Sucrose ingestion after exhaustive exercise accelerates liver, but not muscle glycogen repletion when compared to glucose ingestion in trained athletes

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ABSTRACT

Purpose: To assess the effects of sucrose versus glucose ingestion on post-exercise liver and muscle glycogen repletion. **Methods:** Fifteen well-trained male cyclists completed 2 test days. Each test day started with glycogen-depleting exercise, followed by 5 h of recovery, during which subjects ingested 1.5 $g \cdot kg^{-1} \cdot h^{-1}$ sucrose or glucose. Blood was sampled frequently and ^{13}C magnetic resonance spectroscopy and imaging were employed 0, 120, and 300 min post-exercise to determine liver and muscle glycogen concentrations and liver volume. **Results:** Post-exercise muscle glycogen concentrations increased significantly from 85±27 vs 86±35 $mmol \cdot L^{-1}$ to 140±23 vs 136±26 $mmol \cdot L^{-1}$ following sucrose and glucose ingestion, respectively (no differences between treatments: P=0.673). Post-exercise liver glycogen concentrations increased significantly from 183±47 vs 167±65 $mmol \cdot L^{-1}$ to 280±72 vs 234±81 $mmol \cdot L^{-1}$ following sucrose and glucose ingestion, respectively (time x treatment, P=0.051). Liver volume increased significantly over the 300 min period after sucrose ingestion only (time x treatment, P=0.001). As a result, total liver glycogen content increased during post-exercise recovery to a greater extent in the sucrose treatment (from 53.6±16.2 to 86.8±29.0 g) compared to the glucose treatment (49.3±25.5 to 65.7±27.1 g; time x treatment, P<0.001), equating to a 3.4 $g \cdot h^{-1}$ (95%CI: 1.6 to 5.1 $g \cdot h^{-1}$) greater repletion rate with sucrose vs glucose ingestion. **Conclusion:** Sucrose ingestion (1.5 $g \cdot kg^{-1} \cdot h^{-1}$) further accelerates post-exercise liver, but not muscle glycogen repletion when compared to glucose ingestion in trained athletes.

This trial was registered at clinicaltrials.gov as NCT02344381.

Keywords: 13C magnetic resonance spectroscopy; carbohydrate; recovery; fructose; endurance exercise

New & Noteworthy statement (69 words)

This is the first study to assess both muscle and liver glycogen repletion post-exercise after ingesting different types of carbohydrates in large amounts. We observed that sucrose ingestion accelerates post-exercise liver glycogen repletion compared to glucose ingestion in spite of lower insulinemia and reduced gut discomfort. Therefore, when rapid recovery of endogenous carbohydrate stores is a goal, ingestion of sucrose at 1.5 g/kg/h would be more appropriate than glucose.

INTRODUCTION

Carbohydrates are a main substrate source used during prolonged moderate to high intensity exercise (35, 42). Both exogenous and endogenous carbohydrate stores can contribute to carbohydrate oxidation during exercise. Endogenous carbohydrate stores include liver and skeletal muscle glycogen, which can provide sufficient energy to sustain 45-60 min of high-intensity exercise (8, 10). However, at longer exercise durations (>60 min) endogenous glycogen stores may become depleted, causing early fatigue (1, 4-6, 9, 16, 20, 39). Due to the apparent relationship between glycogen depletion and exercise capacity (1, 4-6, 9, 12, 19, 20), the main factor determining the time needed to recover from exhaustive exercise is the rate of glycogen repletion. This is particularly relevant when exercise performance needs to be regained within 24 h, for example during tournament-style competitions or in between stages in races such as during the Tour de France.

Previous studies have shown that muscle glycogen repletion rates can reach maximal values when glucose (polymers) are ingested in an amount of 1.2 $g \cdot kg^{-1} \cdot h^{-1}$ (2, 43), with no further improvements at higher glucose ingestion rates (18). It has been speculated that post-exercise muscle glycogen synthesis rates may be further increased when ingesting multiple transportable carbohydrates (i.e., mix of glucose and fructose). Glucose and fructose are absorbed by several similar (GLUT2, GLUT8 and GLUT12) as well as different intestinal transporters (SGLT1 and GLUT5, respectively) (24, 37). Hence, the combined ingestion of both glucose and fructose may augment intestinal carbohydrate uptake and accelerate their subsequent delivery into the circulation (24, 37). To date, only one study investigated this hypothesis, showing no further improvements in post-exercise muscle glycogen repletion rates after the ingestion of ~1.2 $g \cdot kg^{-1} \cdot h^{-1}$ (or 90 $g \cdot h^{-1}$) of multiple transportable carbohydrates compared to an equivalent dose of glucose (44).

The use of multiple transportable carbohydrates is potentially more relevant for liver

glycogen repletion, as fructose is preferentially metabolized and retained in the liver (30). Factors that contribute to this are the high first pass extraction of fructose by the liver and the high hepatic expression of fructokinase and triokinase, which are essential enzymes for the metabolism of fructose (30). Furthermore, it has been shown that intravenously administered fructose leads to greater increases in liver glycogen content when compared with intravenous glucose administration (33). Yet, few studies have tried to assess the effects of carbohydrate ingestion on post-exercise liver glycogen repletion (9, 14, 15, 31). This is mainly due to obvious methodological limitations, as liver biopsies are not considered appropriate for measuring liver glycogen concentrations for research purposes *in vivo* in humans (17). With the introduction of ^{13}C-Magnetic Resonance Spectroscopy (^{13}C-MRS), a non-invasive measurement to study changes in liver and muscle glycogen (40, 41), it has been demonstrated that post-exercise liver glycogen resynthesis is stimulated by carbohydrate ingestion (9, 14, 15). Only two studies assessed the effects of fructose ingestion on post-exercise liver glycogen resynthesis rates. Décombaz *et al.* (14) reported elevated liver glycogen resynthesis rates when co-ingesting fructose with maltodextrin (~0.93 g·kg^{-1}·h^{-1}), whereas Casey *et al.* (9) reported no differences in post-exercise liver glycogen repletion following ingestion of ~0.25 g·kg^{-1}·h^{-1} glucose versus sucrose (9). No study has assessed the impact of ingesting multiple transportable carbohydrates on both liver and muscle glycogen repletion when optimal amounts of carbohydrate are ingested during post-exercise recovery.

We hypothesize that ingestion of large amounts of sucrose leads to higher liver and muscle glycogen repletion rates when compared to the ingestion of the same amount of glucose. To test this hypothesis, 15 well-trained cyclists completed glycogen depleting exercise, after which we applied ^{13}C MRS to compare liver and muscle glycogen repletion rates following the ingestion of 1.5 g·kg^{-1}·h^{-1} sucrose or 1.5 g·kg^{-1}·h^{-1} glucose during 5 hours of post-exercise recovery.

METHODS

Subjects

Fifteen well-trained male cyclists participated in this study (age: 22±4 y, bodyweight: 74.4±7.5 kg, body mass index: 22.6±1.8 kg/m^2, maximal workload capacity (W_{max}): 350±30 W, peak oxygen uptake ($\dot{V}O_2$ peak): 61.5±5.2 mL·kg^{-1}·min^{-1}). Subjects were fully informed of the nature and possible risks of the experimental procedures, before written informed consent was obtained. Trials were conducted at the Newcastle Magnetic Resonance Centre (Newcastle-upon-Tyne, UK) in accordance with the Second Declaration of Helsinki, and following approval from the Northumbria University Faculty of Health and Life Sciences Ethics Committee.

Preliminary testing

All subjects participated in a screening session, which was performed ≥1 wk before the first experiment. Subjects performed an incremental cycling test on an electromagnetically braked cycle ergometer (Velotron, RacerMate Inc., Seattle, WA, USA) to determine maximal workload capacity (W_{max}) and peak oxygen uptake ($\dot{V}O_2$ peak). Following a 5 min warm-up at 100 W, the workload began at 150 W and was increased by 50 W every 2.5 min to exhaustion (27). Expired gas was sampled continuously to determine oxygen uptake (Oxycon gas analyser, CareFusion corporation, San Diego, CA, USA).

Diet and physical activity

All subjects received the same standardized dinner (2797 kJ; 666 kcal; providing 23.9 g fat, 83.7 g carbohydrate and 23.9 g protein) the evening before each test day. All volunteers refrained from exhaustive physical activity 24 h before each main trial and kept their diet as constant as possible 2 d before each experimental day. In

addition, subjects filled in food intake and physical activity diaries for 2 d before the start of the first and second trial.

Study design

Participants performed 2 trials in a randomized, double-blind, crossover design separated by at least 7 d. During each trial, they were first subjected to a glycogen depletion protocol on a cycle ergometer. Thereafter, subjects were studied for 5 h while ingesting only glucose in the control trial (GLU) or sucrose in the SUC trial. During the 5 h post-exercise recovery period, subjects remained at rest in a supine position. Magnetic Resonance Spectroscopy (MRS) was performed immediately post-exercise and after 2 and 5 h of post-exercise recovery to determine liver and muscle glycogen concentrations. In addition, Magnetic Resonance Imaging (MRI) was performed immediately post-exercise and after 2 and 5 h of post-exercise recovery to determine liver volume.

Experimental protocol

Participants arrived at Newcastle Magnetic Resonance Centre at 0700-0730 h following a 12 h fast. Liver and muscle glycogen depletion was established by performing an intense exercise protocol on an electromagnetically braked cycle ergometer (26). The exercise protocol started with a 10 min warm-up at 50% W_{max}. Thereafter, subjects cycled for 2-min block periods at alternating workloads of 90% and 50% W_{max}, respectively. This was continued until subjects were no longer able to complete a 2 min, 90% W_{max} exercise period at a cycling cadence of 60 rpm. At this point, the high intensity blocks were reduced to 80% W_{max} after which the same regimen was continued. When subjects were no longer able to complete the 2 min blocks at 80% Wmax, the exercise intensity of the blocks was further reduced to 70%. Subjects were allowed to stop when pedaling speed could not be maintained at

70% W_{max}. Water was provided *ad libitum* during the exercise protocol. Two fans were placed 1 m from the subjects to provide cooling and air circulation during the exercise protocol. After cessation of exercise, gastrointestinal (GI) comfort was assessed using a visual analogue scale. Subsequently, the participants underwent a basal MRS and MRI measurement for approximately 45 min (Fig. 1). After this, they were allowed to take a brief (≤ 15 min) shower before the post-exercise recovery period started. While supine, a catheter was inserted into an antecubital vein of the forearm to allow frequent blood sampling. Following a resting blood sample (10 mL), subjects filled out another visual analogue scale for GI comfort before the first test drink was given (*t*=0 min). Participants were observed for the following 5 h during which they received a drink with a volume of 3.33 $mL \cdot kg^{-1}$ every 30 min until *t*=270 min. Blood samples were taken at 15 min intervals for the first 90 min of recovery and every 30 min thereafter until *t*=300 min. Further visual analogue scales for GI comfort were completed every 30 min until *t*=300 min. Due to time constraints of the MR measurement it was not possible to acquire a blood sample and collect a visual analogue scale at time point *t*=150 min. At *t*=120 and 300 min in the post-exercise recovery period another MR measurement was performed to assess liver and muscle glycogen concentrations as well as liver volume.

GI (dis)comfort

Subjects were asked to fill out computerized visual analogue scales to assess GI comfort. The visual analogue scales consisted of 16 questions. Each question started with “To what extent are you experiencing … right now?” and was answered by ticking a 100 mm line (0 mm = not at all, 100 mm = very, very much). The questions consisted of six questions related to upper GI symptoms (nausea, general stomach problems, belching, an urge to vomit, heartburn, stomach cramps), four questions related to lower GI symptoms (flatulence, an urge to defecate, intestinal

cramps, diarrhea), and six questions related to central or other symptoms (dizziness, a headache, an urge to urinate, a bloated feeling, side aches (left), side aches (right)).

Drinks

Subjects received a drink volume of 3.33 $mL \cdot kg^{-1}$ every 30 min during recovery to ensure a given dose of 1.5 $g \cdot kg^{-1} \cdot h^{-1}$ glucose (GLU) or 1.5 $g \cdot kg^{-1} \cdot h^{-1}$ sucrose (SUC). To minimize differences in carbon isotope ratio between GLU and SUC, similar plant sources with low natural ^{13}C enrichments (i.e. wheat, potato and beet sugar, all of which use C3 metabolism) were selected for use in this study. The carbohydrates in the glucose drink (GLU) consisted of 60% dextrose monohydrate (Roquette, Lestrem, France) and 40% maltodextrin (MD14, AVEBE, Veendam, The Netherlands). The carbohydrate in the sucrose drink (SUC) consisted of 100% sucrose derived from sugar beet (AB Sugar, Peterborough, United Kingdom). Both drinks contained 20 $mmol \cdot L^{-1}$ NaCl (Tesco, Cheshunt, United Kingdom).

Measurement of muscle and liver glycogen concentrations

Glycogen concentration was determined from the magnitude of the natural abundance signal from the C-1 carbon of glycogen at a frequency of 100.3 ppm. A Philips 3 Tesla Achieva scanner (Philips Healthcare, Best, The Netherlands) was used with a 6 cm diameter ^{13}C surface coil with integral ^{1}H decoupling surface coil (PulseTeq, Worton under Edge, UK) to measure muscle glycogen concentration and an in-house built 12 cm $^{13}C/^{1}H$ surface coil used to measure liver glycogen concentration. The intra-individual coefficient of variation of hepatic glycogen content measured by ^{13}C MRS has been shown to be 7% (36).

For muscle glycogen concentration measurements, the surface coil was placed over the widest part of the *vastus lateralis* muscle and was held in position with fabric

straps to prevent movement. Pulse power was calibrated to a nominal value of 80° by observing the power dependent variation in signal from a fiducial marker located in the coil housing, containing a sample exhibiting ^{13}C signal with short T_1 (213 mM [2-^{13}C]-acetone and 25 mM $GdCl_3$ in water). Automated shimming was carried out to ensure that the magnetic field within the scanner was uniform over the active volume of the ^{13}C coil. The ^{13}C spectra were acquired over 15 min using a non-localized ^{1}H decoupled ^{13}C pulse-acquire sequence (TR 120 ms, spectral width 8 kHz, 7000 averages, WALTZ decoupling). ^{1}H decoupling was applied for 60% of the ^{13}C signal acquisition to allow a relatively fast TR of 120 ms to be used within Specific Absorption Rate safety limitations.

For liver glycogen measurements the $^{13}C/^{1}H$ surface coil was placed over the right lobe of the liver. Spectra were acquired over 15 min using non-localized ^{1}H decoupled ^{13}C pulse acquisition sequences (TR 300 ms, spectral width 8 kHz, 2504 averages, WALTZ decoupling, nominal ^{13}C tip angle of 80°). Scout images were obtained at the start of each study to confirm optimal coil position relative to the liver.

Tissue glycogen concentration was calculated from the amplitude of the C1-glycogen ^{13}C signal using Java Based Magnetic Resonance User Interface (jMRUI) version 3.0 and the AMARES algorithm [7]. For each subject the separation between RF coil and muscle / liver tissue was measured from ^{1}H images, and ^{13}C coil loading assessed from ^{13}C flip angle calibration data. Tissue glycogen concentration was determined by comparison of glycogen signal amplitude to spectra acquired from liver- and leg-shaped phantoms filled with aqueous solutions of glycogen (100 mM) and potassium chloride (70 mM). Phantom data were acquired at a range of flip angles and separation distances between coil and phantom. Quantification of each human ^{13}C spectrum employed a phantom dataset matched to body geometry and achieved flip angle so that account differences in coil sensitivity profile and loading were taken into account for each subject.

Measurement of liver volume

A turbo spin echo (TSE) sequence was used to obtain T_2-weighted axial images of the liver with a repetition time (TR) of 1687 msec. The matrix size was 188x152 mm, with a field of view of (303x240x375) mm. The body coil was used for both transmission and reception. Slice thickness was 10 mm with a 0 mm gap. Scans were obtained on expiration. The total number of liver slices used for volume analysis differed between subjects due to anatomical differences but numbered on average 20 slices. Liver volumes were measured in the open source Java image processing program ImageJ (38).

Calculation of liver glycogen content

Total liver glycogen content was calculated by multiplying liver volume with liver glycogen concentration. Subsequent conversion from mM to g was performed by using the molar mass of a glycosyl unit (i.e., 162 $g \cdot M^{-1}$).

Plasma analysis

Blood samples (10 mL) were collected in EDTA-containing tubes and immediately centrifuged at 3000 rpm for 10 min at 4°C. Plasma was then aliquoted and stored at -80°C for subsequent determination of glucose and lactate concentrations (Randox Daytona spectrophotometer, Randox, Ireland), insulin (IBL International, Hamburg, Germany) and non-esterified fatty acid concentrations (WAKO Diagnostics, Richmond, VA).

Statistics

Sample size estimation was based on previous data on liver glycogen content (14). Based on this, the expected effect size was calculated from the difference in post-

exercise liver glycogen content after ingesting a mixture of maltodextrin with fructose vs glucose (polymer) (52±23 vs 23±9 g, respectively). A sample size of n=10 in a crossover design would provide statistical power above 90% with an α-level of 0.05. We therefore recruited 15 participants to ensure adequate power and ample data sets.

Unless otherwise stated, all data are expressed as mean±SD. Differences between primary outcomes in the text and the data in the figures are presented as mean±95% confidence interval (CI). All data were analyzed by two-way repeated measures ANOVA with treatment (GLU vs SUC) and time as within-subject factors. In case of a significant interaction, Bonferroni post hoc tests were applied to locate the differences. For non-time-dependent variables, a paired Student's t-test was used to compare differences between treatments. A P value <0.05 was used to determine statistical significance. All calculations were performed by using the SPSS 21.0.0.0 software package.

RESULTS

Glycogen depletion protocol

Maximal workload capacity measured during preliminary testing averaged 350±30 W (4.75±0.6 W/kg). Consequently, average workload settings in the depletion protocol were 315±27, 280±24, 245±21, 175±15 W for the 90, 80, 70, and 50% W_{max} workload intensity respectively. On average, subjects cycled a total of 21±7 and 19±5 high-intensity blocks, which resulted in a total cycling time of 93±27 and 89±21 min in the SUC and GLU experiments, respectively. Total cycling time did not differ between trials (P=0.434).

Drink ingestion and gastrointestinal complaints

The total amount of drink ingested in both treatments was 2.48±0.25 L. The first drinks were ingested 75±7 min after cessation of exercise, due to timing of the MR measurements. Subjects reported upper GI issues following ingestion of the glucose drink only, and these issues included nausea, general stomach problems, belching and urge to vomit. These symptoms all displayed significant differences over time and between treatments (time x treatment, P<0.05; data not shown) and for every symptom the sucrose drink was better tolerated than the glucose drink.

Liver glycogen concentration

No significant differences in baseline liver glycogen concentrations were found between SUC and GLU (P=0.210; Table 1). Liver glycogen concentrations increased significantly over time during post-exercise recovery in both SUC and GLU (P<0.001). Liver glycogen repletion rates during 5 h of post-exercise recovery in SUC and GLU were 19±8 versus 14±12 $mmol \cdot L^{-1} \cdot h^{-1}$, respectively ($P$=0.052). Differences

259 in liver glycogen repletion rates between SUC vs GLU were 5.8 mmol·L^{-1}·h^{-1} (95%CI:
260 0.4 to 11.2 mmol·L^{-1}·h^{-1}).
261
262 *Liver volume*
263 Liver volume data are shown in Table 1. Over the 5 h post-exercise recovery period,
264 liver volume increased significantly in SUC (*P*=0.036), whereas no significant
265 changes were observed in GLU (*P*=0.151). A significant time x treatment interaction
266 was found between SUC and GLU (*P*=0.001).
267
268 *Liver glycogen content*
269 Liver glycogen content increased over time in both treatments (*P*<0.01; Fig. 2). Over
270 time, liver glycogen content increased significantly more in the SUC compared to the
271 GLU treatment (time x treatment interaction, *P*<0.001). Liver glycogen repletion rates
272 during 5 h of post-exercise recovery in SUC and GLU were 6.6±3.3 versus 3.3±3.0
273 g·h^{-1}, respectively (*P*=0.002). Differences in liver glycogen repletion rates between
274 SUC vs GLU were 3.4 g·h^{-1} (95%CI: 1.6 to 5.1 g·h^{-1}), leading to a 17 g difference
275 (95%CI: 8 to 26 g) over the 5 h recovery period.
276
277 *Muscle glycogen concentration*
278 No significant differences in baseline muscle glycogen concentrations were observed
279 between SUC and GLU (*P*=0.940; Fig. 3). Muscle glycogen concentrations increased
280 significantly over the 5 h recovery period in both SUC and GLU (*P*<0.001). No
281 significant differences were observed between treatments (time x treatment,
282 *P*=0.673). Muscle glycogen repletion rates during 5 h of post-exercise recovery in
283 SUC and GLU were 11±3 versus 10±5 mmol·L^{-1}·h^{-1}, respectively (*P*=0.558).
284 Differences in muscle glycogen repletion rates between SUC vs GLU were 0.9
285 mmol·L^{-1}·h^{-1} (95%CI: -1.9 to 3.6 mmol·L^{-1}·h^{-1}).

286

287 *Plasma analyses*

288 In both experiments, plasma glucose concentration increased during the first 45 min
289 of post-exercise recovery, after which concentrations gradually declined to baseline
290 values (Fig. 4A). Plasma glucose concentrations were significantly higher at *t*=60, 75
291 and 90 min in the GLU compared to SUC treatment ($P<0.05$), whereas they were
292 significantly higher in the sucrose treatment at time point 270 min ($P<0.05$). Plasma
293 lactate concentrations increased significantly after 15 min in the SUC trial compared
294 to GLU and remained significantly higher over the entire post-exercise recovery
295 period ($P<0.01$; Fig. 4B). Plasma insulin concentrations increased during the first 120
296 min of post-exercise recovery. Thereafter, plasma insulin concentrations decreased
297 but remained elevated compared to baseline values during the entire post-exercise
298 recovery period (Fig. 4C). Plasma insulin concentrations were significantly higher in
299 the GLU compared with the SUC treatment at *t*=45, 75 and 90 min ($P<0.05$). Plasma
300 NEFA concentrations decreased immediately after carbohydrate ingestion and
301 remained low over the entire recovery period, with no differences between
302 treatments (Fig. 4D).

303

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DISCUSSION

In this experiment we observed that sucrose ingestion (1.5 $g \cdot kg^{-1} \cdot h^{-1}$) during recovery from exhaustive exercise results in more rapid liver glycogen repletion, despite lower plasma insulin levels, when compared with the ingestion of glucose. Ingestion of sucrose or glucose did not result in differences in post-exercise muscle glycogen repletion rates.

Carbohydrate ingestion during 5 h of post-exercise recovery allowed substantial increases in muscle glycogen concentrations (Figure 3). This represents muscle glycogen repletion rates of 10±5 $mmol \cdot L^{-1} \cdot h^{-1}$ after glucose ingestion and 11±3 $mmol \cdot L^{-1} \cdot h^{-1}$ after sucrose ingestion. Assuming a skeletal muscle mass density of 1.112 $g \cdot cm^3$ (46) and a wet-to-dry mass ratio of 4.28 (22), our muscle glycogen repletion rates assessed using ^{13}C MRS would translate to glycogen repletion rates of 39±20 and 42±11 $mmol \cdot kg^{-1}$ $dw \cdot h^{-1}$, respectively. These values are in line with previously published data on post-exercise muscle glycogen resynthesis rates when ingesting ample amounts of carbohydrate (~1.2 $g \cdot kg^{-1} \cdot h^{-1}$), based upon muscle biopsy collection and concomitant muscle glycogen analyses, showing values ranging between 30-45 $mmol \cdot kg^{-1}$ $dw \cdot h^{-1}$ (3, 23, 43, 44). We did not observe differences in muscle glycogen repletion rates following ingestion of either sucrose or glucose (polymers) during the 5 h post-exercise recovery period (P=0.558). Hence, muscle glycogen resynthesis rates are not limited by exogenous carbohydrate availability when large amounts of glucose, glucose polymers and/or sucrose (≥1.2 $g \cdot kg^{-1} \cdot h^{-1}$) are consumed. This supports the contention that ingestion of ≥1.2 g carbohydrate$\cdot kg^{-1} \cdot h^{-1}$ maximizes post-exercise muscle glycogen synthesis rates. This also implies that the limitation in exogenous carbohydrate oxidation rates residing in the rate of intestinal glucose absorption does not impose a restriction for post-exercise muscle glycogen synthesis in a post-exercise resting condition.

After exhaustive exercise, the ingestion of glucose and sucrose resulted in liver

glycogen repletion rates of 14±12 and 19±8 mmol·L^{-1}·h^{-1}, respectively. These liver glycogen repletion rates together with our observed liver glycogen content values (Figure 2) are comparable to previous observations made by Décombaz and colleagues (14). However, we extend on previous work by showing a doubling of liver glycogen synthesis rates during recovery from exercise when sucrose as opposed to glucose (polymers) were ingested (6.6±3.3 versus 3.3±3.0 g·h^{-1}, respectively: *P*=0.002). When looking at the present data together with the results of Décombaz *et al.* (14), it can be concluded that ingestion of both submaximal (~0.93 g·kg^{-1}·h^{-1}) and maximal amounts (1.5 g·kg^{-1}·h^{-1}) of multiple transportable carbohydrates further accelerate post-exercise liver glycogen repletion compared to the ingestion of glucose (polymers) only. These observations can be attributed to the differential effects that glucose and fructose exert on hepatic carbohydrate metabolism. Glucose is a relatively poor substrate for hepatic glycogen synthesis (14, 32, 33) and much of it seems to be released into the systemic circulation to be either oxidized or stored as muscle glycogen (7, 10, 11). In contrast, fructose is primarily taken up by the liver where it can be phosphorylated and converted to glycogen or metabolized to lactate and glucose (28, 29). Lactate will subsequently be released into the bloodstream for oxidation in extrahepatic tissues or can be used as substrate for muscle glycogen synthesis (via gluconeogenesis) (45). In agreement, we observed substantial differences in circulating plasma lactate concentrations between treatments (Figure 4B).

With liver glycogen contents returning to 66 and 87 g it seems that hepatic glycogen stores were not fully replenished within the 5 h recovery period, despite ingesting large amounts of glucose and sucrose. Liver glycogen content was significantly greater and closer to a normal liver glycogen content of ~100 g (21) following sucrose ingestion when compared to glucose ingestion. Since a significant relationship has been found between liver glycogen content at the end of post-

359 exercise recovery and subsequent exercise time-to-exhaustion (9), sucrose as
360 opposed to glucose ingestion may be of benefit for those athletes who need to
361 maximize performance during a subsequent exercise task. To put this into
362 perspective, the difference in liver glycogen content (15-20 g; 57-76 kJ assuming
363 22% efficiency) could provide enough energy to sustain an additional 3-5 minutes of
364 exercise at 75% W_{max}. This difference is by no means negligible for trained cyclists
365 as it represents a 7-14% difference in time to exhaustion (9). Future research should
366 aim to prove the ergogenic benefit of accelerating liver glycogen repletion on
367 subsequent performance in various (laboratory) exercise settings.
368 Besides the benefits of sucrose over glucose (polymer) ingestion to maximize liver
369 glycogen repletion, we also observed much better tolerance to the ingestion of large
370 amounts (1.5 $g \cdot kg^{-1} \cdot h^{-1}$) of sucrose when compared with glucose (polymers). In the
371 present study we found considerably lower subjective ratings of upper gastro-
372 intestinal complaints (including nausea, general stomach problems, urge to vomit
373 and belching) after sucrose as opposed to glucose ingestion (P<0.05). These
374 findings are not surprising, as after ingesting large amounts (≥1.2 g/kg/h) of a
375 multiple transportable carbohydrate source (i.e., sucrose) more transporters in the
376 gastrointestinal tract will be utilized, thereby decreasing water retention, enhancing
377 absorption and subsequently causing less upper abdominal discomfort when
378 compared to the ingestion of glucose (polymers) only (13). The form in which these
379 carbohydrates are ingested may be of lesser importance, as previous work has
380 shown no differences in post-exercise muscle glycogen repletion when ingesting
381 carbohydrate in either liquid or solid form (25, 34).
382 In conclusion, post-exercise sucrose ingestion (1.5 $g \cdot kg^{-1} \cdot h^{-1}$) accelerates liver, but
383 not muscle glycogen repletion when compared with glucose (polymer) ingestion.
384 Ingestion of large amounts of sucrose are better tolerated than glucose (polymers),

385 making sucrose a more practical carbohydrate source to ingest during acute, post-
386 exercise recovery.

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Figure legends

Figure 1. Schematic representation of the experiment. The initial glycogen depletion exercise protocol was followed by three ^{13}C MRS & MRI measurements at *t*=0, *t*=120 and *t*=300 min of post-exercise recovery. The test drink was ingested every 30 min from *t*=0 to *t*=270 min in the post-exercise recovery period as indicated in the figure. Blood samples were obtained every 15 min during the first 90 min of post-exercise recovery. Thereafter they were obtained every 30 min. Visual analogue scales of gastrointestinal (GI) comfort were obtained immediately post-exercise and every 30 min thereafter. At *t*=150 min, no blood sample and visual analogue scale were obtained due to MR scanning.

Figure 2. Liver glycogen contents during 5 h of post-exercise recovery while ingesting glucose or sucrose in well-trained cyclists (*n*=15). # *P*<0.05, significantly different when compared with baseline values; @ *P*<0.05, significantly different when compared to values at 120 min; * *P*<0.05, significantly different from the glucose treatment.

Figure 3. Muscle glycogen concentrations during 5 h of post-exercise recovery while ingesting glucose or sucrose in well-trained cyclists (*n*=15). # *P*<0.05, significantly different when compared with baseline values; @ *P*<0.05, significantly different when compared to values at 120 min. No significant differences between treatments (*P*=0.673).

Figure 4. Plasma glucose (A), lactate (B), insulin (C) and NEFA (D) concentrations during 5 h of post-exercise recovery with ingestion of glucose or sucrose in well-trained cyclists (*n*=15). * *P*<0.05, significantly different between glucose and sucrose treatment. NEFA, non-esterified fatty acid.

Table 1. Liver glycogen concentration, liver volume and liver glycogen content

		Time (min)		
		0	120	300
Liver glycogen concentration (mmol·L^{-1})	GLU	167±65	191±66 $^{\#}$	234±81 $^{\#@}$
	SUC	183±47	219±63 $^{\#}$	280±72 $^{\#@}$
Liver volume (L)	GLU	1.79±0.28	1.70±0.24 $^{\#}$	1.72±0.24
	SUC	1.80±0.26	1.78±0.24 *	1.89±0.28 $^{\#@}$*

Values are mean±SD. Liver glycogen concentration (mmol·L^{-1}) and Liver volume (L) at t=0, 120 and 300 min post-exercise, after ingesting 1.5 g·kg^{-1}·h^{-1} glucose (n=15: GLU) or sucrose (n=15: SUC). Mean values were significantly different from baseline values: $^{\#}$ P<0.05; 120 min: $^{@}$ P<0.05; and significantly different from GLU: * P<0.05. GLU, glucose; SUC, sucrose.

Figure 1

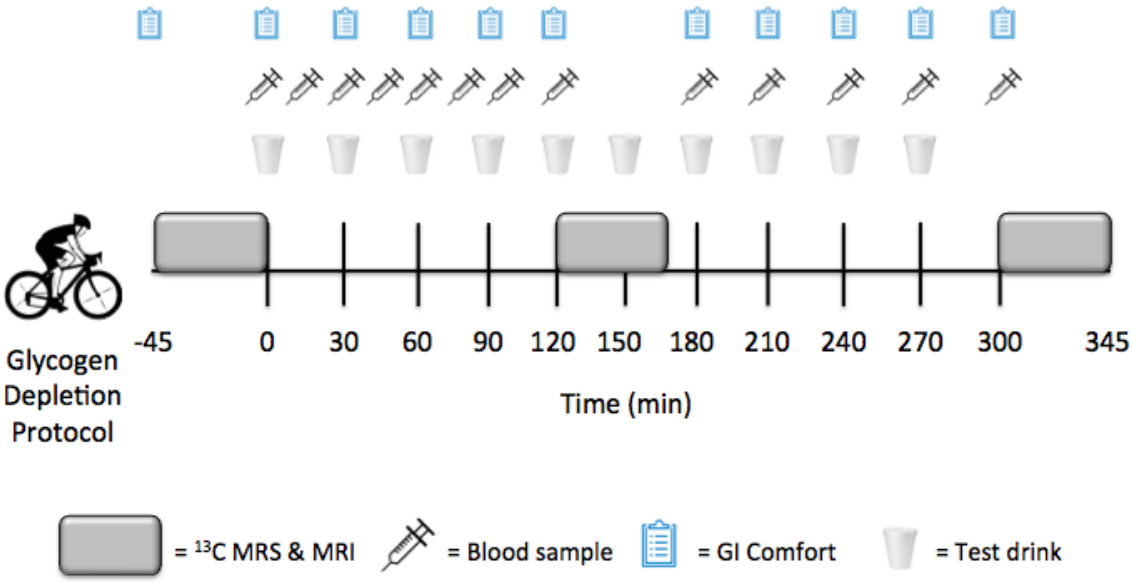

Glycogen Depletion Protocol
-45
0
30
60
90
120
150
180
210
240
270
300
345
Time (min)
= 13C MRS & MRI
= Blood sample
= GI Comfort
= Test drink

Figure 2

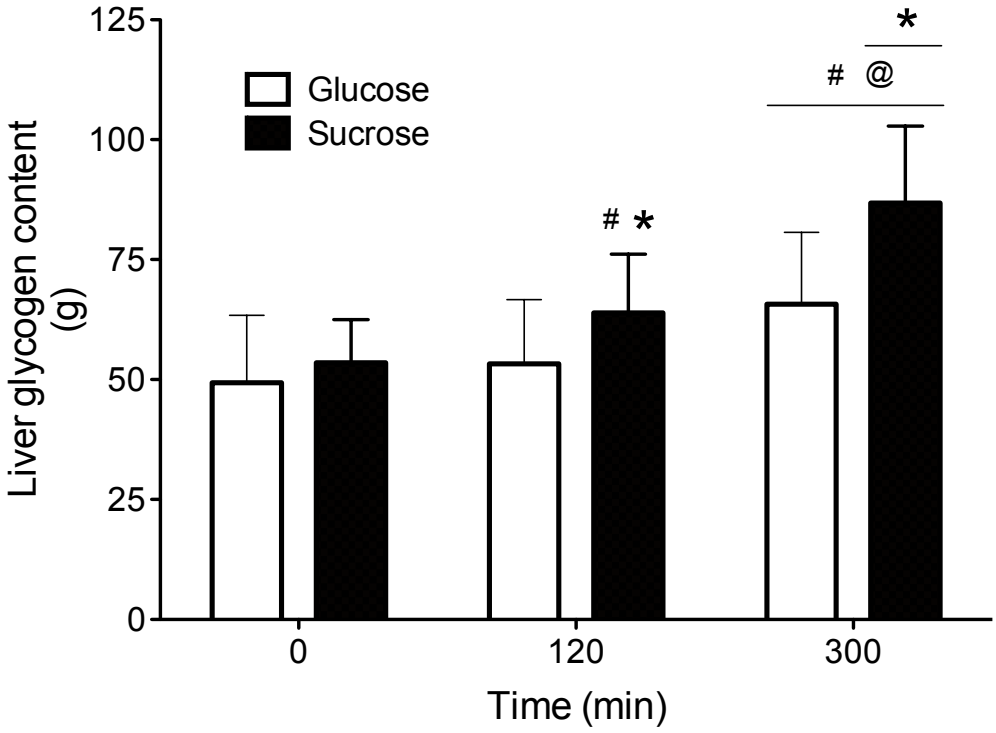

125
100
75
50
25
0
Liver glycogen content (g)
Glucose
Sucrose
*
@
*
0
120
300
Time (min)

Figure 3

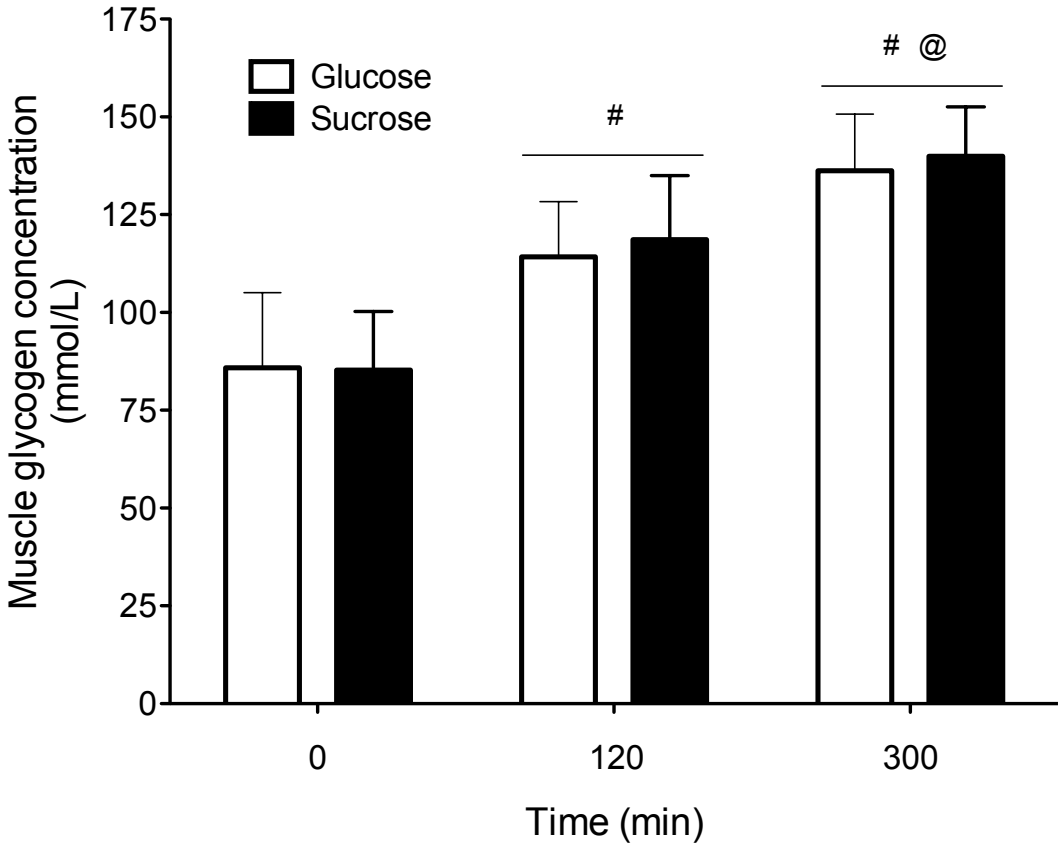
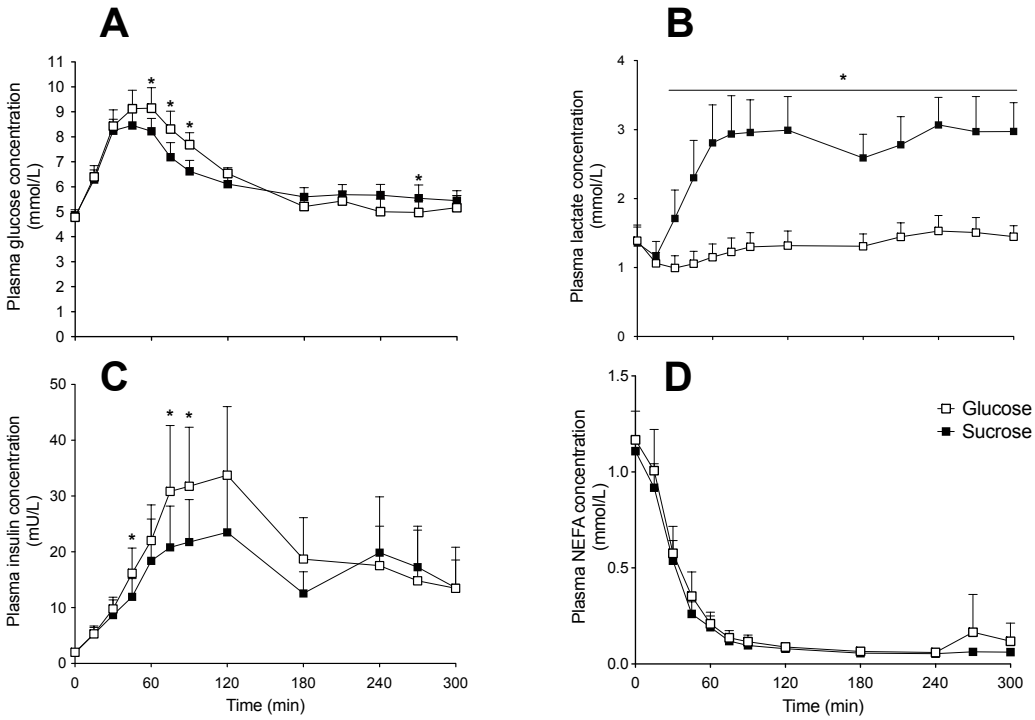

175
150
125
100
75
50
25
0
Muscle glycogen concentration (mmol/L)
Glucose
Sucrose
#
@
0
120
300
Time (min)

Figure 4


A
B
C
D
Plasma glucose concentration (mmol/L)
Plasma lactate concentration (mmol/L)
Plasma insulin concentration (mU/L)
Plasma NEFA concentration (mmol/L)
Time (min)
Glucose
Sucrose