data from the GLU trial.

The $^{14}CO_2$ radioactivity of expired breath samples (corrected for background) is shown in Fig. 2B. In the GLU, M–GLU+SUC, and H–GLU+SUC trials, ^{14}C activity of the expired CO_2 increased significantly ($P < .001$) during exercise, reaching peak values of 1600 to 2500 dpm toward the end of exercise.

3.4. Plasma metabolites

Plasma glucose and lactate concentrations at rest and during exercise are shown in Fig. 3A and B. Plasma glucose concentrations during WAT decreased from 4.2 ± 0.1 mmol/L at the start of exercise to 3.6 ± 0.2 mmol/L by the end of exercise ($P < .01$). In the CHO trials, plasma glucose concentrations peaked within the first 15 to 30 minutes of exercise ($P < .01$) at values of 5.0 to 5.6 mmol/L. Plasma glucose concentrations then returned to toward resting values and remained stable for the entire duration of exercise. Plasma glucose concentrations in the H–GLU+SUC trial were higher ($P < .01$) throughout the 120 minutes of exercise when compared with the WAT trial and were also higher ($P < .01$) during the final 45 minutes of exercise when compared with the SUC trial. Plasma glucose concentrations at t = 15, 30, 105, and 120 were significantly higher ($P < .05$) in GLU, SUC, and M–GLU+SUC compared with WAT. Furthermore, plasma glucose levels were significantly higher ($P < .05$) in GLU compared with WAT at t = 60 and 75 and in GLU compared with M–GLU+SUC at t = 75 and 90.

Resting concentrations of plasma lactate were not different among trials (on average; 0.9 ± 0.1 mmol/L)

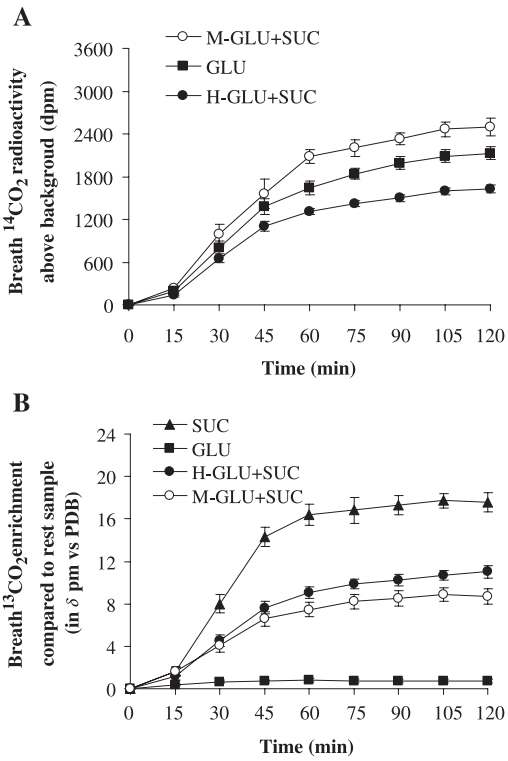

Fig. 2. Values are means ± SE, n = 8. Change in breath $^{13}CO_2$ enrichment (A) during exercise (compared with resting breath sample) with ingestion of sucrose (SUC), with ingestion of glucose (GLU), with ingestion of moderate amounts of glucose and sucrose (M–GLU+SUC), or with ingestion of large amounts of glucose and sucrose (H–GLU+SUC). Breath $^{14}CO_2$ radioactivity (B) during exercise (corrected for background) with ingestion of glucose (GLU), with ingestion of moderate amounts of glucose and sucrose (M–GLU+SUC), or with ingestion of large amounts of glucose and sucrose (H–GLU+SUC).

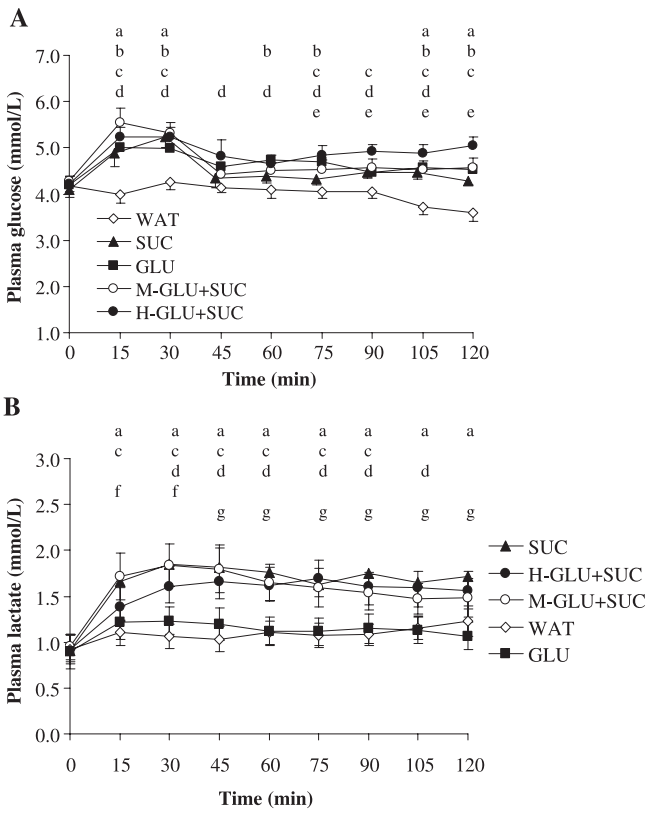

Fig. 3. Values are means ± SE, n = 8. Plasma glucose (A) and lactate (B) during exercise with ingestion of water (WAT), with ingestion of sucrose (SUC), with ingestion of glucose (GLU), with ingestion of moderate amounts of glucose and sucrose (M–GLU+SUC), or with ingestion of large amounts of glucose and sucrose (H–GLU+SUC); a, denotes SUC significantly different from WAT ($P < .05$); b, GLU significantly different from WAT ($P < .05$); c, M–GLU+SUC significantly different from WAT ($P < .05$); d, H–GLU+SUC significantly different from WAT ($P < .05$); e, H–GLU+SUC significantly different from SUC ($P < .05$); f, M–GLU+SUC and SUC significantly different from GLU ($P < .05$); g, H–GLU+SUC, M–GLU+SUC and SUC significantly different from GLU ($P < .05$).

(Fig. 3B). Plasma lactate levels increased during the first 15 to 30 minutes of exercise in all 5 trials. Plasma lactate concentrations were higher throughout exercise in the SUC, M–GLU+SUC, and H–GLU+SUC trials compared with the WAT trial, although M–GLU+SUC and H–GLU+SUC failed to reach statistical significance at $t = 15$, 105, and 120 ($P > .05$). Furthermore, plasma lactate levels between $t = 45$ and 120 were significantly higher ($P < .05$) in SUC, M–GLU+SUC, and H–GLU+SUC compared with GLU.

3.5. GI discomfort and ratings of perceived exertion

GI and related complaints were registered by a questionnaire. Subjects reported slightly more GI problems after ingestion of CHO compared with ingestion of plain water (data not shown). However, no obvious differences were observed in GI discomfort among the 4 CHO trials. The most frequently reported complaints were bloated feeling, nausea, flatulence, and urge to urinate and defecate.

No significant differences in RPE overall or RPE legs were observed among the 5 experimental trials (on average 10.9 ± 1.0 and 11.3 ± 1.0, respectively).

4. Discussion

Exogenous CHO oxidation rates have been reported to increase up to approximately 1.0 g/min when a single CHO is ingested during exercise [23-27]. When glucose and sucrose are ingested simultaneously during prolonged exercise, oxidation rates up to 1.25 g/min have been found [6]. In the present study, exogenous CHO oxidation rates reached peak values of 1.21 g/min when glucose and sucrose were ingested at a rate of 2.4 g/min. These results and previous findings from our laboratory [6] suggest that the rate of exogenous CHO oxidation does not further increase when the rate of sucrose intake is increased from 0.6 to 1.2 g/min, and glucose is ingested simultaneously at a rate of 1.2 g/min.

Interestingly, in the H–GLU+SUC trial, both exogenous glucose and sucrose were oxidized at lower rates compared with their oxidation rates when ingested individually (GLU and SUC). Sucrose is hydrolyzed at the brush border of the intestinal epithelium to glucose and fructose. There is some evidence suggesting that sucrose (and other disaccharides) is absorbed by a disaccharidase-related transport mechanism which provides a direct transfer of glucose and fructose (released from sucrose) across the brush border membrane [28,29]. However, it seems more likely that the absorption of glucose and fructose released from sucrose occurs via the same intestinal CHO transporters as free glucose (SLGT1) and free fructose (GLUT-5) [10,12]. In a jejunal perfusion study by Sandle et al [12], it was shown that the total glucose absorption rate from an equimolar glucose + sucrose mixture was less than the sum of the glucose absorption rates from glucose and sucrose when ingested separately. In another intestinal perfusion study [30], it was shown that the addition of galactose (also transported by SLGT1) to a sucrose solution decreased the rate of absorption of glucose released from sucrose hydrolysis but had no effect on fructose absorption. These findings indicate that free glucose and glucose released from sucrose hydrolysis compete for the same intestinal transporters (SGLT1). The lower glucose oxidation rates in the present study when glucose was ingested in combination with sucrose (H–GLU+SUC) compared with glucose alone (GLU) may have been caused by competition for intestinal absorption between free glucose and glucose from sucrose.

It has been suggested that intestinal glucose transporters (SGLT1) may become saturated when large amounts of glucose or glucose polymers are ingested (>1.2 g/min), and hence, intestinal CHO absorption may be a limiting factor for exogenous CHO oxidation [7]. If we assume that exogenous sucrose oxidation consists of equal amounts of

glucose and fructose oxidation, then the "estimated" exogenous glucose oxidation rate during the last 60 minutes of exercise in H–GLU+SUC was approximately 0.82 g/min (0.53 + 0.29 = 0.82 g/min), which is in close agreement with the glucose oxidation rate found in our previous study [7]. It is not unlikely that SGLT1 transporters, in the H–GLU+SUC trial, were saturated. Although speculative, when SGLT transporters become saturated (either from ingested glucose and/or glucose released from sucrose hydrolysis), hydrolysis of sucrose may be inhibited [12,30], and this might limit the amount of sucrose available for absorption and subsequent oxidation. Furthermore, inhibition of sucrose hydrolysis may have contributed, at least in part, to the lower sucrose oxidation rates observed when sucrose was ingested in combination with glucose (H–GLU+SUC) compared with sucrose ingestion alone (SUC).

In most studies that have reported higher oxidations rates when mixtures of CHOs were ingested compared with ingestion of a single CHO, large amounts of CHO were provided (average ingestion rate 1.8-2.4 g/min) [6-8]. In the present study, ingestion of moderate amounts of glucose + sucrose (M–GLU+SUC) resulted in significantly higher exogenous CHO oxidation rates compared with the ingestion of an isocaloric amount of GLU. This finding confirms the data of a study by Adopo et al [13] in which combined ingestion of moderate amounts of glucose and fructose resulted in 27% higher exogenous oxidation rates than when an isocaloric amount of glucose was ingested. When a mixture of glucose and sucrose (or glucose + fructose) is ingested at moderate amounts, there is (most probably) less competition of glucose molecules for absorption via SGLT1 transporters compared with the ingestion of an isocaloric amount of glucose. It is likely that a reduced competition of CHO for intestinal transport may result in higher CHO oxidation rates. Although the mechanism(s) remain(s) speculative, the present data and findings of others [13] clearly demonstrate that ingestion of multiple transportable CHO at moderate intake rates (varying between 0.8 and 1.2 g/min) can also result in higher oxidation rates compared with the ingestion of an isocaloric amount of glucose.

Another interesting finding of the present study was that exogenous CHO oxidation rates in SUC were higher compared with GLU. Although the aim of this study was not to compare the oxidation rates of ingested sucrose and glucose, the present findings are somewhat surprising because previous studies found similar oxidation rates for sucrose and glucose [31] or maltodextrins [27]. The discrepancy between the results of previous studies and the present study might be caused by the relatively small sample sizes with different characteristics or might be because of differences in the experimental design, including variations in the duration and intensity of exercise, CHO ingestion rate, and isotope techniques used.

In summary, combined ingestion of moderate amounts of glucose and sucrose during 2 hours of cycling exercise resulted in approximately 21% higher exogenous CHO oxidation rates compared with the ingestion of an isocaloric amount of glucose. However, combined ingestion of glucose and sucrose during exercise did not lead to higher oxidation rates when compared with the ingestion of an isocaloric amount of sucrose. The present data also demonstrated that when a mixture of glucose and sucrose was ingested at high rates (2.4 g/min) during cycling exercise, exogenous CHO oxidation rates reached peak values of approximately 1.20 g/min. Furthermore, these results and previous findings from our laboratory [6] suggest that the rate of exogenous CHO oxidation does not further increase when glucose is ingested at a rate of 1.2 g/min and the rate of sucrose intake is increased form 0.6 to 1.2 g/min. High rates of CHO oxidation and the maintenance of high blood glucose concentrations toward the end of prolonged exercise have been associated with improvements in performance observed when CHO is ingested during exercise [3,23]. However, it remains to be investigated whether ingestion of a mixture of glucose and sucrose during prolonged exercise will also lead to an improved exercise performance compared with the ingestion of an isocaloric amount of glucose or sucrose.

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References

[1] Levine SA, Gordon B, Derick CL. Some changes in chemical constituents of blood following a marathon race. JAMA 1924;82:1778-9.

[2] Coggan AR, Coyle EF. Reversal of fatigue during prolonged exercise by carbohydrate infusion or ingestion. J Appl Physiol 1987;63:2388-95.

[3] Coyle EF, Coggan AR, Hemmert MK, et al. Muscle glycogen utilization during prolonged strenuous exercise when fed carbohydrate. J Appl Physiol 1986;61:165-72.

[4] Hawley JA, Dennis SC, Noakes TD. Oxidation of carbohydrate ingested during prolonged endurance exercise. Sports Med 1992;14:27-42.

[5] Jeukendrup AE, Jentjens R. Oxidation of carbohydrate feedings during prolonged exercise: current thoughts, guidelines and directions for future research. Sports Med 2000;29:407-24.

[6] Jentjens RL, Venables MC, Jeukendrup AE. Oxidation of exogenous glucose, sucrose, and maltose during prolonged cycling exercise. J Appl Physiol 2004;96:1285-91.

[7] Jentjens RL, Moseley L, Waring RH, et al. Oxidation of combined ingestion of glucose and fructose during exercise. J Appl Physiol 2004;96:1277-84.

[8] Jentjens RL, Achten J, Jeukendrup AE. High oxidation rates from combined carbohydrates ingested during exercise. Med Sci Sports Exerc 2004;36:1551-8.

[9] Burant CF, Takeda J, Brot-Laroche E, et al. Fructose transporter in human spermatozoa and small intestine is GLUT5. J Biol Chem 1992;267:14523-6.

[10] Davidson RE, Leese HJ. Sucrose absorption by the rat small intestine in vivo and in vitro. J Physiol 1977;267:237-48.
[11] Ferraris RP, Diamond J. Regulation of intestinal sugar transport. Physiol Rev 1997;77:257-302.
[12] Sandle GI, Lobley RW, Warwick R, et al. Monosaccharide absorption and water secretion during disaccharide perfusion of the human jejunum. Digestion 1983;26:53-60.
[13] Adopo E, Peronnet F, Massicotte D, et al. Respective oxidation of exogenous glucose and fructose given in the same drink during exercise. J Appl Physiol 1994;76:1014-9.
[14] Riddell MC, Bar-Or O, Wilk B, et al. Substrate utilization during exercise with glucose and glucose plus fructose ingestion in boys ages 10-14 yr. J Appl Physiol 2001;90:903-11.
[15] Scherrer S, Haldimann B, Kruper A, et al. Hepatic metabolism of aminopyrine in patients with chronic renal failure. Clin Sci Mol Med 1978;54:133-40.
[16] Borg G. Ratings of perceived exertion and heart rates during short-term cycle exercise and their use in a new cycling strength test. Int J Sports Med 1982;3:153-8.
[17] Jeukendrup AE, Vet-Joop K, Sturk A, et al. Relationship between gastro-intestinal complaints and endotoxaemia, cytokine release and the acute-phase reaction during and after a long- distance triathlon in highly trained men. Clin Sci (Lond) 2000;98:47-55.
[18] Frayn KN. Calculation of substrate oxidation rates in vivo from gaseous exchange. J Appl Physiol 1983;55:628-34.
[19] Craig H. Isotopic standards for carbon and oxygen and correction factors. Geochim Cosmochim Acta 1957;12:133-49.
[20] Pirnay F, Lacroix M, Mosora F, et al. Glucose oxidation during prolonged exercise evaluated with naturally labeled [^{13}C]glucose. J Appl Physiol 1977;43:258-61.
[21] Robert JJ, Koziet J, Chauvet D, et al. Use of ^{13}C-labeled glucose for estimating glucose oxidation: some design considerations. J Appl Physiol 1987;63:1725-32.
[22] Pallikarakis N, Sphiris N, Lefebvre P. Influence of the bicarbonate pool and on the occurrence of $^{13}CO_2$ in exhaled air. Eur J Appl Physiol 1991;63:179-83.
[23] Bosch AN, Dennis SC, Noakes TD. Influence of carbohydrate ingestion on fuel substrate turnover and oxidation during prolonged exercise. J Appl Physiol 1994;76:2364-72.
[24] Hawley JA, Dennis SC, Nowitz A, et al. Exogenous carbohydrate oxidation from maltose and glucose ingested during prolonged exercise. Eur J Appl Physiol 1992;64:523-7.
[25] Jeukendrup AE, Wagenmakers AJM, Stegen JHCH, et al. Carbohydrate ingestion can completely suppress endogenous glucose production during exercise. Am J Physiol 1999;276:E672-83.
[26] Saris WH, Goodpaster BH, Jeukendrup AE, et al. Exogenous carbohydrate oxidation from different carbohydrate sources during exercise. J Appl Physiol 1993;75:2168-72.
[27] Wagenmakers AJM, Brouns F, Saris WHM, et al. Oxidation rates of orally ingested carbohydrates during prolonged exercise in man. J Appl Physiol 1993;75:2774-80.
[28] Malathi P, Ramaswamy K, Caspary WF, et al. Studies on the transport of glucose from disaccharides by hamster small intestine in vitro. I. Evidence for a disaccharidase-related transport system. Biochim Biophys Acta 1973;307:613-26.
[29] Ramaswamy K, Malathi P, Caspary WF, et al. Studies on the transport of glucose from disaccharides by hamster small intestine in vitro. II. Characteristics of the disaccharidase-related transport system. Biochim Biophys Acta 1974;345:39-48.
[30] Gray GM, Ingelfinger FJ. Intestinal absorption of sucrose in man: interrelation of hydrolysis and monosaccharide product absorption. J Clin Invest 1966;45:388-98.
[31] Moodley D, Noakes TD, Bosch AN, et al. Oxidation of exogenous carbohydrate during prolonged exercise: the effects of the carbohydrate type and its concentration. Eur J Appl Physiol 1992; 64:328-34.