Comparison of exogenous glucose, fructose and galactose oxidation during exercise using $^{13}$C-labelling

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Six subjects exercised for 120 min on a cycle ergometer ($65$ (SE $3$) % $\dot{V}O_2_{\max}$) when ingesting a placebo or glucose, fructose or galactose (100 g in 1000 ml water) labelled with $^{13}$C. The oxidation of energy substrates including exogenous hexoses was compared using indirect respiratory calorimetry and $^{13}$CO$_2$ production at the mouth. Total carbohydrate progressively decreased and total fat oxidation increased over the 120 min exercise period in the four experimental situations. During the 120 min of exercise, the amount of fructose oxidized ($38.8$ (SE $2.6$) g; $9.0$ (SE $0.6$) % energy yield) was not significantly (approximately $4\%$) lower than that of exogenous glucose ($40.5$ (SE $3.4$) g; $9.2$ (SE $0.8$) % energy yield), while that of galactose ($23.7$ (SE $3.5$) g; $5.5$ (SE $0.9$) % energy yield) was only $59\%$ and $61\%$ that of glucose and fructose, respectively. When compared with the placebo, the ingestion and oxidation of the three hexoses did not significantly modify fat oxidation or total carbohydrate oxidation, but it significantly reduced ($9–13\%$) endogenous carbohydrate oxidation. The present data indicate that fructose and exogenous glucose ingested during exercise could be oxidized at a similar rate, but that the oxidation rate of galactose was only approximately $60\%$ that of the exogenous glucose and fructose, presumably because of a preferential incorporation of galactose into liver glycogen (Leloir pathway). The reduction in endogenous carbohydrate oxidation was, however, similar with the three hexoses.

**Stable isotope: Exogenous hexoses: Calorimetry**

When they are ingested in large amounts ($1.8—2.4$ g/min) during prolonged moderate exercise, the oxidation of exogenous glucose or glucose polymers could exceed 1 g/min and could provide up to $30–40\%$ of the energy yield (Couture et al. 2002; Jentjens et al. 2004a,b; Wallis et al. 2005). When compared with that of exogenous glucose or starch, the oxidation of fructose has shown to be $15\%$ higher (Décombaz et al. 1985), similar (Slama et al. 1989; Burelle et al. 1997) or approximately $20–25\%$ lower (Massicotte et al. 1986, 1989, 1990, 1994; Guézennec et al. 1989; Jandrain et al. 1993; Adopo et al. 1994), and both hexoses have been shown to reduce endogenous carbohydrate (CHO) oxidation (Massicotte et al. 1986, 1989, 1990, 1994; Wagenmakers et al. 1993; Jeukendrup et al. 1999; Couture et al. 2002; Jentjens et al. 2004a,b). As for galactose, Stellaard et al. (2000) observed that the ingestion of galactose would be only about half that exogenous glucose. We hypothesized that the oxidation rate of fructose would be slightly lower than that of exogenous glucose, whereas that of galactose would be about $60\%$ that of exogenous glucose and fructose. We also hypothesized that the reduction in endogenous CHO oxidation would be lower with galactose than with glucose or fructose.

**Methods**

**Subjects**

The experiments were conducted on six active healthy male subjects who gave their informed written consent to participate in the study, which was approved by the Institutional Board on the Use of Human Subjects in Research. Their mean age, body mass, height, fasting plasma glucose concentration and maximal oxygen uptake on a cycle ergometer were

Abbreviations: CHO, carbohydrate; $\dot{V}CO_2$, carbon dioxide production; PDB-1, Pee Dee Bilemniella.

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21 (SE 1) years, 65 (SE 2) kg, 172 (SE 2) cm, 4·76 (SE 0·21) mmol/l and 4·40 (SE 0·06) l/min, respectively.

Experimental protocol

The \( V_{\text{O}_{2\text{max}}} \) and experimental workloads on a cycle ergometer (Ergomeca, La Bayette, France) were determined for each subject during a preliminary test session using open-circuit spirometry (1100 Medical Gas Analyser; Marquette Electronics, Milwaukee, Wisconsin, USA). Subsequently, at 1-week intervals beginning at 13.00 hours, all subjects performed four exercise sessions of 120 min duration at a workload corresponding to 65 (SE 3)\% \( V_{\text{O}_{2\text{max}}} \) (218·3 (SE 10·6) W). The last evening meal (19.00 hours: 5450 kJ, approximate values 50 % CHO, 35 % fat, 15 % protein) were standardized.

In addition, in order to keep a low background \( ^{13}\text{C} \) enrichment of expired \( \text{CO}_2 \), the ingestion of CHO from plants with a \( \text{C}_4 \) photosynthetic cycle, which are naturally enriched in \( ^{13}\text{C} \) (Lefebvre, 1985), was avoided during the period of experiments. Subjects also refrained from exercising, and from drinking coffee and alcohol for 2 d before each experiment.

During the exercise period, the subjects ingested 1000 ml water at room temperature with a low-calorie sweetener (Aspartin; Nabisco, Etobicoke, Ontario, Canada) as a placebo, or 100 g glucose, fructose or galactose in 1000 ml water. The solutions were given in five 200 ml doses taken immediately before the beginning of the exercise and at 20, 40, 60 and 80 min during the exercise period. The hexoses ingested were artificially labelled with \( ^{13}\text{C} \). Glucose, fructose (Biopharm, Laval, Quebec, Canada; \(-11\text{.}03 \text{ and } -10\text{.}91\% \delta ^{13}\text{C} \) Pee Dee Bilemmitella (PDB-1), respectively) and galactose (Sigma Chemicals, St Louis, MO, USA; \(-23\text{.}4 \% \delta ^{13}\text{C} \) PDB-1) were respectively enriched with [\( ^{1}\text{U} \)\text{C}_6\text{-glucose}, [\( ^{1}\text{U} \)\text{C}_6\text{-fructose and [\( ^{1}\text{U} \)\text{C}_6\text{-galactose} (ICN Pharmaceuticals Inc, Costa Mesa, CA, USA) in order to achieve final isotopic compositions close to +25 \% \delta ^{13}\text{C} \) PDB-1 (actual values measured by mass spectrometry +24.5, +24.1 and +24.2 \% \delta ^{13}\text{C} \) PDB-1, for glucose, fructose and galactose, respectively).

Measures and calculations

Observations were made at rest immediately before exercise and every 30 min during the exercise period. Fat and CHO oxidation were computed from oxygen consumption (\( \text{VO}_2 \)) and carbon dioxide production (\( \text{VCO}_2 \)) using open-circuit spirometry (10 min collection periods). For the measurement of \( ^{13}\text{C}^{12}\text{C} \) in expired \( \text{CO}_2 \) 80 ml samples of expired gas were collected and stored in Vacutainers (Becton Dickinson, Franklin Lakes, NJ, USA). Finally, 8 ml blood samples were withdrawn through a catheter (Baxter Health Care Corp., Valencia, CA, USA) inserted into an antecubital vein 30 min before the beginning of the experiment, for the measurement of plasma glucose (Sigma Diagnostics, Sigma, Mississauga, Ontario, Canada) and insulin (KTSP-11 001; Immunocorp Sciences, Montreal, Quebec, Canada) concentrations. Plasma samples were stored at \(-80^\circ \text{C} \) until analysis.

Measurements of \( ^{13}\text{C}^{12}\text{C} \) in expired \( \text{CO}_2 \) and in \( \text{CO}_2 \) from the combustion of ingested glucose, fructose and galactose were performed by mass spectrometry (PVG, Manchester, UK) following cryodistillation as previously described (Adopo et al. 1994). The isotopic composition was expressed in \( \% \delta \) difference by comparison with the PDB-1 Chicago Standard: \( \% \delta ^{13}\text{C} \) PDB-1 = \((R_{\text{exp}}/R_{\text{std}}) - 1\) \times 1000, where \( R_{\text{std}} \) and \( R_{\text{exp}} \) are the \( ^{13}\text{C}^{12}\text{C} \) ratio in the sample and standard (1·1237 %), respectively (Craig, 1953).

The oxidation of CHO (expressed in g glucose/min) and fat were calculated from \( \text{VO}_2 \) and \( \text{VCO}_2 \) as follows (Péronnet & Massicotte, 1991):

\[
\text{CHO} = 4.59 \times (\text{VCO}_2 - 3.23 \times \text{VO}_2) \quad (1)
\]

\[
\text{Fat} = 1.69 \times (\text{VO}_2 - \text{VCO}_2) \quad (2)
\]

with mass in g and gas volume in LSTPD. The oxidation rate of the exogenous hexose (\( m_{\text{exo}} \), g/min) was calculated as follows:

\[
m_{\text{exo}} = \frac{\text{VCO}_2 [(\text{R}_{\text{exp}} - \text{R}_{\text{ref}})/(\text{R}_{\text{exo}} - \text{R}_{\text{ref}})]/k}{\text{LSTPD}} \quad (3)
\]

where \( \text{VCO}_2 \) is in LSTPD/min, \( \text{R}_{\text{exp}} \) is the \( ^{13}\text{C}^{12}\text{C} \) observed in expired \( \text{CO}_2 \), \( \text{R}_{\text{ref}} \) is the \( ^{13}\text{C}^{12}\text{C} \) in expired \( \text{CO}_2 \) in the control trial, \( \text{R}_{\text{exo}} \) is the \( ^{13}\text{C}^{12}\text{C} \) in the exogenous glucose, fructose or galactose ingested, and \( k \) (0·747 1/g) is the volume of \( \text{CO}_2 \) provided by the complete oxidation of glucose, fructose or galactose. Endogenous CHO oxidation (g glucose/min) was calculated by the difference between total CHO and exogenous hexose oxidation. The contribution of the oxidation of the various substrates to the energy yield was computed from their respective energy potential.

Statistics

Data are presented as means with their standard errors. The main effects of time and exogenous substrate ingested, as well as time–substrate interactions, were tested by repeated-measures ANOVA (Statistica package; StatSoft, Tulsa, OK, USA). Newman–Keuls post hoc tests were used to identify the location of significant differences \((P<0.05)\) when ANOVA yielded a significant \( F \) ratio.

Results

Over the 120 min of exercise, \( \text{VO}_2 \), which was stable, and RER, which significantly decreased, were not significantly different in the four experimental situations (Table 1). At rest before ingestion of the placebo or the \( ^{13}\text{C} \)-hexose, the \( ^{13}\text{C}^{12}\text{C} \) in expired \( \text{CO}_2 \) was not significantly different in the
four experimental situations and averaged $-22.99 \pm 0.03$; pooled data, n 24) (Fig. 1). In response to exercise with ingestion of the placebo, $^{13}$C:12C in expired CO$_2$ increased slightly, as commonly observed (Burelle et al. 2001), and reached a plateau after 30 min exercise. The increase in $^{13}$C:12C was much higher when $^{13}$C-enriched hexoses were ingested, but the values observed were significantly higher beginning at 60 min with the ingestion of glucose and fructose than with the ingestion of galactose (main effect).

Substrate oxidation over the exercise period is presented in Table 2. Total CHO and fat oxidation decreased and increased, respectively, from the first to the second hour of exercise in the four experimental situations but was not significantly different with the placebo and the ingestion of the three hexoses. The amounts of exogenous hexoses oxidized significantly increased from the first to the second hour of exercise, with no significant difference between exogenous glucose and fructose oxidation. In contrast, the amount of exogenous galactose oxidized was significantly lower (approximately 60 %) than that of exogenous glucose and fructose over both the first and second hour of exercise. As a consequence, galactose oxidation only contributed 5.5% to the energy yield (significantly lower than the percentage energy yield from the oxidation of exogenous glucose and fructose: 9.2% (SE 0.8)% to the energy yield (significantly lower than the percentage energy yield from the oxidation of exogenous glucose and fructose: 9.2% (SE 0.8)% to the energy yield, and was not significantly different, respectively, in the four experimental situations (Fig. 2).

No significant differences were observed between trials for basal plasma glucose and insulin concentration (Fig. 3). Throughout the exercise period, plasma glucose concentration remained at or slightly above basal values (approximately 5.5 mmol/l) when glucose or fructose was ingested. Although this did not reach significance, plasma glucose concentration steadily decreased when placebo or galactose was ingested, and the values observed were significantly lower than with glucose or fructose ingestion at 80 min. The plasma insulin concentration significantly decreased in response to exercise but was not significantly different between the four situations (main effect).

Discussion

The results from the present experiment show that, compared with glucose and for similar amounts ingested during exercise,
the oxidation of galactose was significantly lower (approximately 40%), whereas the oxidation of fructose was only about 4% lower and not significantly different. The ingestion of hexoses did not significantly modify total CHO and fat oxidation, but it significantly reduced (by 9–13%) endogenous CHO oxidation over the 120 min exercise.

Only one study is available concerning the oxidation of ingested galactose during prolonged exercise (Leijssen et al. 1995). In this study, the oxidation rates of 155 g exogenous glucose and galactose were compared during 120 min exercise at 65% VO_{2max} (3.52 l/min). The amount of galactose oxidized over the exercise period (33.4 g) was 46% that of exogenous glucose (71.7 g). Results from the present experiment are in line with these findings as the amount of galactose oxidized over the exercise period (33.4 g) was 46% that of exogenous glucose (71.7 g). Results from the present study are in line with these findings as the amount of galactose oxidized over the 120 min exercise period was only approximately 4% lower and not significantly different. The ingestion of hexoses did not significantly modify total CHO and fat oxidation, but it significantly reduced (by 9–13%) endogenous CHO oxidation over the 120 min exercise.

In the present experiment, the amount of exogenous fructose oxidized over the 120 min of exercise period was only approximately 4% lower than that of exogenous glucose, and the difference was not statistically significant. This observation confirms the fact that, in certain situations, fructose oxidation could be similar to exogenous glucose oxidation. On the basis of the limited experimental data available, however, it is difficult to identify the factor(s) explaining how, in certain

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**Fig. 2.** Percentage contribution to the energy yield of fat (□), endogenous CHO (□) and exogenous hexoses (▾) over the first and second hours of exercise (mean and their standard errors; n 6). Values were significantly different from those for the placebo (P<0.05). †Values were significantly different from those for glucose and fructose (P<0.05). §Values were significantly different from the first hour (P<0.05).

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**Fig. 3.** Plasma concentration of glucose (A) and insulin (B) in the four experimental conditions (mean and their standard errors; n 6). †Values were significantly different from those for glucose and fructose (P<0.05). ‡Values were significantly different from the corresponding value at 0 min (P<0.05). ––, Placebo; ––, glucose; ––, fructose; ––, galactose.
situations, fructose oxidation could be lower than, similar to or even higher than that of exogenous glucose. Finally, in the present experiment, in line with several studies comparing the effect of glucose and fructose ingestion (Massicotte et al. 1986, 1990, 1994; Jandrain et al. 1993; Adopo et al. 1994), the reduction in endogenous CHO oxidation observed with fructose was very similar to that observed with ingestion of glucose (12–17%).

When compared with that of exogenous glucose, the lower oxidation rate of exogenous galactose and fructose, when present, could be due to difference in intestinal absorption, changes in plasma concentration and renal handling, and in metabolism of the three hexoses in the liver and peripheral tissues (mainly muscle during exercise).

No data are currently available for directly comparing the intestinal absorption of glucose, fructose and galactose at rest or exercise in man, and the mechanisms by which each of these three hexoses is absorbed are not fully understood (Kellett, 2001; Santer et al. 2003; Wright et al. 2003). Glucose, fructose and galactose cross the brush-border membrane of the enterocytes through an active transport mechanism (SGLT1 co-transporter, with a similar affinity for glucose and galactose but none for fructose; see Wright et al. 2003 for a review) or facilitated diffusion (GLUT2 transporters, which have a higher affinity for glucose but can handle all three hexoses (Kellet, 2001; Wright et al. 2003); GLUT5 transporters, which are highly specific for fructose) (Ferraris & Diamond, 1997). As for absorption across the basolateral membrane of the enterocyte, the three hexoses appear to share the common facilitated diffusion mediated by GLUT2 transporters (Wright et al. 2003). Glucose could also be absorbed following the formation of glucose-6-phosphate, transport within the endoplasmic reticulum, vesicle trafficking and the release of free glucose outside the cell (Stümpel et al. 2001; Santer et al. 2003). Taken together, these data suggest that the intestinal absorption of glucose could be slightly more efficient than that of galactose, which in turn could be more efficient than that of fructose. These differences in the intestinal absorption of hexoses could at least partly explain why, in most studies (Massicotte et al. 1986, 1989, 1990, 1994; Guézennec et al. 1989; Slama et al. 1989; Jandrain et al. 1993; Adopo et al. 1994; Burelle et al. 1997), the oxidation rate of exogenous fructose has been shown to be slightly lower (albeit not always statistically significantly lower) than that of exogenous glucose. This does not, however, explain why the oxidation rate of exogenous galactose in response to exercise is much lower than that of exogenous glucose, as shown by Leijssen et al. (1995) as well as in the present experiment.

One possible explanation for the much lower oxidation rate of galactose than fructose or glucose is the loss of galactose in the urine. In contrast to what is observed following the ingestion of glucose (Jeukendrup et al. 1999; Couture et al. 2002; Jentjens et al. 2004a,b) or fructose (Jandrain et al. 1993; Burelle et al. 1997), the ingestion of galactose results in a marked increase in plasma galactose concentration (e.g. 12 mmol/l at the end of exercise with an ingestion of 155 g galactose; Leijssen et al. 1995). Because the renal threshold for galactose could be as low as 0.5 mmol/l (Williams, 1986), this explains why Ganda et al. (1979) recovered from the urine approximately 16% of a 32.5-g dose of galactose ingested at rest (plasma galactose concentration 19 mmol/l). Although this was not measured by Leijssen et al. (1995) or in the present study, losses of galactose in the urine could be suspected owing to the large amounts ingested.

Finally, as discussed by Leijssen et al. (1995) for galactose, and as shown for fructose (Jandrain et al. 1993), the lower oxidation rate of these hexoses compared with glucose during prolonged exercise is probably mainly due to their different metabolic fate in the liver and peripheral tissues. Because of the much higher affinity of muscle hexokinase than liver glucokinase for glucose, and because of the stimulation of muscle glucose uptake in response to exercise (for a review, see Pereira & Lancha, 2004), the oxidation rate of plasma glucose increases markedly, and the oxidation rate of exogenous glucose can reach about 1.2 g/min in as much as the ingestion rate is large enough (Jeukendrup et al. 1999; Couture et al. 2002; Jentjens et al. 2004a,b).

In contrast, because of the presence of a fructokinase and a galactokinase, fructose and galactose could be preferentially taken up by the liver (Chen & Whistler, 1977; Williams, 1986). Data from Ahlborg & Björkman (1990) indicate that only small amounts of fructose if any are taken up by the muscle, except when the plasma fructose concentration is very high (8.8 mmol/l in their study). Data from Jandrain et al. (1993) indicate that exogenous 13C-fructose ingested during exercise, and presumably taken up by the liver, was quickly converted into 13C-glucose, which was released in the blood and became available for oxidation in the muscle. The same phenomenon has been shown following 13C-galactose ingestion at rest (Berry et al. 1995), but no data are currently available on possible conversion of exogenous galactose to plasma glucose during exercise.

Because of the presence of the Leloir pathway (Williams, 1986), galactose could be preferentially converted into liver glycogen, thus escaping oxidation. A preferential incorporation of exogenous galactose into liver glycogen during exercise is suggested by data from Leijssen et al. (1995). In their study, following a 60-min recovery period after the first 120-min period of exercise, the oxidation rates of 13C-galactose and 13C-glucose were similar during a subsequent 30-min period at 60% maximal workload. This could reflect the release and oxidation of glucose from liver glycogen synthesized from 13C-galactose during the first exercise period and the subsequent recovery.

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References


