

**CARBOHYDRATE INTAKE AND METABOLISM
DURING PROLONGED ENDURANCE EXERCISE**

by

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Abstract

It is well accepted that CHO ingestion can improve endurance performance. However, a number of questions remain open regarding fine-tuning CHO intake recommendations during prolonged endurance events.

A way to measure the bioavailability of ingested CHO is to measure exogenous CHO oxidation with the use of ^{13}C or ^{14}C tracers. This, however, has been studied only with CHO solutions, predominantly during cycling. In this thesis, we demonstrated that CHO (glucose + fructose) ingested in the form of a gel (1.8 g/min) is as effectively oxidized as an isocarbohydrate solution (1.44 ± 0.29 g/min vs 1.42 ± 0.23 g/min, respectively). Accordingly, the ingestion of CHO in the form of a solid bar (1.55 g CHO/min) was demonstrated to be oxidized at high rates (1.25 ± 0.15 g/min), comparable to a solution (1.34 ± 0.27 g/min). A comparison of CHO ingestion (1.5 g/min) during cycling and running at the same relative, moderate intensity ($\sim 60\%$ of the exercise-specific $\text{VO}_{2\text{max}}$) resulted in similar exogenous CHO oxidation rates (1.25 ± 0.10 g/min vs 1.19 ± 0.08 g/min, respectively).

The present thesis also tested the gastrointestinal (GI) tolerance of high CHO ingestion rates (1.4 g CHO/min), previously recommended to athletes. High intakes in the form of a glucose + fructose gel were, on average, well tolerated during a 16-km outdoor run, and there was no difference between tolerance of glucose and glucose + fructose gel during a similar run. A questionnaire-based field study of 221 athletes during prolonged endurance events (running, cycling and triathlon) revealed that voluntary CHO intake rates vary greatly between events and individual athletes (6-136 g/h). High CHO intakes were related to increased scores for nausea and flatulence as well as to better performance. GI distress during all studies was correlated with a reported history of GI distress. Findings from those studies suggest a need for more individualized nutritional advice that optimizes CHO and fluid delivery to enhance performance, while minimizing GI discomfort.

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List of publications

Journal papers

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Abstracts

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Accepted for poster presentation at ACSM meeting, 2008

Pfeiffer B, Cotterrill A, Grathwohl D, Stellingwerff T, and Jeukendrup AE. The effect of carbohydrate composition of gels on gastrointestinal tolerance during a 16 km run. *Accepted for oral presentation at ACSM meeting, 2008*

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Awards

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List of abbreviations

AMP	adenosine monophosphate
ANOVA	analysis of variance
ATP	adenosine triphosphate
°C	degree Celsius
C	carbon
CO ₂	carbondioxide
CHO	carbohydrate
CV	coefficient of variation
d	day
DRINK	CHO solution
EA-IRMS	elemental analyzer-isotope ratio mass spectrometry
EDTA	ethylenediaminetetraacetic acid
FFA	free fatty acids
FRC	fructose
g	gram
GC	gas chromatography
GEL	CHO gel
GI	gastro-intestinal
GLU	glucose
GLUT-1	glucose transporter 1
GLUT-2	glucose transporter 2
GLUT-4	glucose transporter 4
GLUT-5	glucose transporter 5
GLUT-7	glucose transporter 7
h	hour
HIGH	high CHO intake rate (1.4 g/min)

HR	heart rate
IRMS	isotope ratio mass spectrometry
kcal	kilocalories
kg	kilogram
km	kilometer
L	liter
LT	lactate threshold
m	meter
mg	milligram
min	minute
mL	milliliter
mmol	millimoles
MOD	moderate CHO intake rate (1 g/min)
n	number of subjects
O ₂	oxygen
p	probability value
PDB	Pee Dee Bellemnitella
RER	respiratory exchange ratio
RPE	ratings of perceived exertion
rpm	revolutions per minute
s	seconds
SE	standard error
SD	standard deviation
SGLT-1	sodium-glucose transporter 1
t	time
TT	time trial
TTE	time to exhaustion
μl	microliter

VCO_2	carbon dioxide production
VE	minute ventilation
VO_2	oxygen consumption
$\text{VO}_2 \text{ max}$	maximum oxygen consumption
vs	versus
W	Watt
WAT	water
wk	weeks
Wmax	maximum power output
y	year

Coefficients of variation for laboratory measurements

Blood measures

Spectrometric measures on a semiautomated analyser (Cobas Mira S-Plus, ABX Diagnostics, UK) as reported in Chapter 3, 4 and 5:

Plasma glucose	(Glucose HK, ABX Diagnostics, UK)	2.4%
Plasma lactate	(Lactic Acid, ABX Diagnostics, UK)	3.2%
Plasma Free Fatty Acids	(NEFA-C Kit, Alpha Laboratories, UK)	0.7%

ELISA technique as described in Chapter 4 and 5:

Plasma Insulin	(Ultrasensitive Insulin ELISA, DRG Instruments GmbH, Germany)	6.8%
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Breath measures

Expired air samples analysed with the Douglas bag technique as described in Chapter 3 and 4:

VO₂ 3.3%

VCO₂ 5.1%

Expired air samples analysed with an automated gas analyses system (Oxycon Pro; Jaeger, Germany) as described in Chapter 5:

VO₂ 4.7%

VCO₂ 5.3%

Analyses of C¹³/C¹² ratio by continuous flow IRMS (GC, Trace GC Ultra; IRMS, Delta Plus XP; both Thermo Finnigan, Herts, UK) as described in Chapter 3, 4 and 5:

C¹³/C¹² ratio 0.9%

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Chapter 1

General Introduction

1.1 Importance of nutrient intake during exercise

During prolonged, moderate- to high-intensity exercise, carbohydrate (CHO; blood glucose, muscle and liver glycogen) is the principle substrate for the contracting muscle (115, 133). However, endogenous CHO stores are limited, and potentially as a consequence, fatigue during endurance exercise often coincides with hypoglycaemia and the depletion of muscle glycogen stores (20, 29). To maximize prolonged endurance performance, it is recommended that athletes should consume CHO during endurance events (2-4, 68). Over the past few decades, many studies have investigated the metabolic and ergogenic effects of CHO during endurance exercise. However, the majority of research studies was conducted under laboratory conditions and focused on the effects of CHO solutions with the use of cycling protocols. Results from those studies might not always be applicable in a race situation, for example, during running or when solid CHO is ingested. Consequently, this thesis focuses on several questions needed to fine-tune CHO feeding strategies during exercise. The following chapter will give an overview of the previous research in the area and discuss the purpose of each study in the present thesis.

1.2 Carbohydrate (CHO) intake during exercise

The first studies to directly examine the effect of CHO intake on endurance exercise performance were conducted in the 1980s. Coyle *et al.* (24) demonstrated that time to fatigue during cycling at about 74% $\text{VO}_{2\text{max}}$ increased from 134 min to 157 min with the ingestion of a CHO solution. Since then, many studies have investigated the effect of CHO ingestion on cycling endurance capacity and performance (for review, see 68). The majority of studies showed improved endurance cycling capacity (20, 24, 28, 59) and performance

(32, 53, 58), while some studies failed to detect an ergogenic effect (6, 43, 83). Accordingly, the majority of research in running demonstrated enhanced performance with the ingestion of CHO (59, 86, 129). It is therefore widely accepted that the intake of CHO can delay the onset of fatigue and enhance endurance exercise performance. However, the mechanisms behind the ergogenic effect of CHO are not entirely clear and may be different during shorter exercise durations (~1 h) with high intensity (80-85% VO_2max) compared with longer exercise durations (>2 h), where the exercise intensity is lower (60-75% VO_2max).

During shorter durations (~1 h), an ergogenic effect of CHO has been demonstrated, even when CHO was not ingested. Rinsing the mouth with CHO has been shown to improve 40-km cycling time-trial (TT) performance (15) and 1-h running performance (114). Recently, Chambers *et al.* (16) established that a CHO mouthwash can activate brain regions believed to be involved in reward and connected to motor control. Interestingly, those receptors seem to be independent from sweet taste receptors, as non-sweet maltodextrin had the same effect as glucose, while an artificial sweetener elicited no response in the brain. The results from those studies suggest that, during shorter exercise durations, the improvements in exercise performance are due to central effects (16), and only minimal amounts are needed to improve performance.

Several studies have demonstrated that the ingestion of CHO during prolonged endurance exercise can maintain blood glucose levels and high CHO oxidation rates (19, 24, 29, 69), while fatigue often coincides with low RER values and hypoglycaemia (19, 29). For example, Coyle *et al.* (29) found that the duration of exercise to exhaustion increased from

about 3 h to about 4 h with the ingestion of CHO (~100 g/h). During the placebo trial, plasma glucose concentrations decreased to ~2 mmol/L, while the ingestion of CHO maintained plasma glucose concentrations (4.2-5.2 mmol/L). Similarly, CHO oxidation rates decreased during the placebo trial, with RER values falling from 0.85 to 0.80 at exhaustion. In the CHO ingestion trial, the total CHO oxidation rates remained high (average RER at exhaustion of 0.86). The authors therefore suggested that an ergogenic effect of CHO can be attributed to the prevention of hypoglycaemia and the maintenance of high CHO oxidation rates. However, not all studies that demonstrated a beneficial effect of CHO reported hypoglycaemia in the control trial (41, 59). Especially when running was chosen as the mode of exercise, plasma glucose concentrations appeared to remain comparatively constant with the ingestion of water (7, 86, 129). Hence in these studies the ergogenic effect of CHO cannot be attributed to a prevention of hypoglycaemia.

A further benefit of CHO ingestion during exercise could be attenuated liver glycogen utilization (9, 70). Jeukendrup *et al.* (70) showed that the ingestion of glucose (63 g/h) markedly suppressed hepatic glucose output, and high ingestion rates of 175 g/h completely suppressed endogenous glucose production during 120 min cycling at 50% VO_2max . Hepatic glycogen is the primary source of endogenous glucose to maintain plasma glucose concentrations during exercise. This means that the “sparing” of hepatic glycogen can ensure a supply of glucose at the end of exercise to sustain blood glucose concentrations and high CHO oxidation rates.

Whether or not CHO intake during exercise can “spare” muscle glycogen stores is still debated. The majority of studies did not measure a significant attenuation in muscle

glycogen use with the ingestion of CHO, using muscle biopsies (7, 24, 42-44, 52, 90) or stable isotope measures (70, 73). However, a small number of studies detected a significant muscle glycogen sparing effect with CHO intake (36, 53, 123, 131, 132). One of these studies compared the intake of a 10% CHO solution to a water placebo during 190-min intermittent cycling exercise (45 and 75% $\text{VO}_{2\text{max}}$) and detected significantly (35%) higher muscle glycogen concentrations after exercise with CHO ingestion (53). The authors speculated that, during the periods of lower-intensity exercise, CHO intake could have stimulated muscle glycogen re-synthesis. Two studies by Tsintzas *et al.* (131, 132), which detected a significant glycogen “sparing” effect, used a running protocol, and they proposed that muscle glycogen breakdown is reduced during running (130). They suggested that CHO ingestion leads to a more marked elevation in plasma insulin concentrations during running, which could cause increased muscle glucose uptake and reduced glycogenolysis. However, a study that compared both modes of exercise did not find a significant reduction in muscle glycogen use in running or cycling (7), and it remains to be established whether there is a difference between modes of exercise. In general, it seems that discrepancies between studies are likely to be due to differences in exercise mode, duration and intensity, training status and glycogen loading of the subjects, methods of measurements and CHO feeding protocol. However, it seems unlikely that CHO ingestion leads to a considerable attenuation in muscle glycogen utilization during prolonged moderate intensity exercise.

Although it seems plausible that increased oxidation of ingested CHO is linked to improved performance, direct evidence for this is lacking. Some evidence can be derived from dose-response studies that investigate different CHO intake rates on exercise performance. Even though those studies did not measure exogenous CHO oxidation, it can be assumed that

oxidation would increase with increasing intake (in the range used in these studies). However, the results from the dose-response studies are contradictory, and most studies failed to detect a dose-response effect (43, 86, 89, 90, 94, 95). For example, in a study by Mitchell *et al.* (90), CHO intakes of 34, 39 and 50 g/h during 2-h intermittent exercise resulted in similar times to complete an isokinetic TT at the end of exercise. In a study by Murray *et al.* (94), the consumption of glucose at intake rates of 26 g/h and 78 g/h significantly increased exercise performance (4.8-km TT; preceded by 2-h intermittent cycling at 65-75% $\text{VO}_{2\text{max}}$) compared with placebo, while no significant performance benefit was reported with the intake of 52 g/h. In another study from the same research group (43), similar volumes of three different CHO solutions (5% glucose; 6% glucose/sucrose and 7% glucose polymer/fructose) or a placebo were administered during intermittent cycling exercise (140 min at 55 and 65% $\text{VO}_{2\text{max}}$). A subsequent TT was completed significantly faster with the two 6% solutions compared with the 5% solution. Furthermore, a correlation between the CHO intake rate and performance was detected. The first study that measured exogenous CHO oxidation and exercise performance simultaneously found no difference in performance as the exogenous CHO oxidation rates increased in a cold ($\sim 10^{\circ}\text{C}$) environment (46). The intake of 2, 6 and 12% glucose solutions resulted in increased exogenous CHO oxidation rates, but no differences in cycling endurance capacity were detected compared with placebo or between CHO solutions. However, the exercise duration of about 90 min might be too short to benefit significantly from differences in exogenous CHO oxidation rates, which become relevant after about 45 min (67). This might also be the reason why a number of dose-response studies failed to detect differences in endurance performance (43, 86, 89, 90, 94, 95). In addition, the current performance measures may not be sensitive enough to measure potentially small

differences between varying doses. Indirect evidence that high exogenous CHO oxidation rates might be beneficial for prolonged endurance performance originates from two recent studies. Those studies (32, 128) linked the ingestion of CHO in the form of glucose and fructose with superior exercise performance compared with glucose alone. Currell *et al.* (32) demonstrated that ingestion of glucose + fructose (1.8 g/min) results in a significant 8% improvement in performance compared with glucose alone (40-km TT, preceded by 120 min of moderate-intensity cycling). Previously, the ingestion of a similar glucose + fructose solution was related to higher exogenous CHO oxidation rates compared with glucose alone (67). The higher exogenous CHO oxidation rates were also associated with a sparing effect in endogenous CHO stores (63, 69, 135). In conclusion, exogenous CHO oxidation along with the associated endogenous CHO sparing effect could lead to enhanced prolonged endurance performance, but further research is necessary to establish a direct link.

1.3 Exogenous CHO oxidation

Considerable evidence about the properties of different CHOs and CHO mixtures to be oxidized by the human body originates from tracer studies using stable (^{13}C) and radioactive (^{14}C) isotopes. Those studies have identified a number of factors that influence exogenous CHO oxidation rates, including the dose and type of CHO, which will be discussed in the following section. A number of questions, however, remain open, such as a possible difference in CHO availability from different CHO forms (such as gel or solid) or during different modes of exercise. Those questions will be addressed in **Chapters 3, 4 and 5** of this thesis.

1.3.1 Bioavailability of ingested CHO

It is known that the ingestion of very large amounts of CHO will not result in exogenous CHO oxidation rates >1 g/min (138). Understanding the possible limitations of exogenous CHO oxidation not only is important from a scientific standpoint but also to determine an optimal dosage of CHO for athletes. Exogenous CHO oxidation is potentially limited by gastric emptying, intestinal digestion and absorption, liver glucose extraction, muscle glucose uptake and oxidation, or a combination of these factors.

A substantial body of evidence, however, demonstrates that the capacity of the muscle to extract and oxidize CHO is most likely not rate limiting for the oxidation of ingested CHO. In a glucose infusion study, Hawley *et al.* (55) induced hyperglycemia (~ 10 mmol/L) in healthy subjects exercising at 70% VO_2max . Exogenous CHO oxidation rates in this study were reported to exceed 1 g/min, previously described as the upper limit of oxidation from ingested glucose. Further evidence was derived by Jeukendrup *et al.* (73), who measured the rate of glucose appearance in the systemic circulation with the use of stable isotope methodology during 120-min cycling at 50% Wmax . The authors reported that with the ingestion of a low dose of CHO (~ 0.43 g/min) the rate of glucose ingestion equalled the rate of appearance in plasma. In contrast, with a large dose of glucose (3 g/min), only about one-third (0.96-1.04 g/min) of the CHO was measured in the circulation. However, almost all of the CHO that appeared in plasma was subsequently taken up and oxidized (90-95%). It appears from these findings that the entry of CHO into the systemic circulation limits exogenous CHO oxidation, rather than the capacity of the working muscles to extract and oxidize glucose.

It might seem apparent that gastric emptying could determine oxidation rates. In a number of studies, high CHO concentrations were reported to limit gastric emptying rates (30, 93, 136). For instance, Vist *et al.* (136) compared the gastric emptying rates of an 18% CHO solution and a 4% CHO solution administered in a single 600-mL bolus. The gastric emptying rates of the more concentrated solution were significantly slower compared with the diluted drink. However, CHO delivery to the small intestines was still significantly higher with the 18% solution compared with the 4% drink. Furthermore, studies measuring exogenous CHO oxidation and gastric emptying simultaneously found that only up to about 50% of the CHO that was delivered to the small intestine was oxidized (56, 109, 118). A study by Rehrer *et al.* (109) measured exogenous CHO oxidation and gastric emptying simultaneously. The ingestion of 220 g CHO during 80 min cycling at 70% $\text{VO}_{2\text{max}}$ resulted in a CHO delivery of only 120 g to the small intestines. However, only 38 g CHO was found to be oxidized. The authors concluded that gastric emptying is not a major rate-limiting step for exogenous CHO oxidation (75, 109).

As a consequence, it has been speculated that absorption is most likely the bottleneck for the delivery of CHO to the muscle (75). Studies have repeatedly shown that exogenous CHO oxidation rates with the ingestion of glucose peak at high rates about 1 g/min (65, 67, 106). Even when very high rates of glucose (2.4 g/min) were administered, oxidation rates did not exceed 1.18 g/min (65). In contrast, when fructose is ingested in combination with glucose, 20-55% higher exogenous CHO oxidation rates can be reached compared with glucose alone (62, 63, 67, 69, 139). A study by Jentjens *et al.* (66) compared the intake of two different doses of glucose (1.2 and 1.8 g/min) with a combined intake of glucose (1.2 g/min) and fructose (0.6 g/min). Both glucose doses resulted in similar average exogenous

CHO oxidation rates (0.75 g/min), suggesting that the uptake of glucose was saturated. Co-ingestion with fructose led to similar mean exogenous glucose oxidation rates of 0.77 g/min. However, on top of oxidized glucose, mean exogenous fructose oxidation rates of 0.36 g/min were measured, resulting in ~48% higher mean and ~55% higher peak exogenous CHO oxidation rates (1.26 g/min) compared with both glucose doses (~0.8 g/min). It has been proposed that the high exogenous CHO oxidation rates from large intakes of glucose + fructose were the result of different transport mechanisms for glucose and fructose across the brush border membrane (but not the basolateral membrane). According to the classical model of absorption, glucose is actively transported via the sodium-dependent SGLT-1 transport protein from the intestinal lumen into the cytosol (31). In contrast, fructose is predominantly transported via GLUT-5, which exclusively binds to fructose (for review, see 140, 141). Hence, both monosaccharides use different carrier systems and do not have to compete for the same transport mechanism on the brush border membrane. The subsequent transport through the basolateral membrane of the enterocyte via GLUT-2 (for review, see 38) into the bloodstream is similar for both hexoses. Basolateral carriers, however, follow a concentration gradient, and therefore, the transport on the apical side of the enterocyte determines the potential for absorption.

However, recently an additional transport system for glucose and fructose has been suggested. Kellett *et al.* (for review, see 78) proposed that SGLT-1 transport saturates at 30-50 mM (0.5-0.9% glucose solution). According to Kellett *et al.* (78, 79), higher transport rates could be due to trafficking of basolateral GLUT-2 toward the apical membrane when higher glucose concentrations are present in the small intestine. This theory, however, is based on studies in rats, partly *in vitro*, and whether this finding is

relevant for humans is questionable. It is known that intact mucosa is needed for rapid up-regulation of glucose transporters (SGLT-1) by luminal glucose (120). Therefore, absorption of isolated rat mucosa might be limited compared with an *in vivo* situation.

In line with the theory that absorption via SGLT-1 transport limits exogenous CHO oxidation rates, a study by Hulston *et al.* (58) showed that exogenous CHO oxidation rates from ingestion of glucose + fructose at low rates (0.8 g/min glucose: 0.54 g/min and fructose: 0.26 g/min) was not different compared with glucose. The ingestion rates of glucose were below 1.1 g/min, which had previously been postulated as the saturation rate of the SGLT-1 transporter in humans (64). Consequently, replacing glucose with fructose was not advantageous over the ingestion of single glucose at those low ingestion rates.

In summary, it is most likely that exogenous CHO oxidation is limited by the rate of the intestinal absorption of a CHO or CHO mixture.

1.3.2 The optimal CHO

1.3.2.1 Glucose and glucose polymers

The most widely studied CHO during exercise is glucose, which has been shown to be oxidized at high rates, up to about 1.1 g/min (65, 67, 106). Similarly, high exogenous CHO oxidation rates have been shown with the ingestion of most glucose polymers.

A number of studies have shown that the ingestion of maltose is as effective as glucose intake (56, 64). Hawley *et al.* (56) investigated the oxidation of 180 g maltose or glucose during 90 min of cycling at 70% VO_2max . Similarly, high peak oxidation rates (0.9 g/min and 1.0 g/min for glucose and maltose, respectively) were reached at the end of exercise. In

an additional study, co-ingestion of glucose and maltose (1.2 and 0.6 g/min, respectively) resulted in similar exogenous CHO oxidation rates (1.06 g/min) compared with ingestion of an isoenergetic glucose solution (1.8 g/min) (64). The authors suggested that digestion of the disaccharide maltose via maltase-glycoamylase occurs rapidly, and arising glucose would compete for the same intestinal transporters as described before. Accordingly, Wagenmakers *et al.* (138) demonstrated that the ingestion of maltodextrin results in similar exogenous CHO oxidation rates as previously reported for glucose. The ingestion of maltodextrin at rates of 0.6 and 1.2 g/min elicited exogenous CHO oxidation rates of 0.53 and 0.89 g/min, respectively. Further increase of the intake, however, had little effect on exogenous CHO oxidation rates, and a plateau was reached at about 1 g/min (67).

Ingestion of high-molecular-weight glucose (98-99% amylopectin waxy maize starch; molecular weight 500,000-700,000 g/mol) was compared with that of glucose in a study by Rowlands *et al.* (116). It has been demonstrated that amylopectin results in similar peak exogenous CHO oxidation rates compared with glucose (0.93 g/min). Saris *et al.* reported that naturally occurring cornstarch, however, is oxidized at about a 30% lower rate compared with glucose (118). The cornstarch used in this study contained 24% amylose and 76% amylopectin, and studies have shown that amylose is digested less rapidly than amylopectin (99, 121), which most likely determined the lower oxidation rates.

In summary, glucose and glucose polymers (with the exception of amylose-containing starch) are oxidized at high rates and therefore seem to be appropriate choices for ingestion during exercise.

1.3.2.2 Other carbohydrates (fructose, galactose, trehalose, isomaltulose)

Unlike glucose, other CHOs have shown comparatively low oxidative properties when ingested during exercise. A number of studies have investigated the oxidation of ingested fructose during exercise and reported lower exogenous CHO oxidation rates compared with glucose. A recent study reported only 4% lower exogenous CHO oxidation with the ingestion of fructose (11), whereas the majority of studies reported ~20-25% lower oxidation rates (5, 61, 84). For example, a study by Adopo *et al.* (84) investigated the oxidation of ingested glucose and fructose during 120 min of steady state cycling at 60% VO_2max . The ingestion of 50 g or 100 g of either fructose or glucose resulted in about 17% and 27% lower oxidation rates, respectively, from exogenous fructose. Even lower oxidative properties have been demonstrated with the ingestion of galactose. Leijssen *et al.* (81) reported about 50% lower exogenous CHO oxidation rates with the ingestion of galactose compared with glucose (ingestion rate: 0.89 g/kg bodyweight/h; ~1.1 g/min) during 120 min of cycling at about 60% Wmax . This finding was confirmed only recently by a study by Burell *et al.* (11), which reported about 40% lower exogenous CHO oxidation rates when galactose and glucose were ingested at rates of 0.83 g/min. Other CHOs have aroused interest, because common sports drinks based on glucose, sucrose and fructose have been associated with dental erosion and plaque formation (87, 88). In contrast to those CHOs, isomaltulose or trehalose is not fermented in the oral cavity, leading to reduced acid production and a less erosive effect on teeth (82, 96). However, ingestion of isomaltulose (1.1 g/min) produced relatively low exogenous CHO oxidation rates (0.54 g/min), which were 43% lower compared with isocaloric ingestion of sucrose (0.94 g/min). The authors suggested that the lower oxidation rates were caused by slow hydrolysis of the disaccharide in the small intestine. Most recently, a study by Venables *et al.* (135) investigated the

oxidative properties of trehalose compared with maltose. In that study, both CHOs were ingested at a rate of 1.1 g/min, resulting in about 27% lower oxidation rates from trehalose compared with maltose, possibly again due to relatively slow hydrolysis (33, 34).

In conclusion, other CHOs such as fructose, trehalose, isomaltulose and galactose are oxidized at lower rates compared with glucose and may therefore be inferior sources of CHO during exercise.

1.3.2.3 Oxidation of CHO mixtures

As previously mentioned, the combined ingestion of multiple transportable CHOs can lead to superior exogenous CHO oxidation rates compared with single CHOs. The first study to investigate a simultaneous ingestion of glucose + fructose was conducted by Adopo *et al.* (5). In this study, 100 g CHO was administered at the beginning of 120 min moderate intensity cycling (60% VO_2max) and consisted of glucose, fructose or glucose + fructose (in a ratio of 1:1). The average exogenous CHO oxidation rates were demonstrated to be significantly (~21%) higher for the glucose + fructose treatment compared with glucose or fructose alone. The exogenous CHO oxidation rates in this study, however, were generally low (glucose: ~30 g/h and fructose: ~36 g/h). In an attempt to maximize exogenous CHO oxidation rates, our laboratory conducted a series of studies. From those studies, we can conclude that the ingestion of glucose + fructose (>1.5 g/min) during moderate-intensity cycling leads to 20-55% higher exogenous CHO oxidation rates compared with glucose (62, 63, 67, 69, 139). At present, the highest exogenous CHO oxidation rates (1.75 g/min) have been demonstrated with the ingestion of 2.4 g/min glucose + fructose (1:1) (62).

Accordingly, blends of GLU and sucrose or glucose, fructose and sucrose have been identified to result in ~20-55% higher exogenous CHO oxidation rates compared with glucose alone (64, 65).

1.3.3 The optimal dose

The optimal dose of CHO to maximize exogenous CHO oxidation rates highly depends on the bioavailability of the ingested type of CHO. Building upon the accumulated knowledge about absorption rates of various CHOs, we can conclude that with the ingestion of glucose alone absorption rates peak at ~1 g/min (64, 138). Hence, the optimal amount of glucose to ingest during prolonged exercise is approximately 1 g/min. An advantage over glucose alone ingestion can be expected with the ingestion of multiple transportable CHOs (e.g., glucose + fructose). Theoretically, the optimal ingestion rates of glucose + fructose consist of about 1 g glucose/min with additional fructose. A series of previous research studies from our laboratory (58, 66, 67, 69) suggests that increasing the amounts of glucose + fructose will result in increasing exogenous CHO oxidation rates (see Figure 1.1).

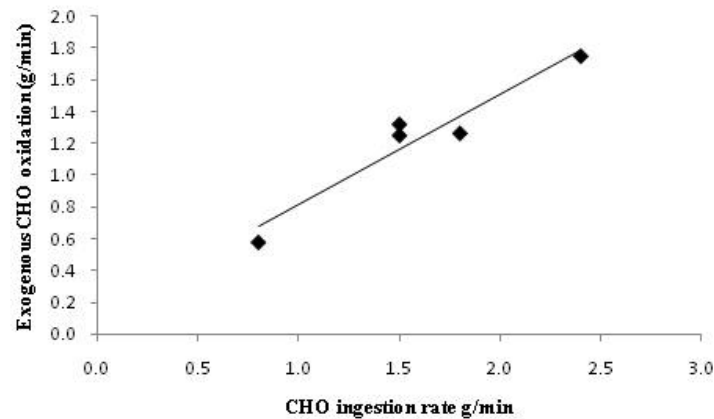


Figure 1.1 Exogenous CHO oxidation rates from glucose + fructose ingestion as a function of CHO intake rates from different studies during moderate intensity exercise (66, 67, 69, 139).

As previously mentioned, very high intakes of glucose + fructose (1:1; 2.4 g/min) produced the highest exogenous CHO oxidation rates of 1.75 g/min (62). However, gastrointestinal distress (GI) has been reported frequently in trials with such high CHO intake rates (62, 128), which might limit CHO intake to lower rates in a practical situation. Residual CHO in the GI tract has been linked to the occurrence of GI distress (62), and therefore, determining a CHO dosage that maximizes exogenous CHO oxidation rates without delivering large amounts of excess CHO that remains in the GI tracts is important. As a measure of how much of the ingested CHO is actually oxidized, the term oxidation efficiency was introduced, which expresses the % of ingested CHO that was actually oxidized (75). To summarize the research on exogenous CHO oxidation rates with different CHO intake rates in the form of glucose + fructose from our laboratory, it appears that CHO intake rates of about 1.5 g/min result in high peak exogenous CHO oxidation rates (~1.4 g/min) and high oxidation efficiencies (% of ingested CHO that was oxidized) of

~77%, without the occurrence of GI distress (74). Furthermore, a study that compared glucose + fructose with glucose ingestion at a rate of 1.5 g/min reported that subjects managed to maintain their cadence better and their scores for perceived exertion tended to be lower with glucose + fructose (69). This study indicates that glucose + fructose is more effective in delaying fatigue compared with glucose at an intake rate of 1.5 g/min, and the authors concluded that this CHO intake rate should serve as a starting point for recommendations (74).

However, research on the tolerance of such high CHO doses in the field is still missing, and this question is addressed in **Chapter 2**.

1.3.4 The optimal form of CHO

One additional practically relevant question for athletes is, whether there is a difference when CHO is ingested in solid (e.g. energy bar) or semi-solid (e.g. gel) form. Both CHO sources are commonly used by athletes during endurance events such as marathons, cycling races or triathlons (54). However, only a few studies have investigated the effect of solid CHO or solid CHO-rich food on metabolism during exercise and endurance performance. Studies have shown increased performance with the ingestion of solid CHO compared with a placebo (14, 42, 53) and similar performance improvements, when the same amount of CHO was ingested in the form of solids compared with liquids (14, 42, 53, 92). Accordingly, evidence about ingestion of semi-solid CHO gels is scarce. A study by Campbell *et al.* (14) compared the effect of CHO ingestion in liquid, solid (jelly beans) and semi-solid (gel) form on prolonged cycling performance: 80 min of cycling at 75% VO_2max with the ingestion of CHO was followed by a 10-km time-trial, and no difference

between treatments was detected. Accordingly, there is some evidence that CHO intake in semi-solid or solid form has an effect on exercise performance. However, studies investigating different forms of CHO intake were generally rather short (up to 2 h), and exogenous CHO oxidation rates from other forms than solution have never been investigated. **Chapters 3 and 4** will therefore investigate CHO ingestion in solid or semi-solid form.

1.4 Gastrointestinal (GI) tolerance of high CHO intake rates

Physical exercise *per se* is associated with changes in the GI tract, such as a reduction in mesenteric blood flow, changes in GI motility, alterations in levels of GI-related hormones and occurrence of GI distress (10, 101, 104, 113). The intake of CHO has been linked to altered GI distress (12, 102) during exercise, which can ultimately reduce performance (12, 127). Hence, it is apparent that GI tolerance of CHO has to be taken into account when giving advice to athletes, and **Chapter 2** of this thesis is dedicated to giving insight into tolerance of different CHOs and CHO doses during exercise.

1.4.1 Prevalence of GI problems during exercise

It is widely accepted that GI symptoms occur frequently during exercise. However, the reported prevalence of GI symptoms varies in different studies (10-87%; (77, 111, 124)) depending on the assessed GI symptoms, method of investigation, study population, sex, age and training status of the athletes as well as the mode and intensity of the exercise studied.

The etiology of GI symptoms during exercise is also far from clear. First, it is difficult to study the GI tract function directly during exercise, as invasive methodology such as enteroscopy, small-bowel biopsies or endoscopic ultrasound become virtually impossible when subjects are exercising. Consequently, studies investigating the prevalence and risk factors of GI distress during exercise rely predominantly on questionnaires that evaluate different symptoms of the upper abdominal tract (such as belching, bloating, nausea, stomach cramps and vomiting) and the lower abdominal tract (such as intestinal cramps, urge to defecate and diarrhoea) (72, 102, 134). However, several limitations are associated with this measure. First, the assessment of symptoms by the athlete is subjective, and an individual predisposition for GI symptoms is thought to exist (77), resulting in large inter-individual differences. Hence, results from studies with small numbers of subjects become difficult to generalize. Furthermore, to date no standardized questionnaire has been published. Thus, a comparison between studies that use different questionnaires and varying statistical approaches is problematic. In some studies, symptoms are reported as present, irrespective of how severely the subjects rated the symptoms. A number of symptoms *per se* can be rated as less severe than others; for example, reflux is less likely to impair performance compared with diarrhoea. This has been taken into account in some (72, 108) but not in all studies.

To give further insight into links between nutritional intake habits and GI distress, **Chapter 6** of this work is designed to use the same methodology to study a large number of athletes competing in different events.

1.4.2 Factors linked to a high prevalence of GI problems during exercise

Several personal characteristics have been linked to a higher prevalence of GI distress during exercise. Females have repeatedly been documented to be more likely to experience GI distress than males (101, 102). Younger athletes also appear to be more susceptible to GI problems than older athletes (77, 102), which might be due to increased years of training as well as a better experience in terms of the right feeding strategy in older athletes or the drop-out of people who experience problems frequently within a sport (10). Moreover, training status has been reported to be negatively correlated with the incidence of GI distress, raising an interesting question whether it is possible to train the GI tract. Unfortunately, answering this question is not possible within the scope of this doctoral thesis, and the subject remains an area of future research.

Important factors that influence the occurrence of GI distress are type, duration and intensity of the exercise an athlete is undertaking. Exercise intensity (77, 124), duration (102, 107) and mode of exercise (102) have been linked to the incidence of GI distress in questionnaire-based field studies. The influences of exercise mode and duration on the prevalence of GI symptoms were also compared in a controlled laboratory setting by Peters *et al.* (103). In that study, 32 male triathletes were requested to exercise for a total of 3 h, consisting of about 45 min alternating bouts of running and cycling at about 75% of the exercise-specific VO_2max . The authors showed that the prevalence of GI distress increased with the exercise duration, but the incidence was also higher during running compared with cycling. The fact that athletes experience more GI problems in a race situation than in training (102) could again be due to higher exercise intensities, but an additional factor that

sets race day apart from training is anxiety. Emotional stress is associated with an inhibition of gastric emptying and stimulation of colonic motor function (125) and consequently could exaggerate GI problems during exercise. Furthermore, several studies have linked increasing levels of dehydration with GI problems that occur during exercise (97, 107). Exercise can cause a reduction in mesenteric blood flow of up to 80% (18), and authors have speculated that increasing levels of dehydration can further impair blood flow to the gut and thereby lead to GI distress (10).

In addition to exercise-induced GI problems, race nutrition and medication can exaggerate or cause GI problems. A high fat and fibre intake have both been identified as a potential cause for GI distress during exercise. Resting studies have shown that the digestion of a solid meal, containing fat and/or fibre, can delay gastric emptying (45, 51), and delayed gastric emptying rates have been linked to GI distress (106).

1.4.3 CHO intake and GI tolerance

Studies have repeatedly documented a correlation between the intake of CHO during exercise and GI distress (102, 108). Especially the ingestion of hypertonic drinks has been associated with a higher prevalence of GI distress (102). Thus far, only two field studies have directly investigated the effect of CHO intake on GI tolerance and race performance in a placebo-controlled, cross-over design. A study by van Nieuwenhoven *et al.* (134) investigated the ingestion of 600 mL of a 6.8% CHO sports drink compared with a similar volume of water during an 18-km run. The frequency and severity of 11 different upper and lower abdominal symptoms were evaluated in a post-race questionnaire. A higher frequency of nausea and flatulence was reported with ingestion of the sports drink.

However, the results need to be interpreted with caution as the subjects were not blinded. Furthermore, CHO intake within this study was only ~26 g/h (~0.43 g/min), and no conclusions about tolerance of higher doses can be made. In a cross-over-designed study by Burke *et al.* (12), 18 trained males received either a CHO gel at an intake rate of ~1 g/min or a water placebo. GI complaints as well as half-marathon performance were compared. No GI problems were recorded with ingestion of water, whereas 3 (15%) runners experienced GI problems with ingestion of gels. Interestingly, the improvement in performance with the CHO gel was trivial in this study, whereas the performance of the subjects experiencing GI problems was impaired by about 2.4%.

In theory, a link between CHO intake and GI distress seems rather logical, as residual CHO in the lower intestine can result in GI distress, most likely as a result of water retention in the gut due to a higher osmotic load (22, 105, 117). In addition, fermentation by bacteria in the gut can lead to gas production as well as to the production of fatty acids that might lead to higher motility of the gut (17). In contrast, multiple transportable CHOs such as glucose and fructose possess different absorptive properties compared with glucose. Hence, it could be speculated that, due to more effective absorption and less remaining CHO in the GI tract, tolerance of those CHOs would be superior compared with glucose. Oxidation efficiency (% of ingested CHO that was oxidized) of multiple transportable CHOs is higher compared with glucose, and in theory, tolerance should be better, too. An indication that this might indeed be the case was given in previous studies that compared exogenous CHO oxidation from glucose and multiple transportable CHO. Those studies reported either no difference between trials (64) or more severe GI distress with glucose compared with multiple transportable CHO (63, 65, 67, 139). Furthermore, in an ultra-endurance cycling

study (5 h; ~58% $\text{VO}_{2\text{max}}$), the subjects reported to be less full with the ingestion of glucose + fructose (1.5 g/min) compared with an isocaloric glucose drink (69). However, as only 8 subjects were investigated in each of the studies, these results have to be regarded with caution.

The question whether there is a difference between the ingestion of CHO in the form of multiple transportable CHOs compared with single glucose is addressed in **Chapter 2**.

1.5 Metabolic difference between running and cycling

The vast majority of studies investigating the effect of CHO on exercise performance and metabolism were conducted in cycling, and it is not clear whether the findings from studies in cycling can be extrapolated to running. The movement and muscle recruitment patterns of the two types of exercise are clearly different (8, 50). While running involves the whole body, cycling exercise predominantly involves the quadriceps, and only comparatively little force is generated by the rest of the body. Additionally, cycling involves concentric muscle contraction, while running also comprises eccentric contractions (39). Possibly as a consequence of stored elastic energy during eccentric exercise, studies have reported that running exhibits greater delta efficiency compared with cycling (8). Considering those differences in movement patterns, it is not surprising that differences in energy metabolism have been suggested (1, 7).

To date, only a limited number of studies have directly investigated differences between running and cycling, and the results from those studies are somehow equivocal. One main reason for different findings among studies could be that findings are confounded by

different exercise intensities. It is well-known that substrate metabolism highly depends on the intensity of exercise (115, 133), and therefore, whether differences that occur in metabolism are a result of varying modes of exercise or rather differences in exercise intensity must be reviewed critically. The majority of studies that compared metabolism during running and cycling did so by matching exercise intensity at % VO_2max . Another approach, which was used in a study by Arkinstall *et al.* (7), is to match exercise intensity at the % lactate threshold. The lactate threshold in equally and well-trained subjects is normally found at a higher percentage of VO_2max during running compared with cycling and elicited exercise intensity of 78% VO_2max during running compared with 69% during cycling. An elegant way to avoid possible differences, linked to exercise intensity, is the use of a graded exercise protocol. However, the use of a graded protocol is limited in terms of measurements. For example, tracer methods require the occurrence of a steady state, which in the case of ^{13}C arises only after about 1 h and makes the use of a graded exercise model impossible.

Several differences in substrate metabolism have been suggested for running and cycling. It has repeatedly been proposed that fat oxidation rates are higher during running compared with cycling (1, 37, 57, 98). In contrast, the study by Arkinstall *et al.* (7) did not detect differences in RER and fat oxidation rates during 60 min of continuous cycling and running at the lactate threshold. However, the most complete picture can be derived from studies that use a graded exercise protocol and measured substrate metabolism over a wide range of intensities. Higher fat oxidation rates during running compared with cycling were measured in a number of studies (1, 122, 126). For example, Achten *et al.* (1) measured substrate oxidation over a wide range of intensities (50-70% VO_2max) and reported higher fat

oxidation rates during uphill walking compared with cycling. It seems therefore likely that total fat oxidation rates indeed tend to be higher during running compared with cycling at moderate exercise intensities.

It has also been speculated that muscle glycogen metabolism might vary between modes of exercise. The potential of CHO to spare muscle glycogen has been measured in a large number of studies during cycling. Only a small number of studies detected a significant attenuation in glycogen usage with CHO intake (53, 123), while the majority of studies failed to detect a significant muscle glycogen sparing effect (9, 42, 43, 70, 76). Conversely, the first studies in runners by Tsintzas *et al.* (131, 132) reported a 25% reduction in muscle glycogen utilization that was specifically attributed to a sparing in type I muscle fibres. The authors assumed that the glycogen sparing effect with CHO ingestion is greater during running compared with cycling (130). This hypothesis, however, was based on studies investigating a single mode of exercise (running or cycling) at different exercise intensities and durations. Furthermore, CHO intake rates and methods of glycogen measurement differed among the studies. A direct comparison was made in the aforementioned study by Arkinstall *et al.* (7). This study failed to detect a sparing in mixed muscle glycogen during 60 min of running and cycling. However, even though they were unable to detect a statistically significant difference, muscle glycogen utilization during running was about 20% reduced with CHO feeding. Therefore, it remains to be established whether glycogen utilization is indeed different during running compared with cycling.

Along with the hypothesis that muscle glycogen “sparing” with CHO ingestion is greater during running, it was proposed that the underlying mechanism is a more pronounced

elevation in blood glucose and insulin concentrations in running compared with cycling (130). This statement, however, was based on studies investigating CHO ingestion during cycling or during running alone, rather than on a direct comparison. A study by Arkinstall *et al.* (7), which directly compared the ingestion of a 6.4% CHO solution during 60 min running or cycling at the individual lactate threshold, reported higher plasma insulin concentrations during running after 20 min. However, the areas under the curve for plasma glucose and insulin did not differ among modes of exercise.

To date, only one study has directly compared the oxidation of ingested CHO during running with that during cycling. Derman *et al.* (37) measured similar peak exogenous CHO oxidation rates during running and cycling at ~80% $\text{VO}_{2\text{max}}$ after 60 min of exercise. However, peak exogenous CHO oxidation rates from glucose ingestion of ~100 g/h (1.7 g/min) were only ~0.40 g/min in both CHO trials, and those very low exogenous CHO oxidation rates are most likely due to methodological limitations with the use of radioactive isotopes (^{14}C -glucose). When the ^{14}C tracer is metabolized, some of the arising $^{14}\text{CO}_2$ will be temporary trapped in the bicarbonate pool. However, during exercise CO_2 production increases several-fold so that a physiological steady state condition will occur relatively rapidly, and $^{14}\text{CO}_2$ in the expired air will equilibrate with the $^{14}\text{CO}_2/\text{H}^{14}\text{CO}_2$ pool, respectively. However, complete recovery of $^{14}\text{CO}_2$ will approach only after ~60 min of exercise (100, 112), which is why usually calculations on exogenous CHO oxidation are made after the first hour. Considering those limitations, conclusions from the study are limited. However, two studies measured high exogenous CHO oxidation rates during running and provided indirect evidence that ingestion of CHO can produce comparable exogenous CHO oxidation rates as during cycling (23, 60). In a study by Jandrain *et al.*

(60), exogenous CHO oxidation was investigated during 3 h of running at 45% $\text{VO}_{2\text{max}}$, and the ingestion of glucose at an intake rate of 0.83 g/min resulted in peak exogenous CHO oxidation rates of 0.81 g/min, which equals an oxidation efficiency of 98%. Furthermore, a study by Couture *et al.* (23) investigated glucose ingestion of 2 g/min during 120 min running at ~69% $\text{VO}_{2\text{max}}$ and measured peak exogenous CHO oxidation rates of 1.2 g/min, which is comparable to previous measures during cycling.

However, a direct comparison of the CHO oxidation from ingested CHO during prolonged endurance exercise is still missing, and the extrapolation of data on exogenous CHO oxidation from cycling studies to endurance running events needs justification. Consequently, **Chapter 5** of this work directly compares exogenous CHO oxidation during running and cycling.

1.6 Recommendations for CHO intake during competition

The beneficial effects of CHO intake during exercise are widely accepted; however, the optimal dose and form of CHO intake are still being debated. The following section of this introduction will therefore give an overview of some of the current recommendations for CHO intake during endurance exercise.

1.6.1 ACSM, IOC and IAAF recommendations

The most commonly accepted recommendations for CHO intake during exercise are published in a joint position stand by the American College of Sports Medicine (ACSM), the American Dietetic Association and Dietitians of Canada (2, 3). The current position stands of ACSM (2, 3), the International Olympic Committee (IOC; (13, 26)) and the International Association of Athletics Federations (IAAF) state, that, during intense

exercise lasting longer than 1 h, the intake of CHO at ingestion rates of 30-60 g/h is beneficial for performance (25). The first position stand of the IOC was published in the early 1990s (27) and stated that “sufficient CHO should be ingested to supply the blood with approximately 1 g/min, late in exercise.” It was argued that the majority of studies that measured a performance effect administered CHO at rates of 30-60 g/h, and this should therefore serve as a starting point for recommendation. The first position stand of the American College of Sports Medicine (ACSM), published in 1996 (21), also stated that CHO should be ingested at intake rates of 30-60 g/h, however, with a slightly different argument. The main aim of this position stand was to prevent athletes from excessive dehydration (>2% bodyweight loss), and CHO ingestion was only a secondary benefit. Increasing the CHO content of a beverage (>10%) was documented to increase the CHO delivery rate but decreased fluid delivery (85, 91, 110, 137). Therefore, the recommended intake rate equals the ingestion of a 4-8% CHO solution at a rate of 600-1200 mL/h, reported to be possible to empty from the stomach by most individuals (25).

More recent IOC recommendations (13, 26) included the fact that ingestion rates of about 1 g/min (60 g/h) of glucose or maltodextrin lead to maximum exogenous CHO oxidation rates and larger intakes do not further increase exogenous CHO oxidation rates (138). The current ACSM position stand still recommends a similar CHO dosage, however, expressed in g/kg BW (0.7 g CHO/kg bodyweight/h). The recommendation also states that athletes should ingest glucose or a mixture of CHOs rather than fructose. However, more recent research that showed that CHO mixtures can have an advantage over single CHO ingestion during prolonged (>2 h) events is not considered (32, 128). It could be argued that those studies used concentrated drinks (>10%), which might impair fluid delivery. However, a

study by Davis *et al.* (35) showed that the gastric emptying rates of a 10% glucose + fructose solution were similar to a 6% maltodextrin solution and to water. A more recent study compared gastric emptying rates and fluid delivery rates of water, a glucose and a glucose + fructose solution (both 8.5%) with the use of three different techniques (dye dilution, ^{13}C -acetate tracer and deuterium tracer). Similar gastric emptying and fluid delivery rates were reported for the glucose + fructose solution compared with water, while an isoenergetic glucose drink significantly suppressed both. Those studies give some indication that multiple transportable CHOs do not impair fluid delivery in the same way as single CHOs, and the current recommendations might need revisiting.

1.6.2 New alternative recommendation

A new alternative recommendation (68, 71) has recently been published and primarily focuses on CHO intake during prolonged (>2 h) endurance events. This recommendation stated that the beneficial effect of CHO during those prolonged events primarily depends on the oxidation of ingested CHO. In this respect, the guideline follows a similar argument as described earlier in this introduction. The recommendation in the new guidelines therefore exceeds the ACSM guidelines and advises serious and well-trained endurance athletes involved in exercise of more than 2 h of duration should take in larger amounts of up to 90 g CHO/h (1.5 g/min), especially in the form of multiple transportable CHO (e.g. glucose + fructose). However, there remain concerns in some situations, regarding the practicality and suitability of such high CHO doses. One could argue that a CHO intake recommendation according to bodyweight would be more suitable, considering possible differences between the body size and weight of athletes. However, it was argued that variations in measures of exogenous CHO oxidation in previous research are generally rather small (standard

deviations ~10%) (65, 67, 69, 139), and therefore a large variation relative to body mass is not likely. Furthermore, there remain the concerns that those high CHO intakes are not tolerated very well in a field situation. As stated earlier, similarly high CHO intake rates might not be reached during running or when other forms of CHO such as solid bars or semi-solid gels are ingested. Those questions will be addressed in this doctoral thesis.

1.7 Nutritional practices of athletes during endurance events

It has been mentioned already that recommendations for CHO intake during exercise are largely based on laboratory research. Our knowledge about the nutritional intake habits of athletes during competitions is very limited, and it is not clear whether athletes are able to match recommendations. The final part of this introduction will therefore give an overview of the research studies documenting nutritional intake habits and especially CHO intake during events.

1.7.1 Limitations of nutritional surveys during competition

Similar to studies investigating GI problems during exercise, nutritional intake surveys are primarily questionnaire or interview based, and some methodological limitations have to be considered when interpreting and comparing surveys. It is clear from previous studies that nutritional intake habits are extremely individual (40, 54, 80). Consequently, relatively large subject numbers must be investigated. The majority of studies (see Table 1.1), however, has investigated subject numbers below 20, and one needs to be cautious when generalizing the findings. On the other hand, it is possible to tightly control smaller subject numbers, and some of those studies have used personal interviews during the races in order to ensure more precise measurements. The downside when larger subject numbers are

investigated is that the only feasible method of investigation is a retrospective interview or questionnaire based on household measures. The challenge for an athlete then becomes to remember what he or she actually consumed during the course of the event. This is especially difficult regarding exact estimates of ingested fluid volume and becomes increasingly difficult with the progressing duration of the race or when races become tactical such as during road cycling. Considering the common CHO concentration in sports drinks (4-6%), errors in fluid intake can also lead to substantial errors in CHO intake estimations.

Additionally, anecdotal evidence suggests that ambient conditions have an influence on the nutritional intake habits of athletes. In some studies, however, no reference to ambient temperature is made.

Furthermore, thus far all nutritional investigations focused on a single event, and drawing conclusions from one sporting event to another may not be possible. A retrospective, questionnaire-based study (102) reported different food and fluid intake habits during competition between triathletes and runners. Moreover, a higher frequency of GI problems during running compared with cycling (103) could lead athletes to different nutritional strategies. Consequently, the question whether athletes have distinct nutritional habits while competing in different events will be addressed in **Chapter 6**.

1.7.2 Current knowledge about CHO intake of athletes during events

A number of surveys have investigated athletes' CHO and fluid intake during events, and the main studies are summarized in Table 1.1.

Table 1.1 Overview of studies, investigating nutritional intake habits of endurance athletes during competition.

Authors	Sport	Event/ Distance	Survey Method	Subjects	Exercise time (h:min)	Ambient temperature	CHO intake	Fluid intake
Saris <i>et al.</i> 1989	Cycling	Tour de France (3 weeks)*	food diary questionnaires	5 m	5:14	n.a.	94 g/h	6700±200 mL/d
Garcia Roves <i>et al.</i> 1998	Cycling	Tour de France (3 stages)*	food diary questionnaires	10 m	n.a.	n.a	25g/h (10-43 g/h)	~1250 mL/d
Havemann <i>et al.</i> 2008	Cycling	Road race (210 km)	food diary questionnaires	45 m	7:18 ± 1:03	28-30 °C	63±23 g/h (28-145g/h)	600±178 mL/h (282- 1.167 mL/h)
Kimber <i>et al.</i> 2002	Triathlon	Ironman	7 interviews during race	18 (10 m/8f)	m: 12:00±0:36 f: 12:36±0:54	21 °C	m: 82 g/h ^f f: 62 g/h ^f	m: ~763 mL/h ^f f: ~628 mL/h ^f
Colombani <i>et al.</i> 2002	Multisport	Gigathlon (244km)	questionnaires before/after; interview at transition/finish	12	18:36 (17:00-19:48)**	n.a.	60 g/h (36-90 g/h) **	560 mL/h (310-790 mL/h) **
Glance <i>et al.</i> 2002	Running	Ultramarathon (160 km)	interview during race (every 13 km)	19 (18 m/1f)	24:18	n.a.	50 g/h	765 mL/h
Glance <i>et al.</i> 2002	Running	Ultramarathon (160 km)	interview during race (every 13 km)	26 (21 m/5f)	26:12±3:36	up to 38 °C	54 g/h***	740 mL/h***
Fallon <i>et al.</i> 1998	Running	Ultramarathon (100km)	dietary record by investigators during event	7 m	10:29	2-17 °C	43±16 g/h	540±210 mL/h
Zimberg <i>et al.</i> 2008	Adventure race*	Laboratory simulation (477km)	dietary record by investigators during event	10 m	67:00	n.a.	~36 g/h	n.a.

* Pro athletes, ** values are median + range *** calculated for 16 finishers

In professional cycling, a study by Garcia Roves *et al.* (47) reported the average CHO intake of 10 cyclists at the Vuelta a España to be only 25 g/h. In contrast, Saris *et al.* (119), reported the average CHO intake rates of five cyclists during the Tour de France to be as high as 94 g/h. One difference that appears striking between those two studies is the large variation in fluid consumption. While Saris *et al.* reported an average fluid intake of 6.7 L during the race, Garcia Roves *et al.* reported only 1.26 L. Hence, possible over- or underestimations in fluid intake might have lead to this discrepancy. A recent study investigated the nutritional intake of 45 male cyclists during a 219-km amateur road race (54), with the use of food questionnaires straight after the race. Average CHO intake was reported to be 63 g/h and consisted of a mixture of solid, semi-solid and liquid CHO forms. General conclusions about cyclists' nutritional intake, however, cannot be drawn from those studies as the protocol, athletes' level and environmental conditions varied considerably. A well-controlled study by Kimber *et al.* (80) investigated the nutritional intake of 18 triathletes during an Ironman. The investigators were able to interview participants on the race course and in the transition area and reported a relatively high CHO intake of ~82 g/h in 10 male triathletes and a lower intake of ~62 g/h in females. Conversely, in ultra-endurance runners lower CHO intakes (between 45-55 g/h) have repeatedly been documented (40, 48, 49).

It could be speculated from those studies that the majority of athletes during endurance events are able to match or even exceed the ACSM guidelines. It could also be speculated that runners tend to take in less CHO compared with cyclists and triathletes, potentially due to a higher risk for GI problems. To clarify whether athletes achieve recommendations and whether there are differences between different sporting events, a large field study with the same methodology is described in **Chapter 6**.

1.8 Aims of the present thesis

The aim of the present thesis was to answer several questions needed to fine-tune CHO feeding strategies during exercise:

- To investigate whether high CHO intake rates, which were previously studied in the laboratory and recommended to athletes, are tolerable during an outdoor running event (**Chapter 2**)
- To investigate whether different CHO blends (GLU vs. GLU+ FRC) are tolerated differently during an outdoor running event (**Chapter 2**)
- To determine whether different forms of CHO intake, such as semi-solid CHO gels or solid CHO bars are as effectively oxidized as previously studied CHO drinks (**Chapter 3 and 4**)
- To examine whether ingested CHO is oxidized as efficiently during running compared with cycling (**Chapter 5**)
- As it is not known whether athletes manage to meet current recommendations during different endurance events, the aim of **Chapter 6** was to quantify and characterize nutrient intakes of athletes during endurance competitions

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Chapter 2

The Effect of Carbohydrate Gels on Gastro-intestinal Tolerance during a 16-km Run

2.1 Abstract

High intake of glucose + fructose (>1 g/min; GLU+FRC) during exercise has been shown to increase exogenous carbohydrate (CHO) oxidation and performance compared with glucose (GLU). However, high CHO intakes have also been linked to gastrointestinal (GI) symptoms during exercise and little is known about GI tolerance of different CHO blends.

Purpose: Study 1: Investigate GI tolerance of CHO gels delivering GLU+FRC at different intake rates during intense running. Study 2: Investigate tolerance of high intakes of GLU+FRC versus GLU gel. **Method:** Both studies used a randomized, two-treatment, two-period cross-over design: Endurance trained males and females (study 1: 26 male, 8 female; 37 ± 11 y; 73 ± 9 kg; 1.76 ± 0.07 m; study 2: 34 male; 14 female; 35 ± 10 y; 70 ± 9 kg; 1.75 ± 0.09 m) completed two 16-km outdoor runs. In study 1 gels were administered to provide 1.0 gCHO/min (MOD) or 1.4 gCHO/min (HIGH). Water was provided *ad libitum* every 3.2 km. In study 2 GLU or GLU+FRC gels were given in a double-blind manner to provide 1.4 gCHO/min. In both studies a post-exercise questionnaire assessed 17 symptoms on a 10-point scale from 0 ("no problem at all") to 9 ("the worst it has ever been"). **Results:** For all treatments, GI complaints were mainly scored at the low end of the scale. In study 1, mean scores ranged from 0.00 ± 0.00 to 1.12 ± 1.90 and in study 2 from 0.00 ± 0.0 to 1.27 ± 1.78 . GI symptoms were grouped into upper abdominal, lower abdominal and systemic problems. There were no significant treatment differences in these categories in both studies. **Conclusion:** Despite high CHO gel intake, and regardless of the blend (GLU vs GLU+FRC), average scores for GI-symptoms were at the low end of the scale, indicating predominantly good tolerance during a 16-km run. Nevertheless, some runners (~10-20%) experienced serious problems and individualized feeding strategies might be required.

2.2 Introduction

It has long been known that carbohydrate (CHO) intake during prolonged exercise can improve endurance performance. The ingestion of CHO has been shown to improve prolonged (>2 h) cycling (8, 10, 15, 28, 29) as well as running performance (17, 27, 39). It is therefore common practice for athletes to ingest CHO during prolonged exercise. But more recently, research efforts have focussed on determining the optimal type, form and dose of CHO to optimize exogenous CHO oxidation rates and performance. However, one aspect that has received little scientific attention is the practicality and gastrointestinal (GI) tolerance of CHO intake during competition.

Recently a study in our laboratory (12) compared the effects of two different types of CHO on cycling time trial performance after 2 h of steady state exercise. An 8% improvement in performance was detected for a glucose + fructose (GLU+FRU) drink compared with isocaloric glucose (GLU) drink at an intake rate of 1.8 g/min. This observed improvement in performance coincides with the repeated finding that the ingestion of GLU+FRC drinks (delivering above ~1.5 g/min) results in 20-55% higher exogenous CHO oxidation rates compared with an isoenergetic GLU drink (19, 22).

However, in order to achieve those high CHO oxidation rates large amounts of a GLU+FRC mixture (>1 g/min) have to be ingested, and this has recently been recommended to athletes when competing in endurance events >2 h (20). This contemporary advice contrasts the American College of Sports Medicine Consensus statement for CHO intake during exercise, which recommends 30-60 g/h (0.5-1 g/min), which is based on single source CHO intake (1). With the ingestion of a single CHO,

regardless of intake rates (>2 g/min), exogenous CHO oxidation rates peak at about 1 g/min. In contrast, we now know that the ingestion of high amounts of multiple CHO sources (~ 1.5 g/min) results in 20 to 55% higher muscle CHO oxidation rates (21). Thus, previous recommendations might need further revisiting.

Although abundant and well-controlled field data is lacking, in reality, athletes seem to fail CHO intake recommendations, as the consumption of small amounts of CHO appears to be common practise (13). Consuming large amounts of CHO in the form of most common sports drinks would require fluid intakes higher than recommendations and much higher than most athletes typically consume. As a consequence this feeding strategy could lead to gastrointestinal (GI) distress, because the use of CHO drinks (2, 40) as well as the unaccustomed intake of high fluid volume are both linked to GI distress (26).

It is common for athletes in the field to consume CHO in the form of gels, which represents a convenient way to ingest larger amounts of CHO. However, at present, little is known about their efficacy or their potential to cause GI distress. A number of studies investigated the effect of gels and other forms of CHO on performance (4, 5, 25, 30, 37), but to the best of our knowledge only two studies documented gastric tolerance of gels (4, 30). In both these studies the ingestion rate of CHO was relatively low and it is not known whether the high rates of CHO intake are tolerable in a field situation when ingested in the form of gels.

Therefore the aim of the first study was to investigate tolerance of a CHO gel delivering CHO in the form of GLU+FRC (2:1) at two rates during a 16-km field-based run. The reason we chose a relatively high intensity running protocol was that running, as well as

high intensity exercise, have been associated with a higher prevalence of GI distress (31, 32).

In a second study we investigated the GI tolerance of gels with different CHO composition. Higher oxidation rates from a combination of GLU+FRC have been related to the fact that the two CHOs use different transporters for absorption in the gut (SGLT-1 and GLUT-5 for glucose and fructose, respectively; (3, 11). The combination of CHOs might also get emptied faster from the stomach than GLU alone (23). It can therefore be hypothesized that faster and more complete intestinal absorption not only leads to higher exogenous CHO oxidation rates, but also to less residual CHO in the gut. As residual intestinal CHO has been linked to GI discomfort (9, 33, 36) a better GI tolerance could be expected. Hence the purpose of the second study was to compare tolerance of gels delivering high rates of CHO either in the form of GLU or GLU+FRC.

2.3 Methods

Subjects:

For both studies club level runners and triathletes were recruited who had been running at least twice a week. They were informed about the purpose of the study, practical details, and risks associated with the procedure before giving their written consent. All subjects were healthy as assessed by a General Health Questionnaire. The studies were approved by the School of Sport and Exercise Sciences ethics subcommittee, University of Birmingham, Birmingham, UK. The subject characteristics for both studies are shown in Table 2.1.

Table 2.1 Subjects characteristics for both studies (mean \pm SD)

	Participants (male/female)	Age, y	Height, m	Body weight, kg	Frequency of running/ week	Frequency of training/ week	Estimated 10 km time
Study 1	34 (26/8)	37 \pm 11	1.76 \pm 0.07	73 \pm 9	3 \pm 1	6 \pm 2	40:44 \pm 5:28
Study 2	48 (34/14)*	35 \pm 10	1.75 \pm 0.09	71 \pm 9	3 \pm 1	3 \pm 2	42:44 \pm 5:13

* one runner had to stop because of GI symptoms, but is still included in the GI results

Experimental design:

Both studies had a counterbalanced cross-over design. Subjects were randomly allocated to an order of treatment and ran 16 km on two occasions spread over three possible consecutive weekends. Thus each subject got a one to two wk wash-out between trials. During study 1, participants ingested either a moderate amount of GLU+FRC gel (1 g/min; MOD) or a high dose of the same gel (1.4 g/min; HIGH). In study 2, subjects received either a high amount (1.4 g/min) of GLU or GLU+FRC gel in a double-blind manner.

The identical course for all runs consisted of a 3.2 km closed loop on mainly flat paved roads through a park which had to be completed five times.

Treatments:

Study 1:

The gels were commercially available gels (PowerBar Inc., Glendale, CA 91203, USA) which consisted of a mixture of GLU+FRC in the ratio of 2:1. GLU was contained in the form of maltodextrin. Both saccharides showed similar results in studies on exogenous CHO oxidation (41), but maltodextrin is less sweet than GLU and, therefore, more acceptable when paired with FRC, which is comparatively sweet. We aimed to provide CHO at an average rate of 1.0 g/min in the MOD group and at an average rate of 1.4 g/min in the HIGH group.

Study 2:

One gel consisted of GLU+FRC in the ratio of 2:1 whereas the other gel contained only GLU. GLU was again administered in the form of maltodextrin. The gels were prepared (Product Technology Center-Orbe, Nestlé Ltd., Orbe, Switzerland) and packaged so that subjects and investigators were blinded to treatment. In spite of different CHO mixtures both gels had similar taste and texture. We aimed to provide CHO at an average rate of 1.4 g/min in both trials.

In both studies runners had access to water (Vittel, Nestlé Waters, Cedex, France) every 3.2 km and were allowed to drink *ad libitum*.

Diet and activity before the runs

Subjects were asked to treat the two experimental field trials as races. The day before each trial subjects were requested to refrain from strenuous exercise and to perform the same training in the days leading up to the runs. The runners were also asked to keep the same routine before each trial, with the same breakfast at the same time, similar to what they would do before a race. Compliance was assessed in a post-trial questionnaire. Runners were asked about their actual food intake before the race in order to detect high fibre or fat intakes which could lead to GI symptoms (34).

Race protocol:

Registration for the runs took place between 9:00 AM and 9:30 AM. Before the first run of each study subjects were asked to fill in a questionnaire which assessed training history, eating habits and history of GI symptoms. After registration, runners were asked to perform their individual pre-race warm-up. Bodyweight of the runners (in race clothes) was measured on a scale, accurate to 0.1 kg (Seca 701, Seca Ltd, Birmingham, UK) in the 15

min before the start, and immediately after the run. All runs commenced at approximately 10:00 AM. Within the MOD trial of the first study gels were ingested immediately before the start after 3.2 and 6.4 km, whereas during all other trials gels were ingested before the start and after 3.2, 6.4 and 9.6 km. A CHO intake of 25 g CHO per gel pouch was assumed and this was confirmed by weighing the pouches before and after use. Each runner had a dedicated water bottle which was picked up after consuming the gel and returned to the researchers after 50 m. Fluid intake was measured by weighing the bottles after each loop on a Bellini electronic scale (Mistral UK Ltd, Warrington, UK; accurate to 1 g). Immediately after the run subjects completed a questionnaire to assess GI symptoms.

GI questionnaires

The questions about GI symptoms were similar in the pre-race questionnaire, which assessed history of GI symptoms, and the post-race questionnaire, which assessed GI symptoms during the runs. The questionnaires were organized in three sections and each section included between four and seven questions. Section one addressed upper abdominal problems (reflux, heartburn, bloating, upper abdominal cramps, vomiting, nausea), section two lower abdominal problems (intestinal cramp, flatulence, urge to defecate, left abdominal pain, right abdominal pain, loose stool, diarrhoea) and section three systemic problems (dizziness, headache, muscle cramp, urge to urinate). Each athlete filled out the 17 questions assessed on a 10-point scale, ranging from 0 "no problem at all" to 9, "the worst it has ever been".

Statistical analysis:

Data for GI complaints during the runs are expressed as mean and standard deviation for each treatment. Additionally minimum and maximum scores are reported. Differences between treatments were calculated as differences between mean values for each complaint and reported together with the standard error. All other data is reported as means \pm standard deviations.

As scores were mainly recorded in the “no problem at all” category, data is not approximately normally distributed and a non-parametric statistical approach was chosen. Primary measure: Since overall 17 questions were answered, the false positive rate of 5% will be inflated due to multiplicity. In order to reduce multiplicity, statistical analysis was performed by section of the questionnaire (upper abdominal problems, lower abdominal problems and systemic problems). The responses of a subject over a section of symptoms were averaged. Sections of symptoms were analysed by Wilcoxon sign-rank tests on averages. Secondary measures: Individual questions were analysed via Wilcoxon sign-rank tests. The p-values of the Wilcoxon sign-rank tests were not adjusted for multiple tests. Therefore the p-values serve as a flag in order to indicate interesting results.

Upper and lower abdominal problems that were scored >4 were classified as “serious”.

Mean run times (for the two different treatments as well as for the first and second run) were compared using a paired t-test. Other possible factors which could have influenced GI tolerance (e.g. training status, fluid intake, bodyweight loss) were analysed using Spearman’s correlation coefficient. For those tests p-values <0.05 were considered significant. All statistics were performed using SPSS 15 for Windows (SPSS Inc., 233 S. Wacker Drive, Chicago, Illinois, USA).

2.4 Results

Environmental race conditions:

All runs took place in relatively mild conditions which were comparable within each study. Average weather conditions across the three experimental days within study 1 were: temperature $7\pm 2^{\circ}\text{C}$; barometric pressure 1013 ± 25 hPa; wind speed 5 ± 3 km/h and relative humidity $90\pm 1\%$. Study 2 took place in slightly warmer conditions: temperature $12\pm 2^{\circ}\text{C}$; barometric pressure 1018 ± 9 hPa; wind speed 7 ± 4 km/h and relative humidity $68\pm 7\%$.

CHO intake and fluid balance:

Study: 1

The average CHO intake of the subjects during the runs was 1.0 ± 0.1 g/min within the MOD trial and 1.4 ± 0.2 g/min within the HIGH trial. Water intake was similar between both trials, with 259 ± 133 mL (min: 28 mL; max: 552 mL) during the MOD trial and 245 ± 141 mL (min: 82 mL; max: 523 mL) during the HIGH trial. Mean body mass loss was 0.9 ± 0.2 kg (min: 0.5 kg; max: 1.7 kg) during the MOD trial and 1.0 ± 0.2 kg (min: 0.4 kg; max: 1.5 kg) during the HIGH trial.

Study 2:

The average CHO intake within the GLU trial was 1.4 ± 0.1 g/min and 1.4 ± 0.1 g/min within the GLC+FRC trial. Water intake was 370 ± 166 mL (min: 131 mL; max: 842 mL) within the GLU trial and 409 ± 153 mL (min: 157 mL; max: 785 mL) within the GLU+FRC trial. Mean body mass loss was 1.0 ± 0.3 kg (min: -0.3 kg; max: 1.3 kg) within the GLU trial and 1.1 ± 0.4 kg (min: -0.2 kg; max: 1.6 kg) within the GLU+FRC trial.

GI symptoms during the runs:

For both studies post-trial questionnaires were evaluated for all runners. Specifically, the runners who experienced severe GI symptoms showed that they kept to the same routine before each trial and none had an excessively high fibre or fat intake.

Study 1:

During both trials the questions on GI symptoms were mostly scored at the low end of the scale (“no problem at all”, “very minor problems”). Scores ranged from 0 to 9 with both treatments. Mean values as well as minimum and maximum scores are represented in Table 2.2. Mean scores ranged from 0.00 ± 0.00 (diarrhoea) to 0.97 ± 1.55 (upper abdominal cramps) with the MOD dose and from 0.09 ± 0.51 (loose stool and diarrhoea) to 1.12 ± 1.90 (upper abdominal cramps) with the HIGH dose.

Table 2.2 Study 1: Reported minimum and maximum scores as well as mean scores and standard deviation for each symptom with both treatments.

Section	Question	MOD			HIGH		
		min	max	mean \pm SD	min	max	mean \pm SD
Upper abdominal problems	Reflux	0	3	0.35 ± 0.77	0	4	$*0.55 \pm 1.12$
	Heartburn	0	3	0.15 ± 0.56	0	1	0.12 ± 0.33
	Bloating	0	6	0.65 ± 1.35	0	3	0.76 ± 1.10
	Upper abdominal cramps	0	7	0.97 ± 1.55	0	9	1.12 ± 1.90
	Vomiting	0	4	0.18 ± 0.72	0	4	0.18 ± 0.72
	Nausea	0	3	0.38 ± 0.82	0	6	0.85 ± 1.56
Lower abdominal problems	Intestinal cramps	0	7	0.56 ± 1.42	0	9	0.76 ± 1.71
	Flatulence	0	4	0.47 ± 0.96	0	4	0.53 ± 1.05
	Urge to defecate	0	4	0.29 ± 0.84	0	5	0.29 ± 1.09
	Left abdominal pain	0	7	0.50 ± 1.40	0	4	$**0.34 \pm 0.90$
	Right abdominal pain	0	4	0.47 ± 0.96	0	9	$*0.82 \pm 1.96$
	Loose stool	0	1	0.03 ± 0.17	0	3	0.09 ± 0.51
	Diarrhoea	0	0	0.00 ± 0.00	0	3	0.09 ± 0.51
Systemic problems	Dizziness	0	4	$*0.39 \pm 0.97$	0	4	0.35 ± 1.01
	Headache	0	5	$*0.30 \pm 0.95$	0	4	0.44 ± 1.16
	Muscle cramp	0	7	$*0.76 \pm 1.56$	0	7	0.76 ± 1.62
	Urge to urinate	0	9	0.61 ± 1.71	0	3	0.44 ± 0.96

* only 33 participants answered the question; ** only 32 participants answered the question

The differences of scores between treatments are displayed in Table 2.3. Our primary outcome showed that mean scores for upper abdominal, lower abdominal and systemic problems were not significantly different. Secondary measures showed higher score for nausea with the HIGH dose (effect estimate=0.47, se=0.19, p=0.02).

Table 2.3 Study 1: Differences in mean scores and standard error between both treatments (HIGH minus MOD)

Section	Question	Individual question mean \pm se	Individual Wilcoxon p values	Section mean \pm se	Section Wilcoxon p values
Upper abdominal problems	Reflux*	0.18 \pm 0.18	0.36	0.16 \pm 0.08	0.26
	Heartburn	-0.03 \pm 0.08	0.71		
	Bloating	0.12 \pm 0.24	0.49		
	Upper abdominal cramps	0.15 \pm 0.32	0.63		
	Vomiting	0.00 \pm 0.17	1.00		
	Nausea	0.47 \pm 0.19	# 0.02		
Lower abdominal problems	Intestinal cramps	0.21 \pm 0.29	0.46	0.09 \pm 0.08	0.24
	Flatulence	0.06 \pm 0.19	0.81		
	Urge to defecate	0.00 \pm 0.12	0.89		
	Left abdominal pain**	-0.13 \pm 0.15	0.49		
	Right abdominal pain*	0.33 \pm 0.36	0.63		
	Loose stool	0.06 \pm 0.09	0.66		
	Diarrhoea	0.09 \pm 0.09	0.32		
Systemic problems	Dizziness*	-0.03 \pm 0.13	0.91	-0.03 \pm 0.14	0.54
	Headache*	0.15 \pm 0.17	0.56		
	Muscle cramp*	0.03 \pm 0.24	0.83		
	Urge to urinate	-0.18 \pm 0.34	0.89		

* only 33 participants are compared; ** only 32 participants are compared

higher scores for nausea with HIGH dose

Three (9%) of the runners reported serious symptoms (score >4) with the HIGH but not with the MOD dose and one runner (3%) reported serious symptoms with both doses.

There was no difference between the occurrence of GI symptoms in male and female runners. Subjects history of GI symptoms, which was reported in the pre-race questionnaire, was positively correlated with the occurrence of GI symptoms during the

runs (Figure 2.1A: upper abdominal problems: $r=0.70$, $p<0.001$; Figure 2.1B: lower abdominal problems: $r=0.46$, $p=0.001$). No correlations were found between indicators of training experience (frequency of running per week, mean run times) and GI symptoms. Further, fluid intake and body mass loss during study 1 did not correlate with GI symptoms.

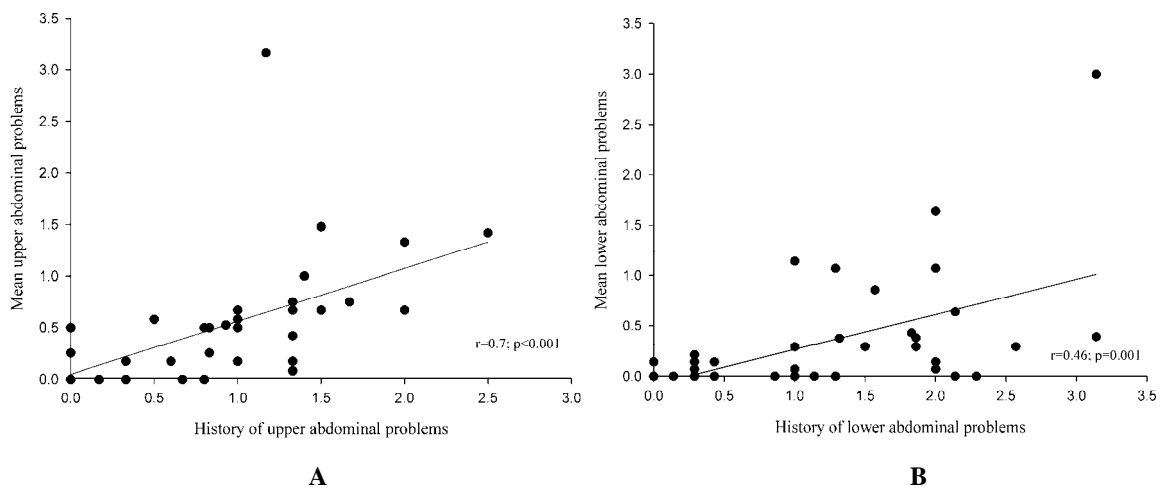


Figure 2.1A/B: Correlation between mean scores of a subject for upper (A) and lower (B) abdominal problems during the runs and their reported history of upper and lower abdominal problems in study 1.

Study 2:

One runner had to stop during one trial (GLU+FRC) because of GI symptoms, and is included in the GI results. Mean values as well as minimum and maximum scores are represented in Table 2.4. Most runners reported scores at the low end of the scale. Scores ranged from 0 to 8 with both treatments. Mean scores ranged from 0.00 ± 0.00 (diarrhoea and loose stool) to 1.23 ± 1.78 (upper abdominal cramps) with GLU and from 0.13 ± 0.73 (diarrhoea) to 1.27 ± 1.78 (upper abdominal cramps) with GLU+FRC.

Table 2.4 Study 2: Reported minimum and maximum scores as well as mean scores and standard deviation for each symptom with both treatments.

Section	Question	GLU			GLU+FRC		
		min	max	mean \pm stdev	Min	Max	mean \pm stdev
Upper abdominal problems	Reflux	0	4	0.58 \pm 1.23	0	5	1.04 \pm 1.57
	Heartburn	0	5	0.35 \pm 1.14	0	4	*0.32 \pm 0.84
	Bloating	0	5	0.94 \pm 1.42	0	7	1.17 \pm 1.75
	Upper abdominal cramps	0	6	1.23 \pm 1.78	0	6	1.27 \pm 1.78
	Vomiting	0	5	0.27 \pm 0.87	0	3	0.23 \pm 0.72
	Nausea	0	6	1.21 \pm 1.66	0	7	1.06 \pm 1.79
Lower abdominal problems	Intestinal cramps	0	4	0.67 \pm 1.10	0	5	1.08 \pm 1.50
	Flatulence	0	4	0.38 \pm 0.94	0	6	0.54 \pm 1.20
	Urge to defecate	0	4	0.48 \pm 1.20	0	8	0.69 \pm 1.78
	Left abdominal pain	0	7	1.13 \pm 1.88	0	6	1.15 \pm 1.68
	Right abdominal pain	0	8	0.92 \pm 1.75	0	6	0.92 \pm 1.65
	Loose stool	0	0	0.00 \pm 0.00	0	8	0.38 \pm 1.36
	Diarrhoea	0	0	0.00 \pm 0.00	0	5	0.13 \pm 0.73
Systemic problems	Dizziness	0	4	0.38 \pm 0.91	0	5	0.23 \pm 0.95
	Headache	0	3	0.19 \pm 0.67	0	5	0.23 \pm 0.88
	Muscle cramp	0	8	0.85 \pm 1.60	0	5	0.60 \pm 1.22
	Urge to urinate	0	4	*0.79 \pm 1.28	0	6	0.56 \pm 1.32

* only 47 people answered the question

The differences in scores between treatments are displayed in Table 2.5. Our primary outcome showed that mean scores for upper abdominal, lower abdominal and systemic problems were not significantly different. Secondary measures showed an increased score for symptoms with the GLU+FRC gel for reflux (effect estimate=-0.46, SE=0.23, p=0.024), intestinal cramps (effect estimate=-0.42, SE=0.2, p=0.041) and loose stool (effect estimate=-0.38, SE=0.2, p=0.043).

Table 2.5 Study 2: Differences in mean scores and standard error between both treatments (GLU minus GLU+FRC)

Section	Question	Individual question mean \pm SE	Individual Wilcoxon p values	Section mean \pm SE	Section Wilcoxon p values
Upper abdominal problems	Reflux	-0.46 \pm 0.23	0.024#	-0.10 \pm 0.14	0.76
	Heartburn *	0.04 \pm 0.19	0.959		
	Bloating	-0.23 \pm 0.25	0.495		
	Upper abdominal cramps	-0.04 \pm 0.29	0.830		
	Vomiting	0.04 \pm 0.15	0.943		
	Nausea	0.15 \pm 0.29	0.505		
Lower abdominal problems	Intestinal cramps	-0.42 \pm 0.20	0.041#	-0.19 \pm 0.14	0.22
	Flatulence	-0.17 \pm 0.16	0.385		
	Urge to defecate	-0.21 \pm 0.27	0.339		
	Left abdominal pain	-0.02 \pm 0.31	0.871		
	Right abdominal pain	0.00 \pm 0.31	0.930		
	Loose stool	-0.38 \pm 0.20	0.043#		
	Diarrhoea	-0.13 \pm 0.11	0.180		
Systemic problems	Dizziness	0.15 \pm 0.14	0.277	0.14 \pm 0.08	0.15
	Headache	-0.04 \pm 0.13	0.915		
	Muscle cramp	0.25 \pm 0.20	0.316		
	Urge to urinate *	0.21 \pm 0.21	0.271		

* only 47 participants are compared

lower GI scores with GLU versus GLU+FRU

Nine (19%) of the runners reported serious symptoms only with the GLU+FRC gel, five (10%) runners reported serious symptoms only with the GLU gels and two (4%) runners reported serious symptoms with both treatments. Reported GI symptoms during the runs were strongly correlated with history of GI symptoms as assessed in the pre-race questionnaire (see Figure 2.2A: upper abdominal problems: $r=0.89$, $p<0.001$; Figure 2.2B: lower abdominal problems: $r=0.90$, $p<0.001$). There was no difference between the occurrence of GI symptoms in male and female runners. No correlations have been found between frequency of running per week and GI symptoms, as well as mean run times and GI symptoms. Fluid intake and body mass loss during study 2 did not correlate with GI symptoms.

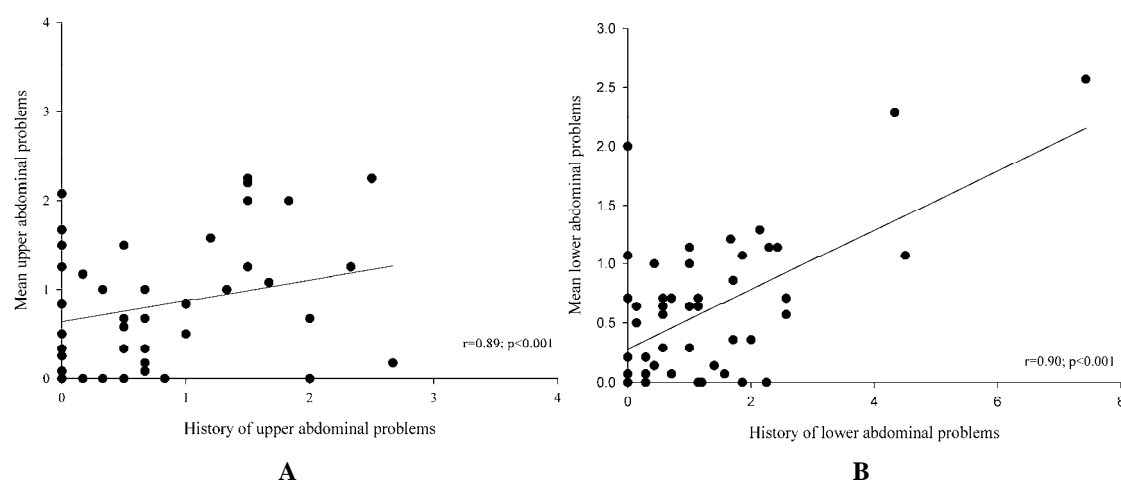


Figure 2.2 A/B Correlation between mean scores of a subject for upper (A) and lower (B) abdominal problems during the runs and their reported history of upper and lower abdominal problems in study 2.

Performance

Study 1:

Mean run times did not differ significantly between MOD (1:12:53±7:24 h:min:sec) and HIGH (1:13:06±7:45 h:min:sec). 16 runners were faster with MOD whereas 18 runners were faster with HIGH. Mean run times between the first (1:13:01±7:09 h:min:sec) and second run (1:12:58±7:07 h:min:sec) run of each subject did not differ significantly.

Study 2:

Results of running times are expressed for 47 runners as one runner did not finish one trial. Mean run times between GLU (1:14:25±7:17 h: min:sec) and GLU+FRC (1:14:41±7:10 h:min:sec) did not differ significantly. Twenty-four subjects ran faster with GLU gel and 25 ran faster with GLC+FRC gel. Mean run time for the second run (1:14:04±7:01 h:min:sec) was significantly ($p=0.005$) faster than for the first run (1:15:02±7:24 h:min:sec).

2.5 Discussion

The aim of the present studies was to test whether high CHO intake rates and varying CHO blends in the form of gels had an impact on GI tolerance. High intensity exercise, and in particular running, has been linked to a high prevalence of GI distress (31). Consequently a high prevalence of GI symptoms could have been expected. Furthermore, a bias towards a higher score of symptoms could have been anticipated as no placebo trial was included. Nevertheless, mean GI symptom scores were on the low end of the scale during all trials and there were no treatment differences, indicating that both gels were well tolerated by the vast majority of the runners.

Effect of CHO intake rate on GI tolerance:

The first study examined different rates of CHO ingestion (MOD=1.0±0.1 g/min; HIGH=1.4±0.2 g/min), and showed an equally good tolerance for both treatments. The only symptom that occurred more often with the HIGH dose was nausea, suggesting that a high intake of CHO might lead to more nausea. But since the test results were not corrected for multiplicity the observation has to be treated with caution. Generally good GI tolerance with scores below four was reported among 30 of the runners (88%). Nevertheless, three runners (9%) had serious symptoms (score >4) only with the HIGH intake, while one runner (3%) had serious GI symptoms with both MOD and HIGH intake, indicating individual GI variability in tolerating CHO intake.

As a HIGH intake rate of gel with a similar composition as in study 1 was used in the GLU+FRC trial in study 2, this trial is directly comparable to the HIGH intake trial in study 1. Surprisingly, more runners (23%) showed serious GI symptoms during the GLU+FRC

trial in study 2 versus the HIGH intake rate in study 1 (12%). This difference could be mainly due to a different disposition to GI symptoms based on GI history of the different runners in each study. In both studies the history of GI symptoms as assessed in the pre-race questionnaire was highly correlated with GI symptoms during the race. Another reason for generally higher scores in the second study could be the different environmental conditions involving considerably warmer weather. It is well-established that decreased blood flow in the gut can lead to GI symptoms (2, 14). This could have been caused by increased blood shunting to the skin under warmer conditions and also due to higher fluid losses during the second study.

Whether the prevalence of GI symptoms in our studies is in accordance to previous studies which investigated CHO intake during running is difficult to judge, as different methodologies and statistical approaches were used. A study of van Nieuwenhoven et al (40) investigated the effect of a CHO sports drink and water on GI tolerance during an 18-km run. A similar 10-point scale (1 until 10) was used and generally higher mean scores (2.0 until 5.5) were reported, not only in the CHO trial, but also in the water trial. In the study of Burke et al (4) CHO gel was given at an intake rate of about 1 g/min and a 15% incidence of GI symptoms was reported. This intake rate matches the CHO administration in the MOD trial in study 1, where 3% of the runners reported serious GI symptoms >4. The slightly lower scores in our study could again be due to different predisposition to GI problems of the runners as well as cooler environmental conditions.

Whether all occurring GI symptoms are related to CHO intake is not possible to answer from this set of studies as no placebo trials were implemented into the study designs in

order to keep statistical power high. Previous studies have shown a high prevalence of GI symptoms during endurance events and running in particular. Prevalence was reported as 10-87%, depending on the sport, duration and method of investigation (24, 35, 38). These findings are confirmed by the high incidence of GI problems reported in the water trial in the study by van Nieuwenhoven (40). It therefore has to be assumed that not all GI symptoms reported in our study are due to CHO intake.

Effect of different CHO composition on GI tolerance:

One of our hypotheses was that due to the use of different intestinal transporters for glucose and fructose, and therefore a possibly higher absorption of a combination of GLU+FRC compared with GLU, less residual CHO would be present in the intestine with the GLU+FRC mix. Residual CHO in the lower intestine can lead to GI distress, most likely as result of water retention in the gut due to a higher osmotic load (9, 33, 36). In addition, fermentation by bacteria in the gut can lead to gas production as well as to the production of fatty acids which might lead to higher motility of the gut (7).

We did not observe a difference in tolerance between the GLU+FRC and GLU gels in this study. One reason why a better tolerance of GLU+FRC was not shown could be that GI tolerance is not exclusively influenced by absorption and residual CHO in the intestine. As discussed previously, factors such as reduced blood flow to the gut or mechanical stress from running can lead to GI symptoms. These mechanisms are not expected to be different between treatments. In addition, a superior effect of faster absorption of different CHOs would be expected later in exercise. Previous studies showed that enhanced exogenous CHO oxidation from a GLU+FRC blend compared with GLU starts to occur after

approximately 45 min of exercise (18, 41). With an average duration of ~70 min for the run, it is possible that residual CHO in the GI tract during the two CHO trials was not significantly different. Even in a prolonged exercise intervention, where significant differences in residual CHO might result between different CHO treatments, we would hypothesize that osmotic effects and fermentation would contribute to adverse GI symptoms in the GLU only treatment.

Although overall there was no difference between the two different CHO gels in study 2, nine (19%) runners had serious symptoms only with the GLU+FRC gel and five (10%) had serious symptoms only with the GLU gel, suggesting that tolerance is highly individual, which is supported by the significant correlations between GI symptoms and history of symptoms. Reflux, intestinal cramps and loose stool occurred more often with the GLU+FRC gel, but as stated earlier, this does not necessarily mean that the intake of GLU+FRC gel leads to more of these symptoms as the test results were not corrected for multiplicity and further confirmation is needed.

Differences in performance with varying CHO gel intake:

As an indicator of differences in performance between treatments running times were compared. Mean running times were not different between the MOD and the HIGH treatment in the first study. This may seem in contrast with previous reports of improved performance with CHO feeding during prolonged exercise. However, when the exercise duration is less than ~70 min, CHO availability may not be the main limiting factor on performance. It has been suggested that the mechanisms for fatigue during this type of exercise are not metabolic (6), but rather are mediated by central mechanisms. If this is the

case, no performance benefits from a large CHO intake compared with a moderate intake would be expected in this short time period. It is equally important to note that no negative effect of the HIGH intake due to GI symptoms was observed, which could have a large performance impact in longer duration exercise situations where endogenous CHO is limiting. Likewise in study 2, there was no difference between treatments, but it has to be noted that one runner had to stop because of GI symptoms during the GLU+FRC trial. Also, a significant difference has been shown between run times of the first and the second run of each subject, possibly indicating a substantial “learning effect”. This effect is likely to be due to the chosen group of well trained but not necessarily competitive runners where a rather high within-athlete variation is to be expected and “learning effects” may be more common (16).

Individual predisposition to GI problems:

A consistent finding in both our studies which seems worthy of note was the strong correlation between a history of GI distress and the reported GI symptoms during the trials. This suggests that an individual predisposition to GI problems during exercise exists and, although anecdotal evidence has existed to support this idea, as far as we are aware this has not been clearly documented before. For athletes, as well as for sports nutritionists, this appears to be very important as it shows that in terms of tolerance, personal advice and individual testing of food and drink intake during exercise is vital.

In summary, the present study showed that high doses of CHO (1.4 g/min) in gel form were well tolerated by the majority of runners. Nevertheless, between 3% and 23% of the runners experienced GI symptoms during the runs and the severity of these symptoms correlated

with their history of GI complaints. Also, although we did not find an overall different tolerance between the GLU and GLU+FRC treatment, some individuals showed more symptoms with one or the other gel. It should therefore be advised that individual athletes, especially the ones that experience GI problems frequently, test their tolerance during hard training sessions, ideally under similar conditions to the races they aim to compete in.

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Chapter 3

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

3.1 Abstract

Recently it has been shown that ingestion of solutions with glucose (GLU) and fructose (FRC) leads to 20-55% higher CHO oxidation rates as compared with GLU alone. Although the vast majority of laboratory studies used solutions to deliver CHO, in practice, athletes often ingest CHO in the form of gels (semi-solid). It is currently not known if CHO ingested in the form of a gel is oxidized as effectively as a drink. **Purpose:** To investigate exogenous CHO oxidation from CHO provided in semi-solid (GEL) or solution (DRINK) form during cycling. **Method:** Eight well trained cyclists (34 ± 7 y; 76 ± 9 kg; $\text{VO}_{2\text{max}}$: 61 ± 7 mL/kg/min) performed three exercise trials in random order. The trials consisted of cycling at $59 \pm 4\%$ $\text{VO}_{2\text{max}}$ for 180 min while receiving one of the following three treatments: GEL plus plain water, DRINK, or plain water. Both CHO treatments delivered GLU plus FRC in a ratio of 2:1 at a rate of 1.8 g/min (108 g/h). Fluid intake was matched between treatments at 867 mL/h. **Results:** Exogenous CHO oxidation from GEL and DRINK showed a similar time-course with peak exogenous CHO oxidation rates being reached at the end of 180 min exercise. Peak exogenous CHO oxidation rates were not significantly different ($p=0.40$) between GEL and DRINK (1.44 ± 0.29 g/min vs. 1.42 ± 0.23 g/min, respectively). Furthermore, oxidation efficiency was not significantly different ($p=0.36$) between GEL and DRINK ($71 \pm 15\%$ vs. $69 \pm 13\%$, respectively). **Conclusion:** This study demonstrates that a GLU+FRC mixture is oxidized to the same degree when administered as either semi-solid GEL or liquid DRINK, leading to similarly high peak oxidation rates and oxidation efficiencies.

3.2 Introduction

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

A further mechanism to explain the beneficial role of CHO during exercise might be the maintenance of high CHO oxidation rates, particularly late in exercise when glycogen stores become limited (7, 8). A series of studies using stable (^{13}C) and radioactive (^{14}C) isotopes has investigated CHO oxidation from the ingestion of different sources of CHOs and CHO mixtures. Particularly interesting was the consistent finding that when ingested at high intake rates (1.5 to 2.4 g/min) mixtures of GLU+FRC produce 20-55% higher exogenous CHO oxidation rates late in exercise compared with an isocaloric amount of GLU only solutions (15, 16, 19, 39). Accordingly, Currell et al (11) demonstrated that a GLU+FRC mixture, which has been associated with high exogenous CHO oxidation rates, coincided with a significant 8% improvement in endurance performance (40-km time-trial (TT) preceded by 2 h of moderate intensity cycling) when compared with GLU alone.

However, to show the ergogenic benefit of GLU+FRC solutions, large fluid volumes (800-1000 mL/h) and high CHO concentrations (>10% CHO solution; >100 gCHO/h) have been implemented in laboratory settings. Currently, common sports drinks are generally less

concentrated (4-8% CHO), and to achieve CHO intake rates of >1.5 g/min would require very large fluid intake rates (~1-2.5 L/h); which likely exceeds sweat rates of most athletes in cool weather conditions (31). In reality, athletes, especially runners, have been reported to take in rather low voluntary fluid volumes ((21, 29) unpublished observation, Chapter 6). An alternative to sports drink consumption for athletes in the field is the ingestion of concentrated CHO gels, which offer the possibility to take in large amounts of CHO with an *ad libitum* amount of fluid, thus dissociating fluid and CHO intakes. Indeed, it seems to be common practice for endurance athletes to take in CHO in the form of gels (13).

However, whether the intake of a semi-solid CHO gel has the same effect on metabolism and exogenous CHO oxidation as a CHO solution is not clear. Rate limiting steps for the oxidation of ingested CHO are most likely at the entrance of the systemic circulation via intestinal transit and absorption (18). The rate of gastric emptying has been reported to depend mainly on gastric volume and energy content of ingested food (22, 26). However, it has also been suggested that other factors such as viscosity of an ingested meal can influence the rate of gastric emptying (24). For example, the addition of gel forming fibres such as guar gum to CHO solutions has been reported to slow down gastric emptying in some studies (25, 34). In contrast, a study by Leiper *et al.* (23) reported faster gastric emptying rates from a gel-forming CHO compared with an isocaloric low-viscosity CHO solution. However, no consequences on plasma glucose or insulin concentrations were reported in that study.

Furthermore, it is theoretically possible that the simultaneously ingested gel and water are not entirely mixed together when leaving the stomach, as it has been described that the

stomach empties in layers, holding back solid and more concentrated foods in the sinus of the stomach (for review, see 33). This could result in differences in CHO concentrations in the gut between a readily dissolved drink as compared with a semi-solid gel and therefore lead to different rates of intestinal absorption and subsequent oxidation. Therefore, the purpose of the present study was to clarify whether there is a difference in oxidation rates from GLU+FRC delivered as a gel plus plain water compared with a CHO solution during prolonged cycling. Considering that endurance athletes consume ~35% of their CHO intake in the form of gels when competing (unpublished observation, Chapter 6), this is very relevant to athletes and to the best of our knowledge the oxidation of CHO delivered in the form of gel has never been studied.

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

3.3 Methods

Subjects:

Eight well trained male endurance cyclists/triathletes (34 ± 7 y; 76 ± 9 kg; 1.78 ± 0.06 m; VO_2max : 61 ± 3 mL/kg/min) volunteered to participate in this study. Subjects trained at least 3 times/wk for more than 2 h/session and had been involved in endurance training for at least 2 y. All subjects were healthy as assessed by a general health questionnaire and informed of the purpose, practical details, and risks associated with the procedures before giving their written informed consent to participate. This study was approved by the School of Sport and Exercise Sciences ethics subcommittee, University of Birmingham, Birmingham UK.

Preliminary testing:

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

Experimental design

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

Experimental treatments:

To quantify exogenous CHO oxidation, corn-derived maltodextrin (Glucidex 19, Roquette, France) and fructose (Krystar 300 Crystalline Fructose, Tate & Lyle, Decatur, Illinois) were used for preparation of the DRINK, which have a high natural abundance of ^{13}C (-11.22 and -11.00 δ ‰ vs Pee Dee Bellemnitella (PDB), respectively). Correspondingly the GEL consisted of maltodextrin (M150 Maltodextrin, Grain Processing Corporation, Muscatine, Iowa) and fructose (Krystar 300 Crystalline Fructose, Tate & Lyle, Decatur, Illinois) with an enrichment of -10.14 and -10.48 δ ‰ vs PDB, respectively). The ^{13}C enrichment of the ingested CHO was determined by elemental analyser-isotope ratio mass spectrometry (EA-IRMS; Europa Scientific GEO 20-20, Crewe, UK).

Diet and activity before testing:

Prior to the first trial, detailed personal advice was given by a nutritionist to follow a diet rich in CHO. It was made sure that CHO intake was $>4\text{g/kgBW}$, which in combination with light training or rest would prevent participants starting the trials with depleted muscle glycogen stores. Subjects were asked to record their food intake and activity patterns for 24 h prior to the first exercise trial and were then instructed to follow the same diet and activities before the next two trials. Compliance was assessed with 24 h recalls the days before the rest of the trials and checked by a nutritionist upon arrival in the laboratory. In addition, subjects were instructed to refrain from strenuous exercise and drinking any alcohol in the 24 h before the exercise trials. Furthermore, 3–7 d before each experimental trial, the subjects were instructed to perform an intense training session (“glycogen-depleting exercise bout”) in an attempt to reduce any endogenous ^{13}C -enriched glycogen stores. Subjects were also instructed not to consume products with a high natural abundance

of ^{13}C (CHOs derived from C4 plants such as maize and sugar cane) at least 1 wk before each experimental trial to reduce the background shift (change in ^{13}C) from endogenous substrate stores. Subjects received detailed guidance on foods, which they needed to avoid as well as advice on potential alternatives and were contacted several times during the weeks before the trials to ensure compliance.

Protocol:

Each subject arrived in the laboratory at the same time in the morning (between 6:00 and 9:00 a.m.) after an overnight fast (10-12 h). All experimental trials were performed at the same time of day to avoid circadian variance. On arrival, subjects were weighed before a 20-gauge Teflon catheter (Venflon, BD, Plymouth, UK) was inserted into an antecubital vein of an arm and attached to a three-way stopcock (Sims Portex, Kingsmead, UK) to allow for repeated blood sampling during exercise. The cannula was kept patent by flushing with 1.0–1.5 mL of isotonic saline (0.9%, BD) after each blood sample collection. The subjects then mounted a cycle ergometer and a resting breath sample was collected into 10-mL Exetainer tube (Labco Ltd., Brow Works, High Wycombe, UK), which was filled directly from a mixing chamber to determine the $^{13}\text{C}/^{12}\text{C}$ ratio in the expired air. A resting blood sample (10 mL) was collected and stored on ice until centrifugation. Subjects then started a 180 min exercise bout at a work rate equivalent to 50% W_{max} (59 ± 4 % $\text{VO}_{2\text{max}}$). Additional blood samples were drawn at 15 min intervals until the cessation of exercise. At the same 15 min intervals expiratory breath samples were also collected. During the first 2 min expired air was sampled into Douglas bags. Douglas bag samples were analysed as described above and oxygen consumption (VO_2), carbon dioxide production (VCO_2), and

respiratory exchange ratio (RER) were determined. Within the last 60 s of each 3 min period Exetainer tubes were filled in duplicate for breath $^{13}\text{C}/^{12}\text{C}$ ratio as described above.

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

Questionnaires:

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

Analysis:

All blood samples were collected into pre-chilled test tubes containing EDTA and centrifuged at 2300 g for 10 min at 4°C. Aliquots of the plasma were frozen and stored at -25°C until further analysis. Plasma samples were analysed enzymatically for glucose (Glucose HK, ABX Diagnostics, UK), lactate (Lactic Acid, ABX Diagnostics), and free

fatty acid (FFA) (NEFA-C Kit, Alpha Laboratories, UK) concentration on a semiautomatic analyser (Cobas Mira S-Plus, ABX). Breath samples were analysed for $^{13}\text{C}/^{12}\text{C}$ ratio by continuous flow IRMS (GC, Trace GC Ultra; IRMS, Delta Plus XP; both Thermo Finnigan, Herts, UK). From indirect calorimetry (VO_2 and VCO_2) and stable isotope measurements (breath $^{13}\text{C}/^{12}\text{C}$ ratio), rates of total fat, total CHO, and exogenous CHO oxidation were calculated.

Calculations:

From VO_2 and VCO_2 (L/min), CHO and fat oxidation rates (g/min) were calculated using stoichiometric equations (20), with the assumption that protein oxidation during exercise was negligible.

$$\text{CHO oxidation} = 4.21 \text{ VCO}_2 + 2.962 \text{VO}_2$$

$$\text{Fat oxidation} = 1.695 \text{VO}_2 + 1.701 \text{ VCO}_2$$

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

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

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

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

$$\text{Exogenous CHO oxidation} = \text{VCO}_2 \cdot \left(\frac{\delta \text{Exp} - \text{Exp}_{\text{bkg}}}{\delta \text{Ing} - \text{Exp}_{\text{bkg}}} \right) \cdot \left(\frac{1}{k} \right)$$

in which δ_{Exp} is the ^{13}C enrichment of expired air during exercise at different time points, δ_{Ing} is the ^{13}C enrichment of the ingested CHO solution, $\delta_{\text{Exp}_{\text{bkg}}}$ is the ^{13}C enrichment of expired air in the WAT trial (background) at different time points, and k is the amount of CO_2 (in liters) produced by the oxidation of 1 g of glucose ($k = 0.7467$ L of CO_2 per gram of glucose). Endogenous CHO oxidation was calculated by subtracting exogenous CHO oxidation from total CHO oxidation.

A methodological consideration when using $^{13}\text{CO}_2$ in expired air to calculate exogenous substrate oxidation is the temporary fixing of $^{13}\text{CO}_2$ in the bicarbonate pool, in which an amount of CO_2 arising from CHO and fat oxidation is retained (32). However, during exercise, the turnover of this pool increases several fold so that a physiological steady state condition will occur relatively rapidly and $^{13}\text{CO}_2$ in the expired air will be equilibrated with the $^{13}\text{CO}_2/\text{H}^{13}\text{CO}_2$ pool, respectively. Recovery of $^{13}\text{CO}_2$ from oxidation will approach 100% after 60 min of exercise when the dilution in the bicarbonate pool becomes negligible (27, 32). As a consequence, all calculations on substrate oxidation were performed over the last 120 min of exercise (60-180 min). The oxidation efficiency was determined as the percentage of the ingested CHO that was oxidized and was calculated by dividing exogenous CHO oxidation rate by the CHO ingestion rate and then multiplied by 100.

Statistical analysis:

A two-way (trial x time) ANOVA for repeated measures was used to compare differences in substrate utilization and in blood metabolites between the three trials. A Tukey post hoc test was applied where a significant F-ratio was detected. Paired sample t-tests were applied when two mean values were compared. All values are presented as mean \pm standard

deviation (SD). Statistical significance was set at $p < 0.05$. All statistics were performed using SPSS 15 for Windows (SPSS Inc., 233 S. Wacker Drive, Chicago, Illinois, USA).

3.4 Results

VO₂, RER, total CHO, and fat oxidation

VO₂, RER, and total CHO and fat oxidation rates over the 60-180 min exercise period are shown in Table 3.1. The rate of oxygen uptake (VO₂) was not significantly different between the three experimental trials.

Table 3.1 Oxygen uptake (VO₂), respiratory exchange ratio (RER), total CHO oxidation (CHO_{total}), total fat oxidation (fat_{total}), endogenous CHO oxidation, and exogenous CHO oxidation with ingestion of WAT, GEL, DRINK. Values are means±SD. a Significantly different from WAT ($p < 0.05$). There were no statistical differences between GEL vs. DRINK.

Trial	Time (min)	VO ₂ (l/min)	RER	CHO _{total} (g/min)	Fat _{total} (g/min)	Endogenous CHO (g/min)	Exogenous CHO (g/min)
WAT	60-90	2.70±0.36	0.83 ± 0.02	1.44 ± 0.13	0.76 ± 0.19	1.44 ± 0.13	
	90-120	2.76±0.37	0.82 ± 0.02	1.33 ± 0.16	0.82 ± 0.19	1.33 ± 0.16	
	120-150	2.78±0.38	0.82 ± 0.02	1.31 ± 0.19	0.86 ± 0.21	1.31 ± 0.19	
	150-180	2.80±0.41	0.81 ± 0.02	1.23 ± 0.21	0.88 ± 0.20	1.23 ± 0.21	
	60-180	2.76±0.38	0.82 ± 0.02	1.35 ± 0.17	0.84 ± 0.20	1.35 ± 0.17	
GEL	60-90	2.69±0.40	0.88 ± 0.04 ^a	2.03 ± 0.37 ^a	0.52 ± 0.21 ^a	0.96± 0.34 ^a	1.07 ± 0.27
	90-120	2.71±0.35	0.88 ± 0.03 ^a	2.00 ± 0.26 ^a	0.54 ± 0.16 ^a	0.75± 0.28 ^a	1.25 ± 0.26
	120-150	2.71±0.36	0.88 ± 0.03 ^a	2.04 ± 0.32 ^a	0.53 ± 0.16 ^a	0.66 ± 0.32 ^a	1.38 ± 0.25
	150-180	2.72±0.37	0.88 ± 0.03 ^a	2.05 ± 0.37 ^a	0.52 ± 0.15 ^a	0.61 ± 0.32 ^a	1.44 ± 0.26
	60-180	2.71±0.37	0.88 ± 0.03 ^a	2.03 ± 0.34 ^a	0.53 ± 0.16 ^a	0.75 ± 0.32 ^a	1.28 ± 0.26
DRINK	60-90	2.70±0.35	0.87 ± 0.03 ^a	1.88 ± 0.27 ^a	0.59 ± 0.18 ^a	0.82 ± 0.18 ^a	1.06 ± 0.22
	90-120	2.70±0.36	0.87 ± 0.03 ^a	1.90 ± 0.26 ^a	0.59 ± 0.16 ^a	0.68 ± 0.18 ^a	1.22 ± 0.22
	120-150	2.72±0.37	0.87 ± 0.02 ^a	1.90 ± 0.24 ^a	0.59 ± 0.16 ^a	0.57 ± 0.17 ^a	1.33 ± 0.25
	150-180	2.73±0.39	0.87 ± 0.02 ^a	1.90 ± 0.28 ^a	0.60 ± 0.16 ^a	0.51 ± 0.27 ^a	1.39 ± 0.23
	60-180	2.73±0.37	0.87 ± 0.02 ^a	1.90 ± 0.25 ^a	0.59 ± 0.16 ^a	0.66 ± 0.21 ^a	1.24 ± 0.23

A significantly lower RER ($p<0.01$) was measured in the WAT trial compared with the two CHO ingestion trials, but RER was not different between the GEL and DRINK trials. Correspondingly, CHO oxidation was not different between the two CHO trials, but was significantly higher than compared with WAT ($p<0.01$). Average total CHO oxidation rates during the last 120 min of exercise were 1.35 ± 0.17 , 2.03 ± 0.34 , and 1.90 ± 0.25 g/min for WAT, GEL and DRINK, respectively. Fat oxidation was significantly higher in the WAT trial than after CHO ingestion ($p<0.01$), but did not differ significantly between the CHO trials. Average fat oxidation rates over the last 120 min of exercise were 0.84 ± 0.20 , 0.53 ± 0.16 and 0.59 ± 0.16 g/min for WAT, GEL and DRINK, respectively.

Exogenous CHO oxidation, endogenous CHO oxidation, and oxidation efficiency

Changes in breath $^{13}\text{CO}_2$ enrichment in the water trial were below 0.5 δ per mil vs. PDB and resting breath $^{13}\text{CO}_2$ enrichment was not significantly different between trials, indicating that $^{13}\text{CO}_2$ enrichment of endogenous CHO stores was low and similar between trials. Breath $^{13}\text{CO}_2$ enrichment and exogenous CHO oxidation rates increased over time (Fig. 3.1A and 3.1B) with both CHO treatments. Peak exogenous CHO oxidation rates were reached at the end of 180 min exercise and were not significantly different between the GEL and DRINK trial (1.44 ± 0.29 g/min vs. 1.42 ± 0.23 g/min, respectively; $p=0.40$). The average exogenous CHO oxidation rates over the final 120 min of exercise were not significantly different between CHO treatments (1.28 ± 0.26 and 1.24 ± 0.23 g/min for GEL and DRINK, respectively ($p=0.19$; Table 3.1). Correspondingly, the oxidation efficiency was not different between the GEL and DRINK trial ($71\pm15\%$ vs. $69\pm13\%$, respectively; $p=0.35$).

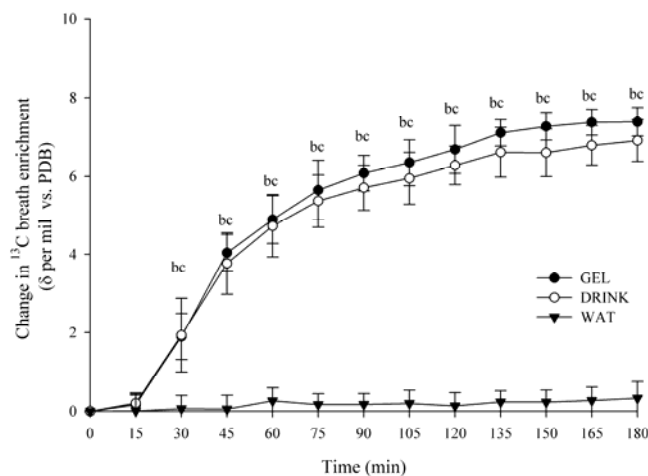


Figure 3.1A Change in breath $^{13}\text{CO}_2$ enrichment (compared with resting) with ingestion of WAT, GEL, DRINK. Values are means \pm SD. b GEL significantly greater than WAT ($p<0.05$). c DRINK significantly greater than WAT ($p<0.05$).

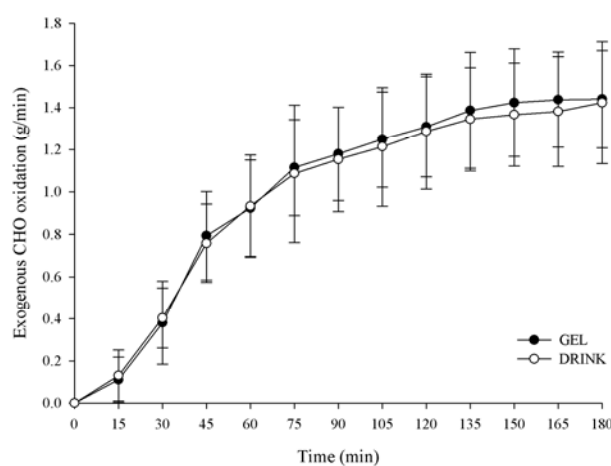


Figure 3.1B Exogenous CHO oxidation in g/min with ingestion of GEL, DRINK. Values are means \pm SD.

The contribution of exogenous CHO to total energy expenditure was 39% and 38% for GEL and DRINK, respectively. Endogenous CHO oxidation contributed to total energy expenditure with 41%, 23% and 25% for WAT, GEL and DRINK respectively (Figure 3.2). Compared with the WAT trial, endogenous CHO oxidation was significantly lower with both forms of CHO ingestion during the last 120 min of exercise ($p<0.05$, Table 3.1; Fig 3.2).

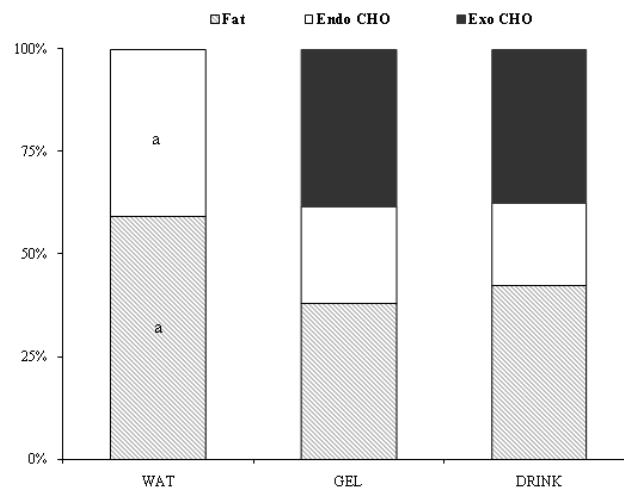


Figure 3.2 Relative contribution of substrates to total energy expenditure calculated during the 60 to 180 min exercise period with WAT, GEL, or DRINK ingestion. Values are presented as mean. a Significantly different than both GEL and DRINK ($p < 0.05$).

Plasma metabolites

Resting plasma glucose, lactate and free fatty acid concentrations before the onset of exercise were similar between all 3 trials. Throughout exercise in the WAT trial plasma glucose concentrations stayed relatively stable and above ~ 5 mmol/L. Plasma glucose concentrations significantly increased (Figure 3.3; $p < 0.05$) with the ingestion of both CHO treatments to peak values of ~ 7.9 mmol/L at 30 min of exercise. In both trials plasma glucose concentrations were significantly higher ($p < 0.05$) over the whole time period except the 45 min time-point with both treatments and the 90 min measure in the GEL trial. Plasma glucose concentrations from both CHO treatments were not significantly different ($p > 0.05$).

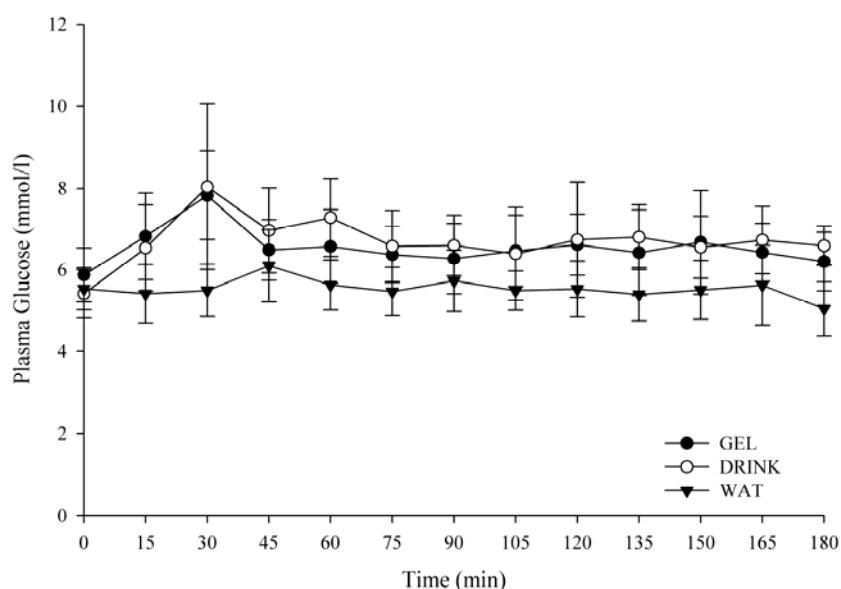


Figure 3.3 Plasma glucose concentrations with ingestion of WAT, GEL, DRINK. Values are mean \pm SD. b GEL trial significantly greater than WAT ($p<0.05$). c DRINK significantly greater than WAT ($p<0.05$).

Plasma lactate (Figure 3.4) increased significantly in the first 15 min during all three trials ($p<0.05$). Within the first 135 min of exercise plasma lactate concentrations were higher within the CHO trials than with WAT, reaching statistical significance between 15-75 min and 120-135 min for the GEL and at 30, 60 and 120 min with DRINK ($p<0.05$).

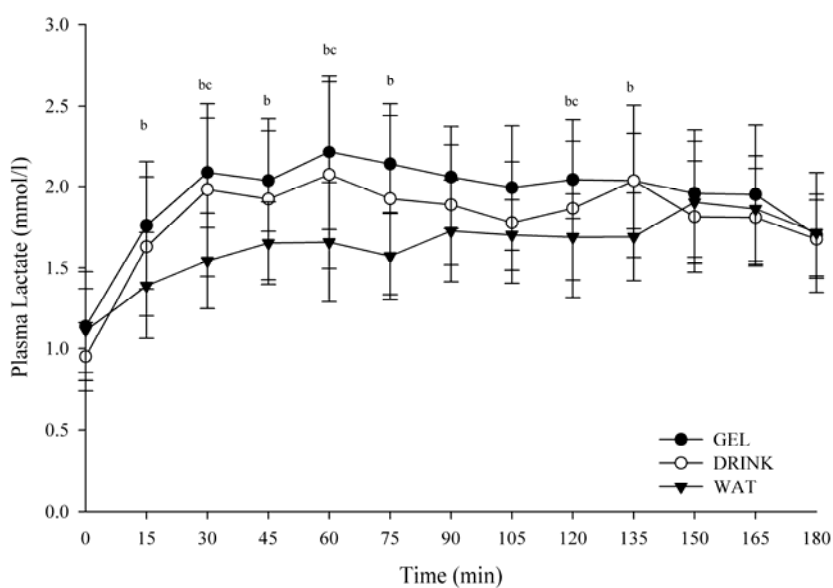


Figure 3.4 Plasma lactate concentrations with ingestion of WAT, GEL, DRINK. Values are mean \pm SD. b GEL significantly higher than WAT ($p<0.05$). c DRINK significantly greater than WAT ($p<0.05$).

Concentrations of FFA in plasma (Figure 3.5) increased during the WAT trial and were significantly higher than during the CHO trials after 30 min until the end of exercise. No significant differences occurred between the CHO trials.

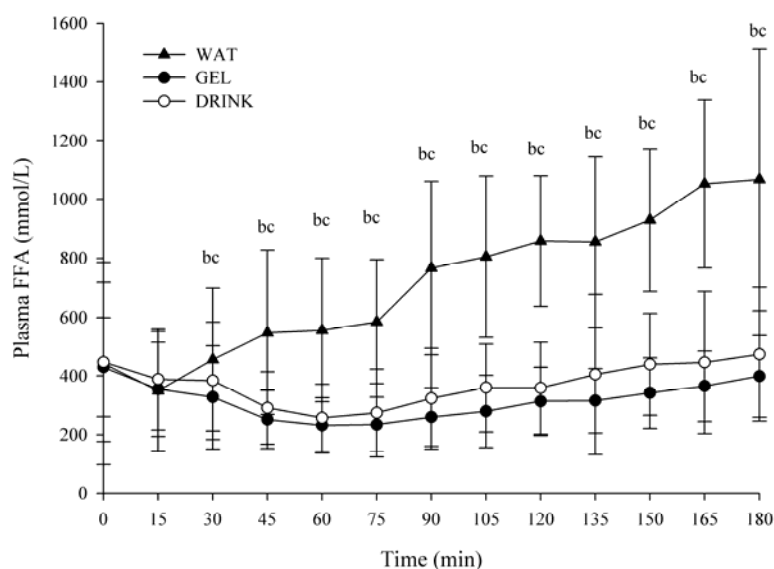


Figure 3.5 Plasma free fatty acid (FFA) concentrations with ingestion of WAT, GEL, DRINK. Values are mean±SD. b WAT significantly greater than DRINK ($p < 0.05$). c WAT significantly greater than DRINK ($p < 0.05$).

GI symptoms, perceived fullness, RPE

No severe GI symptoms (>4) were recorded in any of the trials and no significant differences were detected between trials. Furthermore no difference in perceived stomach fullness was detected. Levels of perceived exertion during the last half hour of exercise were 13 ± 2 , 12 ± 1 and 12 ± 1 in the WAT, GEL and DRINK trials, respectively.

exogenous CHO oxidation rates at the end of 3 h steady state cycling (1.44 ± 0.29 g/min and 1.42 ± 0.23 for GEL and DRINK, respectively).

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

It has been suggested that exogenous CHO oxidation is potentially limited by gastric emptying, intestinal absorption, liver GLU extraction, muscle GLU uptake, or a combination of these factors (18). As mentioned earlier the rate limiting steps for exogenous CHO oxidation are thought to be the entrance into the systemic circulation via absorption in the small intestines rather than intramuscular factors (18). A potential of high CHO concentrations to limit gastric emptying rates of a solution has repeatedly been documented (9, 38). For example, Vist *et al.* (38) reported significantly slower gastric emptying rates with an 18% compared with a 4% CHO solution. However, CHO delivery to the small intestines was still significantly higher with the 18% compared with the 4% solution. In the current study, fluid volume and energy density, the most potent influencers of gastric emptying rates (22, 26), were similar between CHO trials and from this point of view no difference between treatments was expected. The focus of the present study was to purely evaluate the impact of CHO intake form on exogenous CHO oxidation rates.

Previous studies have reported altered gastric emptying rates with changes in viscosity of ingested drinks: The addition of gel forming fibres such as guar gum to CHO solutions has been reported to slow down gastric emptying in some studies (25, 34). In contrast a study by Leiper *et al.* (23) reported faster gastric emptying rates from a gel-forming GLU polymer (78% amylopectin and 22% amylose) compared with an isocaloric, low-viscosity GLU solution (GLU and GLU oligomers). Interestingly, this study did not detect differences in plasma GLU and insulin concentrations and it could be speculated that faster gastric emptying rates of the GLU polymer were “neutralized” by slower digestion and absorption of the GLU polymer (especially amylose) compared with the GLU solution. It has indeed been suggested earlier that α -amylase susceptibility rather than viscosity determine the plasma responses after ingestion of starch containing meals (2).

Furthermore, it has been proposed that intestinal absorption is the more important driver for exogenous CHO oxidation rates compared with gastric emptying rates (18). To date there was no evidence whether CHO from gel or solution are absorbed to a similar extent in the GI tract. As discussed earlier there would have been the possibility that the simultaneously ingested semi-solid GEL and water are not entirely mixed together when leaving the stomach. The stomach empties in layers (for review, see (33)), holding back solid and more concentrated foods in the sinus of the stomach. This could result in differences in CHO concentrations in the small intestine between a readily dissolved drink and a gel and therefore lead to a different time-course of rates of intestinal absorption. Consequently, the similarly high exogenous CHO oxidation rates of the present study give indirect evidence that both CHO treatments (GEL vs. DRINK) are absorbed at similar rates.

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

The similar oxidation rates in the present study fit with the results of a study by Campbell *et al.* (4), which demonstrated a similar effect on performance when a CHO gel was compared with a drink. The beneficial effects of CHO on endurance exercise performance are generally well accepted. However, the mechanism(s) to explain the positive performance findings are not entirely clear, but have partly been attributed to the maintenance of euglycaemia, a sparing of endogenous CHO stores, a central stimulatory CNS effect or the maintenance of high CHO oxidation rates late in exercise. Correspondingly, a recent study utilizing GLU+FRC mixtures, which previously have been shown to increase exogenous CHO oxidation by 20-55%, resulted in an 8% significant increase in TT performance (17). In this study, 2 h of moderate intensity steady state cycling was undertaken with a CHO ingestion rate of 1.8 g/min in the form of GLU or GLU+FRC, and was followed by a 40-km cycling TT. The ingestion of a GLU+FRC drink resulted in an 8% improvement in TT performance compared with GLU and 19%

compared with the water placebo (11). In the present study both forms of CHO intake raised blood glucose above concentrations during the WAT trial and therefore effectively maintained euglycaemia. Accordingly, total CHO oxidation rates also remained ~50% higher ($p < 0.001$) than WAT at the end of exercise with both forms of CHO intake. Furthermore, the ingestion of GEL and DRINK resulted in similar and high exogenous CHO oxidation rates and a substantial suppression of estimated endogenous CHO oxidation (Fig. 2). These current findings help to explain the similar ergogenic effects on endurance performance found with gels versus sports drinks (4).

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

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

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Chapter 4

Oxidation of Solid versus Liquid Carbohydrate

Sources during Exercise

4.1 Abstract

The ingestion of carbohydrate (CHO) solutions has been shown to increase CHO oxidation and improve endurance performance. However, the majority of studies have investigated CHO in solution and sporting practice includes ingestion of CHO in solid (e.g. energy bars) as well as liquid form. It remains unknown whether CHO in solid form is as effectively oxidized compared with CHO solutions. **Purpose:** To investigate exogenous CHO oxidation from CHO provided in either solid (BAR) or solution (DRINK) form during cycling. **Method:** Eight well trained subjects (31 ± 7 y; 73 ± 5 kg; 1.79 ± 0.05 m; $\text{VO}_{2\text{max}}$: 69 ± 6 mL/kg/min) cycled at $58 \pm 4\%$ $\text{VO}_{2\text{max}}$ for 180 min while receiving one of the following three treatments in randomized order: BAR plus water, DRINK, or water. The BAR and DRINK delivered glucose + fructose (GLU+FRC) in a ratio of 2:1 at a rate of 1.55 g/min and fluid intake was matched between treatments. **Results:** During the final 2 h of exercise overall mean exogenous CHO oxidation rate was -0.11 g/min lower in BAR (95% confidence interval: -0.27 to 0.05 g/min; $p=0.19$) relative to DRINK; exogenous CHO oxidation rates were 15% lower in BAR ($p<0.05$) at 120, 135, and 150 min of exercise. Peak exogenous CHO oxidation rates were high in both conditions (BAR: 1.25 ± 0.15 g/min, DRINK: 1.34 ± 0.27 g/min), but were not significantly different ($p=0.36$) between treatments (mean difference: -0.09 g/min, 95% confidence interval: -0.32 to 0.13 g/min). **Conclusion:** The present study demonstrates that a GLU+FRC mix administered as a solid BAR during cycling can lead to high mean and peak exogenous CHO oxidation rates (>1 g/min). The GLU+FRC mix ingested in form of a solid BAR resulted in similar average and peak exogenous CHO oxidation rates and showed similar oxidation efficiencies as a DRINK. These findings suggest that CHO from a solid BAR is effectively oxidized during exercise and can be a practical form of supplementation alongside other forms of CHO.

4.2 Introduction

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

The efficacy of CHOs to improve endurance performance is due, in part, to their capacity to be oxidized by the working muscle. A mixture of glucose (GLU) and fructose (FRC) has been shown to be oxidized at 20-55% higher rates than as GLU alone, when ingested at high rates (1.5 to 2.4 g/min) (15, 16). Recently it was also demonstrated that a similar GLU+FRC drink (1.8 g/min) resulted in superior endurance performance compared with an isocaloric GLU drink (8, 39).

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

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

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

4.3 Methods

Subjects

Eight well trained male endurance cyclists/triathletes (31 ± 7 y; 73 ± 5 kg; 1.79 ± 0.05 m; VO_2max : 69 ± 6 mL/kg/min) volunteered to participate in this study. Subjects trained at least 3 times/wk for more than 2 h/d and had been involved in endurance training for at least 2 y. All subjects were healthy as assessed by a general health questionnaire. Exclusion criteria for the study were: diagnosis of metabolic or intestinal disorders, smoking, associated cycling injuries, regular consumption of medication, and donation of blood in the previous three weeks. All subjects were informed of the purpose, practical details, and risks associated with the procedures before giving their written informed consent to participate. The study was approved by the School of Sport and Exercise Sciences ethics subcommittee, University of Birmingham, Birmingham UK.

Preliminary testing

At least 1 wk before the start of the experimental trials, an incremental cycle test to volitional exhaustion was performed to determine maximal power output (W_{max}) and maximal oxygen consumption (VO_2max) on an electromagnetically braked cycle ergometer (Lode Excalibur Sport, Groningen, The Netherlands). Upon arrival at the laboratory, body mass (Seca Alpha, Hamburg, Germany) and height were recorded. Subjects then started cycling for 3 min at 95 W, followed by incremental steps of 35 W every 3 min until exhaustion. W_{max} was determined by the following formula: $W_{\text{max}} = W_{\text{out}} + [(t/180) \cdot 35]$, where W_{out} is the power output (W) during the last completed stage, and t is the time (s) in the final stage. Heart rate (HR) was recorded continuously by a radio telemetry HR monitor (Polar 625X, Kempele, Finland). W_{max} values were used to determine the 50% W_{max} , which

was later employed in the experimental trials. Respiratory gas measurements were taken using the Douglas bag technique. Douglas bags were collected for 1 min during the final stage and were analysed using a Servomex 1400 Gas analyser (Servomex 1400, Crowborough, Sussex, England).

Experimental design

Each subject completed three exercise trials that consisted of 180 min cycling at 50% W_{\max} while ingesting 1.55 g/min CHO (glucose and fructose in the ratio of 2:1) in the form of a 10.75% maltodextrin plus fructose drink (DRINK), or an isocarbohydrate energy bar plus plain water (BAR), or plain water (WAT). The order of the trials were randomly assigned and separated by at least 5 d.

Experimental treatments

As the BAR contained not only CHO, but fat and protein as well, the CHO treatments were not isocaloric (Table 4.1A).

Table 4.1A: Nutrition facts for both CHO treatments

	per bar (65g)	per 400mL CHO drink
Energy (kcal)	230	172
Protein (g)	8	
Carbohydrate (g)	43	43
Fat (g)	2	
Fibre (g)	2	
Sodium (mg)	200	200

The BAR also consisted of different CHOs (see Table 4.1B). $\frac{2}{3}$ of the CHO consisted of glucose and glucose polymers and $\frac{1}{3}$ of fructose (per BAR 5 g as crystalline Fructose and 9 g contained in cane syrup).

To quantify exogenous CHO oxidation, corn-derived maltodextrin (Glucidex 19, Roquette, France) and fructose (Krystar 300, A. E. Stanley Manufacturing Company, Illinois), which have a high natural abundance of ^{13}C (-11.22 and -10.72 ‰ vs Pee Dee Bellemnitella (PDB), respectively) were used for preparation of the DRINK. In order to ensure a similar amount of sodium in the BAR and in the DRINK, sodium in the form of sodium chloride was added to the DRINK (500 mg sodium/L). The BAR consisted predominantly of ingredients with a high natural abundance of ^{13}C (72%). The enrichment of all CHO sources of the BAR is shown in Table 4.1B. The ^{13}C enrichment of the ingested CHO was determined by elemental analyser-isotope ratio mass spectrometry (EA-IRMS; Europa Scientific GEO 20-20, Crewe, UK).

Table 4.1B: Enrichment of different CHO sources of the BAR

		Mean d13CV-PBD (‰)	% CHO
High enriched CHO	Cane Syrup		
	Maltodextrin	-11.05	72%
	Fructose		
Low enriched CHO	Crisp Rice		
	Oat Bran	-27.15	28%*
	Brown Rice Flour		
	* 5% starch		

Diet and activity before testing

Subjects were asked to record their food intake and activity patterns for 24 h prior to the first exercise trial and were then instructed to follow the same diet and activities before the next two trials. The instructions also contained detailed advice by a nutritionist to follow a diet rich in CHO. It was made sure that CHO intake was >4 g/kgBW, which in combination

with light training or rest would allow participants to start the trials with adequate muscle glycogen stores.

Diet was assessed with 24 h recalls the days before the rest of the trials and CHO intake of all participants was confirmed to be above 4 g/kg BW. In addition, subjects were instructed to refrain from strenuous exercise and drinking any alcohol in the 24 h before the exercise trials. Furthermore, subjects were instructed to perform an intense training session (“glycogen-depleting exercise bout”) 3–7 d before each experimental trial in an attempt to reduce any ^{13}C -enriched glycogen stores. Subjects were also instructed not to consume products with a high natural abundance of ^{13}C ; CHOs derived from C4 plants (maize, sugar cane) had to be avoided at least 1 wk before each experimental trial to reduce the background shift (change in ^{13}C) from endogenous substrate stores. Subjects received detailed guidance on foods, which they needed to avoid as well as advice on potential alternatives and were contacted several times during the weeks before the trials to ensure compliance.

Protocol

The subjects arrived in the laboratory in the morning (between 6:00 and 9:00 a.m.) after an overnight fast (10–12 h). All experimental trials were performed at the same time of day to avoid circadian variance. On arrival, subjects were weighed before a 20-gauge Teflon catheter (Venflon, BD, Plymouth, UK) was inserted into an antecubital vein of an arm and attached to a three-way stopcock (Sims Portex, Kingsmead, UK) to allow for repeated blood sampling during exercise. The cannula was kept patent by flushing with 1.0–1.5 mL of isotonic saline (0.9%, BD) after each blood sample collection. The subjects then mounted a cycle ergometer and a resting breath sample was collected into a 10-mL

Exetainer tube (Labco Ltd., Brow Works, High Wycombe, UK), which was filled directly from a mixing chamber to determine the $^{13}\text{C}/^{12}\text{C}$ ratio in the expired air. A resting blood sample (10 mL) was collected and stored on ice until centrifugation. Subjects then started a 180 min exercise bout at a work rate equivalent to 50% \dot{W}_{max} (58 ± 4 % $\dot{V}\text{O}_{2\text{max}}$). Additional blood samples were drawn at 15 min intervals until the cessation of exercise. At the same 15 min intervals expiratory breath samples were also collected. During the first 2 min expired air was sampled into Douglas bags. Douglas bag samples were analysed as described above and oxygen consumption ($\dot{V}\text{O}_2$), carbon dioxide production ($\dot{V}\text{CO}_2$), and respiratory exchange ratio (RER) were determined. Within the last 60 s of each 3 min period Exetainer tubes were filled in duplicate for breath $^{13}\text{C}/^{12}\text{C}$ ratio as described above. During the first 2–3 min of exercise, subjects ingested an initial bolus of one of the three experimental treatments: 400 mL water (WAT), 400 mL water plus one energy bar (BAR), 400 mL 10.75% CHO drink (DRINK). Thereafter a beverage volume of 200 mL and 32.5 g BAR was provided every 15 min. The total fluid intake during the exercise bout was 2.6 L (867 mL/h), while the total CHO intake was 280 g (93 g/h). All exercise tests were performed under normal and standard environmental conditions (16–24°C dry bulb temperature and 50–60% relative humidity). During the exercise trials, subjects were cooled with standing floor fans to minimize thermal stress.

Questionnaires

Every 30 min during the exercise bout, subjects were requested to verbally answer a short questionnaire to directly assess gastrointestinal (GI) tolerance. GI symptoms were scored on a 10-point scale (0 = no problem at all and 9 = the worst it has ever been). A score >4

was registered as serious. Ratings of perceived exertion (RPE) were collected using a 6-20 point Borg scale (1).

Analyses

All blood samples were collected into pre-chilled test tubes containing EDTA and centrifuged at 2300 g for 10 min at 4°C. Aliquots of the plasma were frozen and stored at -25°C until further analysis. Plasma samples were analysed enzymatically for glucose (Glucose HK, ABX Diagnostics, UK), lactate (Lactic Acid, ABX Diagnostics), and free fatty acid (FFA) (NEFA-C Kit, Alpha Laboratories, UK) concentration on a semiautomatic analyser (Cobas Mira S-Plus, ABX). Insulin was analysed by ELISA (DRG® Ultrasensitive Insulin ELISA, DRG Instruments GmbH, Marburg, Germany). Breath samples were analysed for $^{13}\text{C}/^{12}\text{C}$ ratio by continuous flow IRMS (GC, Trace GC Ultra; IRMS, Delta Plus XP; both Thermo Finnigan, Herts, UK). From indirect calorimetry (VO_2 and VCO_2) and stable isotope measurements (breath $^{13}\text{C}/^{12}\text{C}$ ratio), rates of total fat, total CHO, and exogenous CHO oxidation were calculated.

Calculations

From VO_2 and VCO_2 (L/min), CHO and fat oxidation rates (g/min) were calculated using stoichiometric equations (19), with the assumption that protein oxidation during exercise was negligible.

$$\text{CHO oxidation} = 4.21 \text{ VCO}_2 + 2.962 \text{VO}_2 \text{ [1]}$$

$$\text{Fat oxidation} = 1.695 \text{VO}_2 + 1.701 \text{ VCO}_2 \text{ [2]}$$

The isotopic enrichment was expressed as δ per mil difference between the $^{13}\text{C}/^{12}\text{C}$ ratio of the sample and a known laboratory reference standard according to the formula of Craig (7):

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

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

In the CHO trials, the rate of exogenous CHO oxidation was calculated using the following formula (31):

$$\text{Exogenous CHO oxidation} = \text{VCO}_2 \cdot \left(\frac{\delta_{\text{Exp}} - \text{Exp}_{\text{bkg}}}{\delta_{\text{Ing}} - \text{Exp}_{\text{bkg}}} \right) \cdot \left(\frac{1}{k} \right)$$

in which δ_{Exp} is the ^{13}C enrichment of expired air during exercise at different time points, δ_{Ing} is the ^{13}C enrichment of the ingested CHO solution, $\delta_{\text{Exp}_{\text{bkg}}}$ is the ^{13}C enrichment of expired air in the WAT trial (background) at different time points, and k is the amount of CO_2 (in liters) produced by the oxidation of 1 g of glucose ($k = 0.7467$ L of CO_2 per gram of glucose).

To determine the enrichment of the BAR, an average value of the enrichments of all CHO sources according to their content in the BAR was calculated first. The exogenous CHO oxidation calculated with this approach would assume that all CHOs are oxidized at the same rate and lead to an overestimation (maximum exogenous CHO oxidation). The limitation of this approach is that 28% of CHO in the BAR show low ^{13}C enrichment. 18% of the low ^{13}C -CHO (~5% of total CHO) consists of starch (Table 4.1B). As insoluble starch (24% amylose, 76% amylopectin) has been shown to be oxidized at (about 30%)

lower rates as glucose (36), the small amounts of starch could lead to an overestimation of exogenous CHO oxidation of ~3%. To account for the possible overestimation a second enrichment value (minimum exogenous CHO oxidation) was used, assuming that starch was not oxidized at all. Both enrichment values were then averaged and used for calculations (enrichment: -15.2).

Endogenous CHO oxidation was calculated by subtracting exogenous CHO oxidation from total CHO oxidation. A methodological consideration when using $^{13}\text{CO}_2$ in expired air to calculate exogenous substrate oxidation is the temporary fixing of $^{13}\text{CO}_2$ in the bicarbonate pool, in which an amount of CO_2 arising from CHO and fat oxidation is retained (34). However, during exercise, the turnover of this pool increases several fold so that a physiological steady state condition will occur relatively rapidly and $^{13}\text{CO}_2$ in the expired air will be equilibrated with the $^{13}\text{CO}_2/\text{H}^{13}\text{CO}_2$ pool, respectively. Recovery of $^{13}\text{CO}_2$ from oxidation will approach 100% after 60 min of exercise when the dilution in the bicarbonate pool becomes negligible (30, 34). As a consequence of this, all calculations on substrate oxidation were performed over the last 120 min of exercise (60–180 min). The oxidation efficiency was determined as the percentage of the ingested CHO that was oxidized and was calculated by dividing exogenous CHO oxidation rate by the CHO ingestion rate and then multiplied by 100.

Statistical analyses

A two-way analysis of variance (treatment*time) for repeated measures was used to compare differences in substrate utilization and in blood metabolites between the three trials. A Tukey post hoc test was applied where a significant F-ratio was detected. Paired

sample t-tests were applied when two mean values were compared. Mean values in text, tables and figure are presented as mean \pm standard deviation (SD). Differences between treatments are presented as mean differences with 95% confidence interval. Statistical significance was set at $p < 0.05$. All statistics were performed using SPSS 15 for Windows (SPSS Inc., 233 S. Wacker Drive, Chicago, Illinois, USA).

4.4 Results

VO₂, RER, total CHO, and fat oxidation

VO₂, RER, and total CHO and fat oxidation rates over the 60-180 min exercise period are shown in Table 4.2. There was no significant difference in VO₂ between the three experimental trials. RER was significantly ($p < 0.01$) lower in the WAT trial compared with the two CHO ingestion trials, but was not significantly different between the BAR and DRINK trials. Correspondingly, CHO oxidation was not significantly different between the two CHO trials, but was significantly higher than compared with WAT ($p < 0.01$). The average total CHO oxidation rates during the last 120 min of exercise were 1.64 ± 0.56 , 2.26 ± 0.31 , and 2.22 ± 0.43 g/min for WAT, BAR and DRINK, respectively. Fat oxidation was significantly higher in the WAT trial than after CHO ingestion ($p < 0.01$). Average fat oxidation rates over the last 120 min of exercise were 0.89 ± 0.29 , 0.58 ± 0.21 and 0.57 ± 0.22 g/min for WAT, BAR and DRINK, respectively. Fat oxidation did not differ significantly between the BAR and DRINK trials.

Table 4.2 Oxygen uptake (VO_2), respiratory exchange ratio (RER), total CHO oxidation ($\text{CHO}_{\text{total}}$), total fat oxidation ($\text{fat}_{\text{total}}$), endogenous CHO oxidation, and exogenous CHO oxidation with ingestion of WAT, BAR, DRINK. Values are means \pm SD. a Significant difference between CHO treatments. b Significantly different from WAT.

Trial	Time (min)	VO_2 (l/min)	RER	$\text{CHO}_{\text{total}}$ (g/min)	$\text{Fat}_{\text{total}}$ (g/min)	Endogenous CHO (g/min)	Exogenous CHO (g/min)
WAT	60-90	2.91 ± 0.20	0.83 ± 0.05	1.77 ± 0.53	0.81 ± 0.26	1.77 ± 0.53	
	90-120	2.98 ± 0.22	0.82 ± 0.06	1.64 ± 0.62	0.90 ± 0.30	1.64 ± 0.62	
	120-150	3.02 ± 0.24	0.82 ± 0.06	1.61 ± 0.60	0.93 ± 0.30	1.61 ± 0.60	
	150-180	3.00 ± 0.23	0.81 ± 0.06	1.54 ± 0.60	0.95 ± 0.31	1.54 ± 0.60	
	60-180	2.97 ± 0.22	0.82 ± 0.05	1.64 ± 0.58	0.89 ± 0.29	1.64 ± 0.50	
BAR	60-90	2.95 ± 0.24	0.88 ± 0.03^b	2.23 ± 0.25^b	0.57 ± 0.19^b	1.33 ± 0.27^b	0.90 ± 0.12
	90-120	2.98 ± 0.24	0.88 ± 0.03^b	2.24 ± 0.31^b	0.58 ± 0.19^b	1.26 ± 0.31^b	0.98 ± 0.15
	120-150	2.99 ± 0.25	0.88 ± 0.03^b	2.25 ± 0.32^b	0.58 ± 0.21^b	1.21 ± 0.28^{ab}	1.04 ± 0.13
	150-180	3.03 ± 0.23	0.88 ± 0.04^b	2.27 ± 0.36^b	0.59 ± 0.23^b	1.09 ± 0.31^b	1.17 ± 0.11
	60-180	2.99 ± 0.24	0.88 ± 0.03^b	2.26 ± 0.31^b	0.58 ± 0.21^b	1.23 ± 0.29^b	1.03 ± 0.11
DRINK	60-90	2.91 ± 0.21	0.89 ± 0.04^b	2.22 ± 0.46^b	0.55 ± 0.23^b	1.26 ± 0.38^b	0.96 ± 0.13
	90-120	2.93 ± 0.22	0.89 ± 0.04^b	2.24 ± 0.41^b	0.56 ± 0.22^b	1.12 ± 0.35^b	1.12 ± 0.13
	120-150	2.95 ± 0.23	0.88 ± 0.04^b	2.23 ± 0.40^b	0.57 ± 0.21^b	0.99 ± 0.31^b	1.24 ± 0.16
	150-180	2.95 ± 0.24	0.88 ± 0.04^b	2.19 ± 0.47^b	0.59 ± 0.22^b	0.88 ± 0.33^b	1.30 ± 0.22
	60-180	2.94 ± 0.22	0.88 ± 0.04^b	2.22 ± 0.43^b	0.57 ± 0.22^b	1.08 ± 0.34^b	1.14 ± 0.16

Exogenous CHO oxidation, endogenous CHO oxidation, and oxidation efficiency

Changes in breath $^{13}\text{CO}_2$ enrichment in the water trial were below 0.5 δ per mil vs. PDB and resting breath $^{13}\text{CO}_2$ enrichment was not significantly different between trials, indicating that $^{13}\text{CO}_2$ enrichment of endogenous CHO stores was low and similar between trials. Calculated exogenous CHO oxidation rates gradually increased over time and leveled off after 135 min with the ingestion of the DRINK (Fig. 1). With the BAR, a plateau was reached after 75 min followed by a second significant increase detected after 150 min of exercise. Both treatments lead to high peak exogenous CHO oxidation rates (BAR

1.25±0.15 g/min, DRINK 1.34±0.27 g/min) which were not significantly ($p=0.36$) different between treatments (mean difference: -0.09 g/min, 95% confidence interval: -0.32 to 0.13 g/min). The total amount of the ingested CHO that was oxidized during the entire 180 min exercise was not significantly less with the BAR compared with the DRINK (-16.0 g; -42.4 to 10.2 g; $p=0.19$). Oxidation efficiency for BAR and DRINK was 66±2% vs. 73±4%, respectively and the difference was not significant between CHO trials (-7.1%; confidence limit ±10.5%; $p=0.15$).

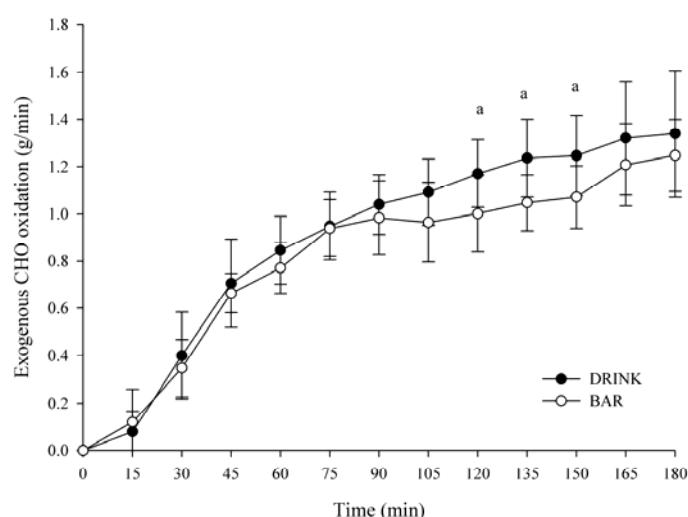


Figure 4.1 Exogenous CHO oxidation in g/min during exercise with ingestion of BAR, DRINK. a Exogenous CHO oxidation in DRINK trial significantly greater than in BAR trial ($p<0.05$).

A treatment over time effect was detected between the CHO trials ($p=0.001$). Significantly higher exogenous CHO oxidation rates from the DRINK as compared with BAR were detected at three intermediate time-points (120, 135, and 150 min). However, the average exogenous CHO oxidation rates over the final 120 min of exercise were high for both treatments (1.03±0.11 and 1.14±0.16g/min for BAR and DRINK, respectively) and not significantly different (-0.11 g/min; -0.27 to 0.05 g/min; $p=0.19$; Table 4.2).

Along with higher exogenous CHO oxidation rates between 120-150 min, endogenous CHO oxidation rates with the DRINK ingestion was significantly lower during this time-period as well. However, no statistically significant differences were found in average endogenous CHO oxidation rates over the last 120 min of exercise between the BAR and DRINK trials (0.11 g/min; -0.09 to 0.32 g/min). Compared with the WAT trial, endogenous CHO oxidation was significantly lower with both forms of CHO ingestion during the last 120 min of exercise ($p=0.02$, Table 4.2).

Plasma metabolites

Plasma glucose and insulin concentrations at rest and during 180 min of exercise are shown in Figures 4.2 and 4.3, respectively. Resting plasma glucose concentrations before the onset of exercise were not significantly different between trials. During exercise in the WAT trial plasma glucose concentration gradually declined from 5.12 ± 0.67 to 4.27 ± 0.76 mmol/L. However, plasma glucose concentrations were maintained throughout the entire exercise period in the BAR and DRINK trials, and were significantly greater than the WAT trial during the last 1 h of exercise. Significantly greater plasma glucose concentrations from the DRINK than compared with the BAR were found after 45 and after 75 min ($p=0.03$ and $p=0.004$, respectively).

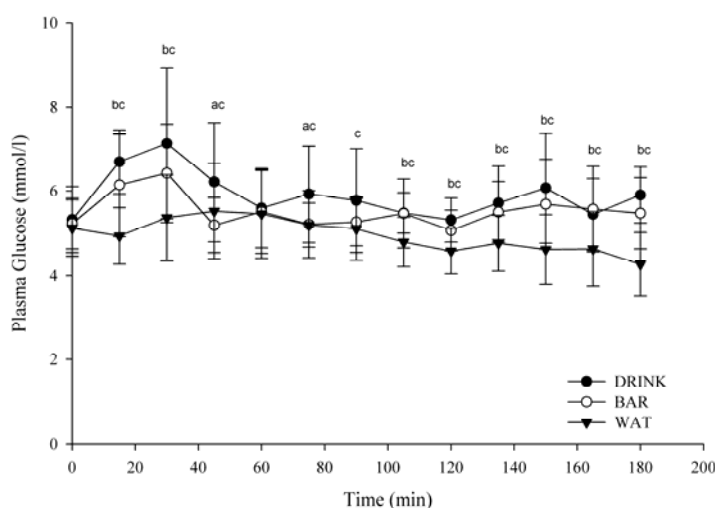


Figure 4.2 Plasma glucose concentrations during exercise with ingestion of WAT, BAR, DRINK. a DRINK significantly greater than BAR trial. b BAR trial significantly greater than WAT. c DRINK significantly greater than WAT.

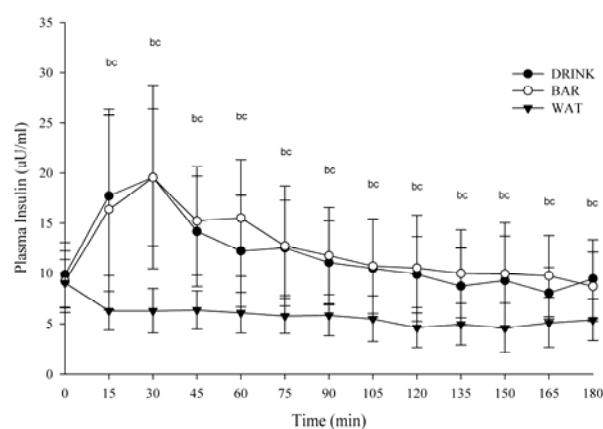


Figure 4.3 Plasma insulin concentrations during exercise with ingestion of WAT, BAR, DRINK. b BAR trial significantly greater than WAT trial. c DRINK significantly greater than WAT.

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

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

Plasma free fatty acid (FFA) concentrations were not significantly different before the onset of exercise (244 ± 118 , 256 ± 169 and 234 ± 168 mmol/L for WAT, BAR and DRINK

respectively). Concentrations of FFA in plasma increased during the WAT trial and were significantly higher than during the CHO trials at all time-points. No significant differences occurred between the CHO trials or over time during exercise.

GI symptoms, perceived fullness, RPE

No severe GI problems were recorded in any of the trials. Mean perceived stomach fullness (Fig. 4.4) during each hour was significantly higher with ingestion of the DRINK than with WAT and significantly higher with the BAR than with both other treatments ($p < 0.05$). Levels of perceived exertion during the last half hour of exercise were 13 ± 2 , 12 ± 2 and 12 ± 1 in the WAT, BAR and DRINK trial, respectively.

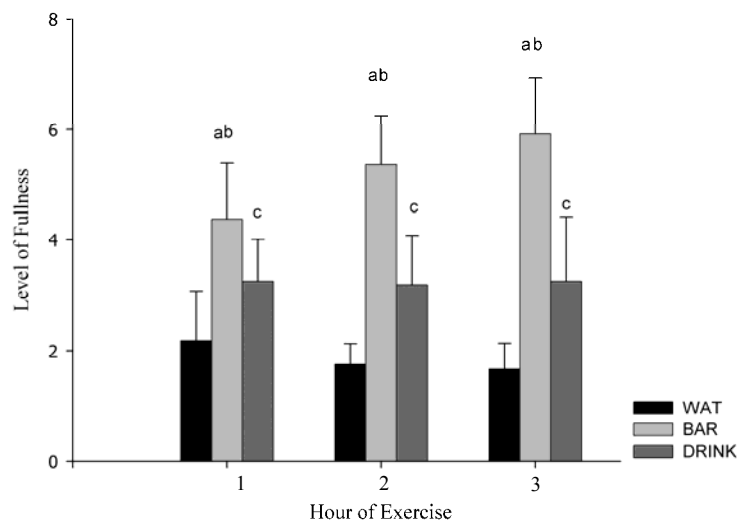


Figure 4.4 Mean perceived stomach fullness during the first, second and third hour of exercise. a BAR trial significantly greater than DRINK trial. b BAR trial significantly greater than WAT trial. c DRINK significantly greater than WAT.

4.5 Discussion

The present study demonstrates that a GLU+FRC mix administered as either a solid BAR or DRINK are both oxidized efficiently and lead to high peak and mean exogenous CHO oxidation rates during exercise. Previously it was thought that despite high intake rates (>1.5 g/min) of single source CHO drinks exogenous CHO oxidation during exercise was limited to peak oxidation rates of ~ 1 g/min (20). In contrast, when drinks containing multiple transportable CHOs are administered, 20-55% higher oxidation rates with peak values of up to 1.75 g/min have been reported (15, 16). In the present study administration of both forms of GLU+FRC (BAR and DRINK) resulted in exogenous CHO oxidation rates above 1 g/min (1.25 ± 0.05 vs. 1.34 ± 0.09 g/min, respectively).

To the best of our knowledge this is the first time that the oxidation of a solid CHO food has been studied during exercise. Technical difficulties are probably the explanation for the lack of studies that measured CHO oxidation from a whole food. Food naturally consists of several CHOs and often other ingredients with different natural enrichments in ^{13}C , making the calculation of exogenous CHO oxidation very complex. As described earlier the BAR used in the current study contained $\sim 5\%$ starch which has been shown to be oxidized at about 30% lower rates as GLU (36) and would have resulted in a possible overestimation of exogenous CHO oxidation rates of $\sim 3\%$. This was avoided by using an average enrichment which assumed that only 50% starch was oxidized. Furthermore, it has repeatedly been documented that endogenous protein oxidation can account for 1-6% of the energy yield during endurance exercise (38). Endogenous protein oxidation would have been reduced by CHO and protein feeding. On the other hand protein from the BAR could have contributed to protein oxidation to a small extent. However, error in total CHO and fat oxidation would

have been small, and with the minimal amount of protein ingested, similar in both conditions. Furthermore, the protein containing sources in the BAR showed a low ^{13}C enrichment (-27.2) and an overestimation of exogenous CHO oxidation through oxidation of ^{13}C from protein is therefore not possible.

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

The rapid increase in exogenous CHO oxidation rates with both treatments goes in line with a similarly quick rise in plasma glucose and insulin concentrations with both treatments. This is in agreement with previous studies, which demonstrated a similar glucose and

insulin response from solid versus liquid at the onset of exercise (21, 33). A ~15% lower oxidation rate for the BAR as compared with the DRINK was detected between 120 and 150 min of exercise. These findings are supported by the study of Robergs et al (33), which found significantly lower blood glucose concentrations from a bar at one time-point (80 min). Both of these studies show a more phasic time course for CHO oxidation and blood glucose from solids as compared with the liquids, respectively. In the current study, after lower oxidation rates from the BAR between 2 and 2.5 h, oxidation rates rise to values >1 g/min, which were not significantly different as compared with the DRINK. This pattern is not only evident in the average data, but also in individual oxidation rates from 7 of 8 participants, a phenomenon that was not seen in data from drinks.

Whether the observed lower exogenous CHO oxidation rates between 2 and 2.5 h could lead to a relevant difference in performance is difficult to answer at this point in time. The exact relationship between increased exogenous CHO oxidation and exercise performance is still unclear. Dose response studies in which the effect of ingestion of different amounts of CHO on performance was investigated have resulted in equivocal findings (for review, see (17)). Although in these studies exogenous CHO oxidation was not measured, it can be assumed that oxidation increased with increasing intake (in the range used in these studies) (17). This increasing intake, however, was not always linked to improved performance (23, 24). No studies have directly investigated the link between increasing exogenous CHO oxidation and performance. Based on the fact that dose responses have not delivered a clear picture, it is likely that substantial increases in exogenous CHO oxidation would be needed to produce a performance benefit. The only (indirect) evidence in this regard is a study by Currell (8) which showed an improvement in performance with GLU+FRC versus GLU.

From a previous study it can be assumed that exogenous CHO oxidation rates were ~35% greater with GLU+FRC ingestion (16). In another study we observed a 13% difference in peak exogenous CHO oxidation during 5 h of exercise at 58%VO₂max (18). Although performance was not measured in the final hour ratings of perceived exertion and self selected cadence were lower in the trial with the higher exogenous CHO oxidation. Whether this would have translated into a performance benefit is unknown. There is only one study in which exogenous CHO oxidation was measured in combination with a performance measurement (35). In this study higher exogenous CHO oxidation rates seemed to be linked to better performance.

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

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Chapter 5

Carbohydrate Oxidation from a Drink during Running Compared with Cycling Exercise

5.1 Abstract

Current recommendations for carbohydrate (CHO) intake in the field for all modes of endurance exercise are largely based on laboratory studies that measured oxidation of ingested CHO. However, the majority of these laboratory studies utilized cycling as the mode of exercise. It is not known whether these results can be extrapolated to running. **Purpose:** To investigate exogenous CHO oxidation from a CHO drink during moderate intensity running (RUN) compared with cycling (CYCLE). **Method:** Eight athletes with comparable CYCLE and RUN training backgrounds (37 ± 7 y; 75 ± 7 kg; 1.77 ± 0.05 m; $VO_{2\max}$ CYCLE: 63 ± 3 mL/kg/min; $VO_{2\max}$ RUN: 65 ± 4 mL/kg/min) performed four exercise trials in random order. The trials consisted of either running or cycling at $\sim 60\%$ of the exercise specific $VO_{2\max}$ for 120 min while receiving either a CHO drink (2:1 glucose:fructose blend; 1.5 g/min) or the same volume of plain water (WAT; 675 mL/h). **Results:** The set workload elicited similar relative exercise intensities of $59.7\pm 2.0\%$ and $59.2\pm 1.9\%$ $VO_{2\max}$ for RUN and CYCLE, respectively. Peak and average exogenous CHO oxidation rates were not significantly different between RUN and CYCLE trials and showed a similar time course (Peak at 120 min: 1.25 ± 0.10 g/min vs. 1.19 ± 0.08 g/min, respectively; $p=0.13$; Average over final h: 1.14 ± 0.10 and 1.11 ± 0.11 g/min, respectively; $p=0.94$). Furthermore, total fat oxidation rates were higher during RUN compared with CYCLE; the difference was significant with ingestion of WAT ($p=0.02$) and failed to reach statistical significance with CHO ($p=0.09$). **Conclusion:** This study demonstrates that exogenous CHO oxidation rates are similar between prolonged running and cycling at a similar relative moderate intensity. These data suggest that previous exogenous CHO oxidation results from cycling studies can be extrapolated to running.

5.2 Introduction

The ingestion of carbohydrate (CHO) improves prolonged cycling as well as running endurance capacity and performance (for review, see 25). Even though a few studies have not shown an ergogenic effect (3, 18, 30), it is generally accepted and recommended that athletes should ingest CHO during prolonged exercise (2, 24). However, the appropriate advice for the dosage rate of CHO during exercise is still under debate. The commonly accepted recommendations of the American College of Sports Medicine (ACSM) (2) are primarily based on laboratory studies conducted on cycle ergometers utilizing a CHO delivery rate of 30-60 g/h (0.5-1 g/min; ~6-8% CHO solutions), with CHO mostly in the form of glucose solutions (10). A more recent, and alternative recommendation (24), is largely based on studies investigating exogenous CHO oxidation during cycling exercise from ingested liquid CHO blends (e.g. glucose + fructose solutions (23, 26, 39)). Based on those studies, the ingestion of larger amounts of CHO blends results in 20-50% greater oxidation rates (23, 26, 39) and performance improvements (15) compared with a single CHO source (e.g. glucose alone). Therefore, this contemporary recommendation advises athletes to take in CHO blends at higher rates of up to 90 g/h (1.5 g/min) during prolonged high intensity exercise (24). These present recommendations (2, 24) are almost exclusively based on laboratory studies that used cycling as the mode of exercise and the validity of these CHO intake recommendations for runners remains to be confirmed.

Currently, little is known about the potential differences in exogenous CHO utilization when comparing cycling *versus* running. To our knowledge there is only one study in the literature that has compared both modes of exercise. In this study, Derman *et al.* (16) showed similar oxidation rates during running compared with cycling. However, the

exercise intensity in that study was set at ~80% $\text{VO}_{2\text{max}}$ and the running trial lasted only ~1 h. As described in the methods section, the tracer methodology that is used to measure exogenous CHO oxidation is limited within the first hour of exercise and can be problematic at higher exercise intensities. Therefore, the examination of exogenous CHO oxidation during prolonged cycling as compared with running remains to be examined.

The movement and muscle recruitment patterns of the two modes of exercise are clearly different (5, 20) and it is not surprising that differences in energy metabolism have been detected (1, 29). A difference in exogenous CHO oxidation could be expected based on the few studies that have investigated exercise metabolism during running compared with cycling (1, 4, 16, 29). Studies investigating substrate oxidation in the fasted state with the use of a graded exercise protocol have detected higher total fat oxidation rates over a wide range of intensities during running as compared with cycling (1, 29). It has also been proposed that CHO ingestion during running causes a higher elevation of plasma glucose and insulin concentrations compared with cycling (4, 36), which would potentially lead to an increase in muscle glucose uptake and reduced glycogenolysis. Furthermore, running is associated with a higher prevalence for GI distress compared with cycling (31, 32) and it was speculated that one factor leading to GI symptoms during running could be altered absorption due to relatively high mechanical stress (19). Taken together, we hypothesized that exogenous CHO would be oxidized less effectively during running as compared with cycling. The present study was therefore designed to investigate whether exogenous CHO oxidation rates are different during prolonged (2 h) running compared with cycling at the same relative sport specific exercise intensity of ~60% $\text{VO}_{2\text{max}}$.

5.3 Methods

Subjects

Eight well trained male endurance cyclists/triathletes (37 ± 7 y; 75 ± 7 kg; 1.77 ± 0.05 m; VO_2max CYCLE: 63 ± 3 mL/kg/min; VO_2max RUN: 65 ± 4 mL/kg/min) volunteered to participate in this study. Subjects undertook both cycling and running training at least 3 times/wk for more than 2 h/session. Furthermore, they had been involved in running and cycling training for a similar length of time and at least 2 y. All subjects were healthy as assessed by a general health questionnaire and were informed of the purpose, practical details, and risks associated with the procedures before giving their written informed consent to participate. The studies were approved by the School of Sport and Exercise Sciences ethics subcommittee, University of Birmingham, Birmingham UK.

Preliminary testing

At least 1 wk before the start of the experimental trials, two incremental exercise tests to volitional exhaustion were performed in randomized order, separated by at least 3 days. Each test was performed in order to determine the relationship between oxygen consumption and power output or speed, as well as maximal oxygen consumption (VO_2max) and lactate threshold (LT), for cycling or running on a cycle ergometer and treadmill, respectively. To determine the exercise intensity for the following experimental trials a linear regression of VO_2 against speed/power output was plotted and the running speed or cycling power output at 60% of VO_2max calculated for running and cycling, respectively. LT was also determined for each mode of exercise according to the method of Coyle *et al.* (13), where LT is defined as the speed/power output at which plasma lactate concentrations rises 1 mmol/L above baseline. During the first visit to the laboratory, body

mass (Seca Alpha, Hamburg, Germany) and height were recorded. Before each test a 20-gauge Teflon catheter (Venflon, BD, Plymouth, UK) was inserted into an antecubital vein of an arm of the subject and attached to a three-way stopcock (Sims Portex, Kingsmead, UK) to allow for repeated blood sampling during exercise and subsequent analyses of plasma lactate.

Preliminary Cycling test protocol:

This test was performed on an electromagnetically braked cycle ergometer (Lode Excalibur Sport, Groningen, The Netherlands). Subjects started cycling for 3 min at 95 W, followed by incremental steps of 35 W every 3 min until exhaustion. A blood sample (~2 mL) was taken at the end of each step. Heart rate (HR) was recorded continuously by a radio telemetry HR monitor (Polar 625X, Kempele, Finland). Breath-by-breath measurements were performed throughout exercise using an automated online gas analysis system (Oxycon Pro; Jaeger, Würzburg, Germany).

Preliminary Running test protocol:

This test was performed on a treadmill ergometer (h/p Cosmos Quasar, h/p/Cosmos, Traunstein, Germany) and was modified according to the protocol of Costill and Fox (11). Prior to commencement of the study the protocol was tested with 4 subjects in order to ensure that $\text{VO}_{2\text{max}}$ values were reached. The subjects started to run at 6 km/h, followed by incremental steps of 2 km/h every 3 min until a speed of 14 km/h was reached. From this point the speed was held constant and the gradient was increased by 1.5% per step. Blood samples were taken at the end of each 3 min step. When the RER reached 1.0 (100%

CHO oxidation) the incremental protocol steps were shortened to 1 min and the test was stopped when a subject clearly indicated exhaustion.

Experimental design

Each subject completed four exercise trials in random order, separated by at least 5 days. The randomized trials consisted of 120 min cycling (CYCLE) or running (RUN) at ~60% $\text{VO}_{2\text{max}}$ while either 1) ingesting 1.5 g/min CHO (glucose and fructose in the ratio of 2:1) in the form of a 13.3% maltodextrin plus fructose drink (CHO), or 2) a control trial of plain water (WAT). The CHO intake rate was based on recent recommendations for CHO intake from multiple transportable CHO (24, 28).

Experimental treatments

To quantify exogenous CHO oxidation, corn-derived maltodextrin (Glucidex 19, Roquette, France) and fructose (Krystar 300 Crystalline Fructose, Tate & Lyle, Decatur, Illinois) were used for preparation of the DRINK, which have a high natural abundance of ^{13}C (-11.22 and -11.00 δ ‰ vs Pee Dee Bellemnitella (PDB), respectively). The ^{13}C enrichment of the ingested CHO was determined by elemental analyser-isotope ratio mass spectrometry (EA-IRMS; Europa Scientific GEO 20-20, Crewe, UK).

Diet and activity before testing

Prior to the first trial, detailed advice was given by a nutritionist to follow a diet rich in CHO. It was made sure that CHO intake was >4 g/kgBW, which in combination with light training or rest would prevent participants starting the trials with depleted muscle glycogen stores. Subjects were asked to record their food intake and activity patterns for 24 h prior to

the first experimental trial and were then instructed to follow the same diet and activities before the next three experimental trials. Compliance was assessed with a 24 h recall the day before each of the remaining trials and checked by a nutritionist upon arrival in the laboratory. In addition, subjects were instructed to refrain from strenuous exercise and drinking any alcohol in the 24 h before the experimental trials. Furthermore, 3–7 d before each experimental trial, the subjects were told to perform a long (>2 h) and hard training session in an attempt to deplete glycogen stores and reduce any ^{13}C -enriched glycogen stores. Subjects were instructed before the first trial about the requirements of a “glycogen depleting exercise”. They were free to choose the exact protocol, but had to repeat the same procedure before each trial. Subjects were also instructed not to consume products with a high natural abundance of ^{13}C (CHOs derived from C4 plants such as maize and sugar cane) at least 1 wk before each experimental trial to reduce the background shift (change in ^{13}C) from endogenous substrate stores. Subjects received detailed guidance on foods, which they needed to avoid as well as advice on potential alternatives and were contacted several times during the weeks before the trials to ensure compliance.

Experimental Protocol

The subjects arrived in the laboratory in the morning (between 6:00 and 9:00 a.m.) after an overnight fast (10–12 h). All experimental trials were performed at the same time of day to avoid circadian variance. On arrival, subjects were weighed before a 20-gauge Teflon catheter (Venflon, BD, Plymouth, UK) was inserted into an antecubital vein of an arm and attached to a three-way stopcock (Sims Portex, Kingsmead, UK) to allow for repeated blood sampling during exercise. The cannula was kept patent by flushing with 1.0–1.5 mL of isotonic saline (0.9%, BD) after each blood sample collection. The subjects then

mounted a cycle ergometer or treadmill and a resting breath sample was collected into a 10-mL Exetainer tube (Labco Ltd., Brow Works, High Wycombe, UK), which was filled directly from a mixing chamber to determine the $^{13}\text{C}/^{12}\text{C}$ ratio in the expired air. A resting blood sample (~10 mL) was collected and stored on ice until centrifugation. Subjects then started the 120 min exercise bout at a work rate calculated to be equivalent to 60% $\text{VO}_{2\text{max}}$ for that respective exercise mode (either CYCLE or RUN). Respiratory gas measures were taken after 10 min and if necessary workload/speed was adjusted in order to match 60% $\text{VO}_{2\text{max}}$. Additional blood samples were drawn at 15 min intervals until the cessation of exercise, along with measures of VO_2 and VCO_2 , using an automated online gas analysis system (Oxycon Pro; Jaeger). Within the last 60 s of each 3 min period Exetainer tubes were filled in duplicate for breath $^{13}\text{C}/^{12}\text{C}$ ratio as described above.

During the first 2–3 min of exercise, subjects ingested an initial bolus of one of the two experimental treatments: 300 mL water (WAT) or 300 mL 13.3% CHO drink (DRINK). Thereafter a beverage volume of 150 mL WAT or 150 mL 13.3% CHO DRINK was provided every 15 min. The total fluid intake during the exercise bout was 1.35 L (675 mL/h), while the total CHO intake was 180 g (90 g/h or 1.5g/min). All exercise tests were performed under normal and standard environmental conditions (16–24°C dry bulb temperature and 50–60% relative humidity). During the exercise trials, subjects were cooled with standing floor fans to minimize thermal stress.

Questionnaires

Every 30 min during the exercise bout, subjects were requested to verbally answer a short questionnaire to directly assess gastrointestinal (GI) tolerance. GI symptoms were scored

on a 10-point scale (0 = no problem at all and 9 = the worst it has ever been). A score >4 was registered as serious. Ratings of perceived exertion (RPE) were collected using a 6-20 point Borg scale (6).

Analyses

All blood samples were collected into pre-chilled test tubes containing EDTA and centrifuged at 2300 g for 10 min at 4°C. Aliquots of the plasma were frozen and stored at -25°C until further analysis. Plasma samples were analysed enzymatically for glucose (Glucose HK, ABX Diagnostics, UK), lactate (Lactic Acid, ABX Diagnostics), and free fatty acid (FFA) (NEFA-C Kit, Alpha Laboratories, UK) concentration on a semiautomatic analyser (Cobas Mira S-Plus, ABX). Insulin was analysed by ELISA (DRG® Ultrasensitive Insulin ELISA, DRG Instruments GmbH, Marburg, Germany). Breath samples were analysed for $^{13}\text{C}/^{12}\text{C}$ ratio by continuous flow IRMS (GC, Trace GC Ultra; IRMS, Delta Plus XP; both Thermo Finnigan, Herts, UK). From indirect calorimetry (VO_2 and VCO_2) and stable isotope measurements (breath ^{13}C enrichment), rates of total fat, total CHO, and exogenous CHO oxidation were calculated.

Calculations

From VO_2 and VCO_2 (L/min), CHO and fat oxidation rates (g/min) were calculated using stoichiometric equations (27), with the assumption that protein oxidation during exercise was negligible.

$$\text{CHO oxidation} = 4.21 \text{ VCO}_2 + 2.962 \text{VO}_2 \text{ [1]}$$

$$\text{Fat oxidation} = 1.695 \text{VO}_2 + 1.701 \text{ VCO}_2 \text{ [2]}$$

The isotopic enrichment was expressed as δ per mil difference between the $^{13}\text{C}/^{12}\text{C}$ ratio of the sample and a known laboratory reference standard according to the formula of (14):

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

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

In the CHO trials, the rate of exogenous CHO oxidation was calculated using the following formula (33):

$$\text{Exogenous CHO oxidation} = \text{VCO}_2 \cdot \left(\frac{\delta \text{Exp} - \text{Exp}_{\text{bkg}}}{\delta \text{Ing} - \text{Exp}_{\text{bkg}}} \right) \cdot \left(\frac{1}{k} \right)$$

in which δExp is the ^{13}C enrichment of expired air during exercise at different time points, δIng is the ^{13}C enrichment of the ingested CHO solution, $\delta \text{Exp}_{\text{bkg}}$ is the ^{13}C enrichment of expired air in the WAT trial (background) at different time points, and k is the amount of CO_2 (in liters) produced by the oxidation of 1 g of glucose ($k = 0.7467 \text{ L of CO}_2 \text{ per gram of glucose}$). Endogenous CHO oxidation was calculated by subtracting exogenous CHO oxidation from total CHO oxidation.

A methodological consideration when using $^{13}\text{CO}_2$ in expired air to calculate exogenous substrate oxidation is the temporary fixing of $^{13}\text{CO}_2$ in the bicarbonate pool, in which an amount of CO_2 arising from CHO and fat oxidation is retained (34). However, during exercise, the turnover of this pool increases several fold so that a physiological steady state condition will occur relatively rapidly and $^{13}\text{CO}_2$ in the expired air will be equilibrated with the $^{13}\text{CO}_2/\text{H}^{13}\text{CO}_2$ pool, respectively. Recovery of $^{13}\text{CO}_2$ from oxidation will approach 100% after 60 min of exercise when the dilution in the bicarbonate pool becomes negligible

(34). As a consequence, all calculations on substrate oxidation were performed over the last 60 min of exercise (60–120 min). The oxidation efficiency was determined as the percentage of the ingested CHO that was oxidized and was calculated by dividing exogenous CHO oxidation rate by the CHO ingestion rate and then multiplied by 100.

Statistical analyses

A two-way (trial x time) ANOVA for repeated measures was used to compare differences in substrate utilization and in blood metabolites between the trials. A Tukey post hoc test was applied where a significant F-ratio was detected. Paired sample t-tests were applied when two mean values were compared. All values are presented as mean \pm standard deviation of the mean (SD). Statistical significance was set at $p < 0.05$. All statistics were performed using SPSS 15 for Windows (SPSS Inc., 233 S. Wacker Drive, Chicago, Illinois, USA).

5.4 Results

VO₂, EE, HR, RPE and LT

Oxygen uptake (VO₂) was not significantly different between treatments within a given mode of exercise. VO₂ over the final 2 h was higher (Table 5.1; $p = 0.002$) during RUN compared with CYCLE within the WAT trial, but not significantly different with CHO treatment ($p = 0.1$). The set workload elicited similar relative exercise intensities of 59.7 ± 2.0 % and 59.2 ± 1.9 % VO₂max for RUN and CYCLE, respectively. Energy expenditure was similar between the CHO and WAT treatments for both running (3603 ± 251 kJ and 3581 ± 266 kJ for WAT and CHO, respectively) and cycling trials (3436 ± 204 kJ and 3464 ± 260 kJ for WAT and CHO, respectively). However, energy expenditure was higher

during RUN compared with CYCLE, during the WAT trials ($p=0.003$), but not significant in the CHO trials ($p=0.08$). Average heart rate over the last hour (127 ± 12 , 123 ± 10 , 130 ± 13 , and 127 ± 12 for WAT RUN, WAT CYCLE, CHO RUN, and CHO CYCLE, respectively) was significantly higher during RUN compared with CYCLE within the WAT trial ($p=0.04$) and not significantly different with CHO treatment ($p=0.06$). RPE values were similar between all trials (11 ± 1 , 12 ± 1 , 11 ± 1 , and 11 ± 1 for WAT RUN, WAT CYCLE, CHO RUN, and CHO CYCLE, respectively). Subjects exercised at significantly higher % LT during RUN compared with CYCLE ($79\pm3\%$ and $72\pm3\%$ LT, respectively; $p=0.02$).

Table 5.1: Oxygen uptake (VO_2), respiratory exchange ratio (RER), total CHO oxidation ($\text{CHO}_{\text{total}}$), total fat oxidation ($\text{fat}_{\text{total}}$), endogenous CHO oxidation, and exogenous CHO oxidation during running (RUN) or cycling (CYCLE) at $\sim 60\%$ $\text{VO}_{2\text{max}}$ with ingestion of WAT or CHO. a significantly different from CYCLE within corresponding WAT or CHO treatment. b CHO significantly different than WAT within corresponding exercise mode. Values are means \pm SD; $p<0.05$.

Trial	Time (min)	VO_2 (L/min)	RER	$\text{CHO}_{\text{total}}$ (g/min)	$\text{Fat}_{\text{total}}$ (g/min)	Endogenous CHO (g/min)	Exogenous CHO (g/min)
WAT RUN	60-90	2.91 ± 217^a	0.81 ± 0.05	1.24 ± 0.49	0.95 ± 0.25^a	1.24 ± 0.49	0
	90-120	2.94 ± 204^a	0.80 ± 0.04	1.21 ± 0.47	0.97 ± 0.23^a	1.21 ± 0.47	0
	60-120	2.92 ± 210^a	0.80 ± 0.04	1.23 ± 0.47	0.96 ± 0.24^a	1.23 ± 0.47	0
WAT CYCLE	60-90	2.75 ± 178	0.83 ± 0.05	1.41 ± 0.41	0.81 ± 0.24	1.41 ± 0.41	0
	90-120	2.80 ± 174	0.82 ± 0.04	1.31 ± 0.40	0.87 ± 0.23	1.31 ± 0.41	0
	60-120	2.78 ± 175	0.82 ± 0.04	1.36 ± 0.40	0.84 ± 0.23	1.36 ± 0.40	0
CHO RUN	60-90	2.87 ± 225	0.85 ± 0.03^b	1.77 ± 0.33^b	0.71 ± 0.17^b	0.71 ± 0.26^b	1.06 ± 0.11
	90-120	2.90 ± 213	0.85 ± 0.03^b	1.80 ± 0.31^b	0.71 ± 0.16^b	0.58 ± 0.27^b	1.22 ± 0.09
	60-120	2.89 ± 217	0.85 ± 0.03^b	1.80 ± 0.31^b	0.71 ± 0.15^b	0.67 ± 0.24^b	1.14 ± 0.10
CHO CYCLE	60-90	2.77 ± 210	0.87 ± 0.03^b	1.91 ± 0.32^b	0.61 ± 0.18^b	0.87 ± 0.26^b	1.03 ± 0.13
	90-120	2.80 ± 219	0.87 ± 0.04^b	1.90 ± 0.41^b	0.63 ± 0.19^b	0.77 ± 0.37^b	1.13 ± 0.11
	60-120	2.79 ± 214	0.87 ± 0.03^b	1.92 ± 0.37^b	0.61 ± 0.19^b	0.81 ± 0.32^b	1.11 ± 0.11

Exogenous CHO oxidation, endogenous CHO oxidation, and oxidation efficiency

Changes in breath $^{13}\text{CO}_2$ enrichment in the water trial were below 0.4 δ per mil vs. PDB and resting breath $^{13}\text{CO}_2$ enrichment was not significantly different between trials, indicating that $^{13}\text{CO}_2$ enrichment of endogenous CHO stores was low and similar between trials. Calculated exogenous CHO oxidation rates increased similarly over time during both modes of exercise (Figure 5.1). Peak exogenous CHO oxidation rates were reached at the end of 120 min exercise and were not significantly different between RUN and CYCLE trials (1.25 ± 0.10 g/min vs. 1.19 ± 0.08 g/min, respectively; $p=0.13$). The average exogenous CHO oxidation rates over the final hour of exercise were also not significantly different between RUN and CYCLE trials (1.14 ± 0.10 and 1.11 ± 0.11 g/min, respectively ($p=0.94$; Table 5.1). Furthermore, the oxidation efficiency was not different between trials ($76 \pm 6\%$ vs. $72 \pm 7\%$, respectively; $p=0.33$).

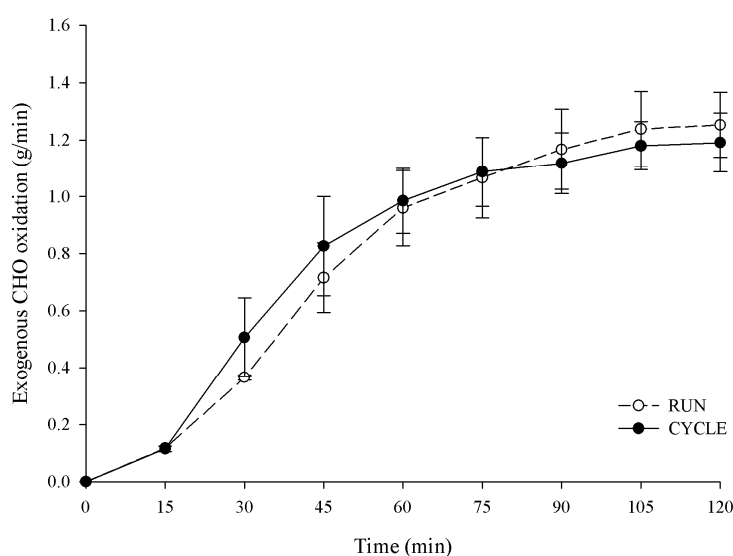


Figure 5.1 Exogenous CHO oxidation in g/min during 120 min running (RUN) and cycling (CYCLE) at $\sim 60\%$ $\text{VO}_{2\text{max}}$. Values are means \pm SD; $p < 0.05$.

Endogenous CHO oxidation during the last 60 min of exercise was significantly lower with CHO ingestion compared with the WAT trials irrespective of mode of exercise ($p=0.005$, $p=0.01$ for RUN and CYCLE, respectively, Table 5.1). There was a trend for lower endogenous CHO oxidation during the RUN compared with the CYCLE trials, however those results were not statistically significant ($p=0.09$ and $p=0.09$ for WAT and CHO, respectively).

RER, total CHO, and fat oxidation

RER, and total CHO and fat oxidation rates over the 60-120 min exercise period are shown in Table 5.1. Significantly lower RER were measured in both WAT trials compared with the two CHO ingestion trials ($p=0.002$ and $p=0.003$ for RUN and CYCLE respectively), but were not significantly different between modes of exercise. Average total CHO oxidation rates over the last 60 min of exercise were not significantly different between WAT RUN and WAT CYCLE or between CHO RUN and CHO CYCLE. Both CHO trials produced significantly higher total CHO oxidation compared with the WAT trials ($p=0.02$ and $p=0.03$ for RUN and CYCLE, respectively).

Average fat oxidation rates over the last hour were significantly lower with CHO ingestion compared with WAT trials ($p=0.003$ and $p=0.005$ for RUN and CYCLE, respectively). With the ingestion of water significantly higher fat oxidation rates were measured in the RUN trial compared with CYCLE ($p=0.02$). With the ingestion of CHO, fat oxidation rates tended to be higher during RUN compared with CYCLE ($p=0.09$).

Plasma measures

Resting concentration of plasma glucose, insulin and lactate were not significantly different, before the onset of the four trials. Within a given treatment (CHO *vs* WAT), there were no statistical differences found between the modes of exercise (CYCLE *vs* RUN) for any of the plasma measures. During exercise in the WAT trial plasma glucose concentrations (Figure 5.2) stayed relatively stable and above ~4.7 mmol/L over the entire exercise period. Plasma glucose concentrations increased with the ingestion of both CHO trials to peak values of ~6.5 mmol/L at 30 min during both modes of exercise. In both the RUN and CYCLE trials plasma glucose concentrations were significantly higher over the whole time period, in CHO *vs*. WAT except the 60 min time-point with both modes, the 120 min measure in the RUN trial, and the 105 min time-point in the CYCLE trial.

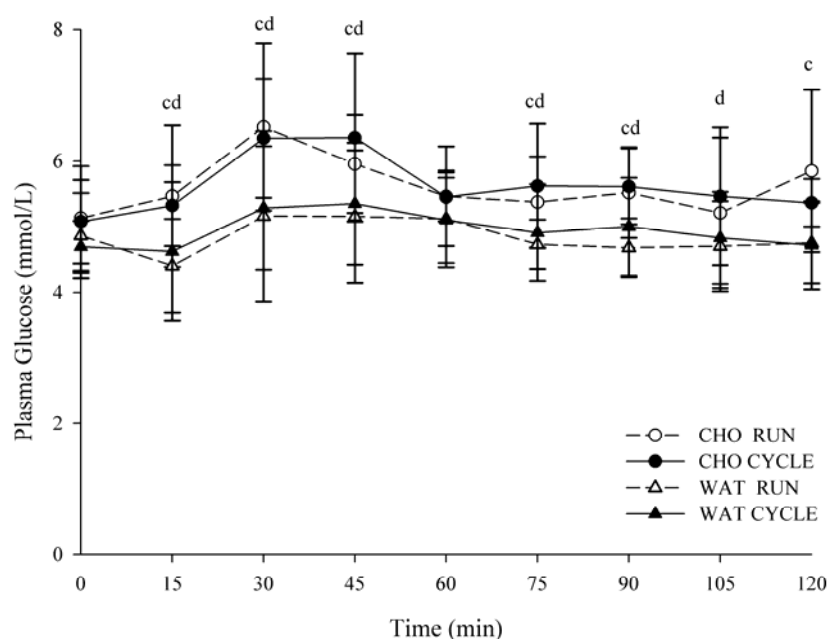


Figure 5.2 Plasma glucose concentration during 120 min running (RUN) or cycling (CYCLE) at ~60% VO_2max with the ingestion of water (WAT) or CHO drink (CHO). Values are means \pm SD; $p < 0.05$. c CHO RUN trial significantly greater than WAT RUN. d CHO CYCLE significantly greater than WAT CYCLE.

Plasma insulin concentrations (Figure 5.3) increased with the ingestion of CHO to peak values of $\sim 35 \mu\text{U/mL}$ after 30 min during RUN and CYCLE trial. In both WAT ingestion trials plasma insulin concentrations decreased to values $\sim 10 \mu\text{U/mL}$ over the 120 min exercise period. Plasma insulin concentrations were significantly higher with the ingestion of CHO over the whole exercise period compared with WAT for both the RUN and CYCLE trials. No difference between modes of exercise was detected with both treatments.

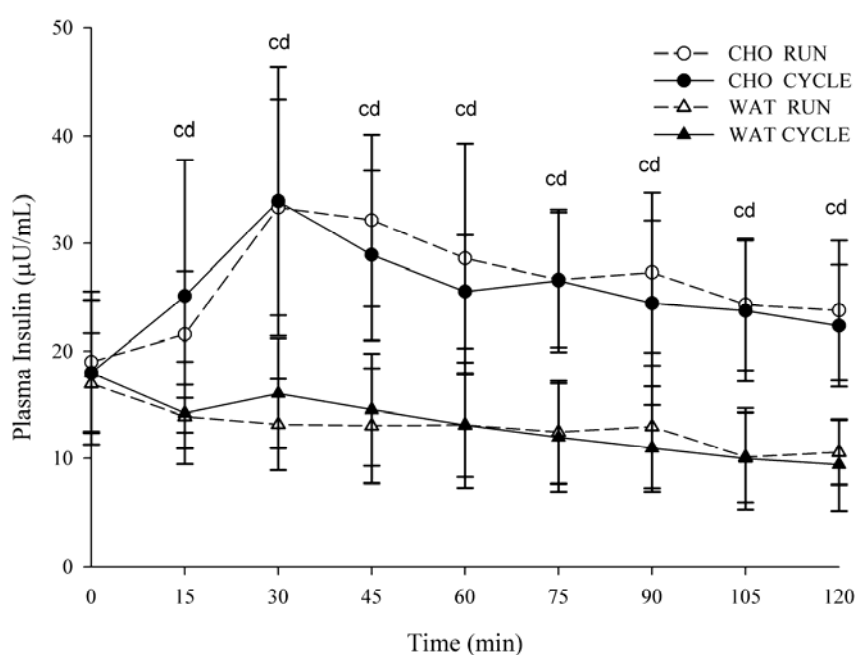


Figure 5.3 Plasma insulin concentration during 120 min running (RUN) or cycling (CYCLE) at $\sim 60\% \text{VO}_2\text{max}$ with the ingestion of water (WAT) or CHO drink (CHO). Values are mean \pm SD; $p < 0.05$. c CHO RUN trial significantly greater than WAT RUN. d CHO CYCLE significantly greater than WAT CYCLE.

Plasma lactate concentrations increased during the first 30 min of exercise in all four exercise trials (Figure 5.4). Thereafter, plasma lactate concentrations remained relatively stable throughout the exercise period. Plasma lactate concentrations were not significantly

different between CHO trials for RUN vs. CYCLE ($p=0.1$). However, higher lactate concentrations were measured during CYCLE trials compared with RUN in the WAT trial ($p=0.03$).

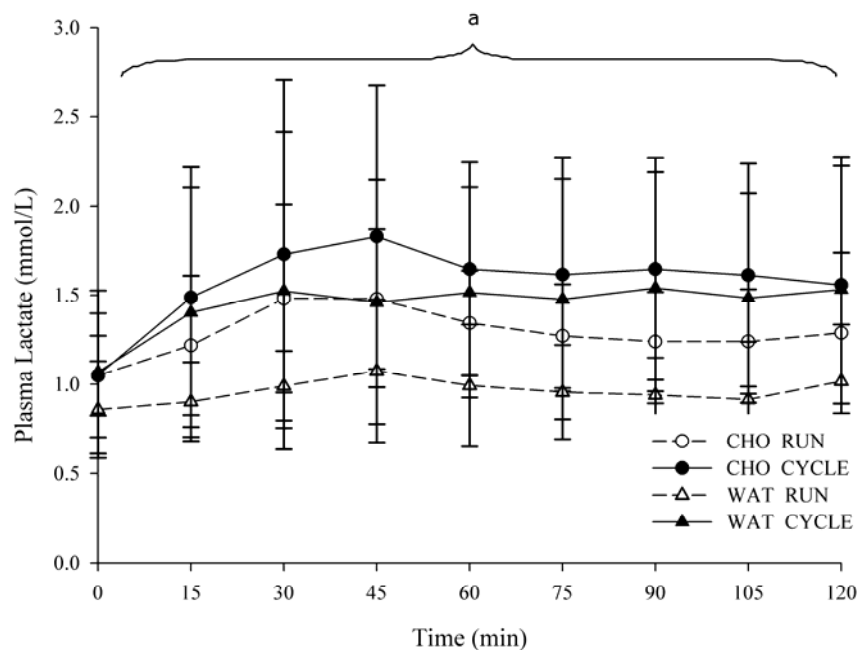


Figure 5.4 Plasma lactate concentration during 120 min running (RUN) or cycling (CYCLE) at $\sim 60\% \text{VO}_2\text{max}$ with the ingestion of water (WAT) or CHO drink (CHO). Values are mean \pm SD; $p < 0.05$. a WAT CYCLE trial significantly greater than WAT RUN.

GI symptoms and perceived fullness

No severe GI problems (>4) were recorded in any of the trials. Mean scores for upper abdominal problems were not significantly different between trials (0.0 ± 0.0 , 0.0 ± 0.0 , 0.0 ± 0.1 and 0.0 ± 0.0 during WAT RUN, WAT CYCLE, CHO RUN and CHO CYCLE, respectively). Accordingly, mean scores for lower abdominal problems were not significantly different between all trials (0.0 ± 0.0 , 0.0 ± 0.0 , 0.1 ± 0.2 and 0.0 ± 0.0 during

WAT RUN, WAT CYCLE, CHO RUN and CHO CYCLE, respectively). Furthermore, no difference in perceived stomach fullness was detected.

5.5 Discussion

In the present study we investigated exogenous CHO oxidation during running compared with cycling at the same relative intensity ($\sim 60\% \text{VO}_{2\text{max}}$). The main finding was that peak and average exogenous CHO oxidation rates were similar between the two modes of exercise. Previous research investigating exogenous CHO oxidation rates have predominantly been conducted on cycle ergometers and these findings have been used to base general CHO intake recommendations during prolonged endurance activities, including running. The similar exogenous CHO oxidation rates in the current study provide evidence that the previous exogenous CHO oxidation findings in cycling studies can also be extrapolated to running.

In contrast to our hypothesis we found no difference in exogenous CHO oxidation rates between both modes of exercise. With the present CHO intake rate of 1.5 g/min of a 2:1 GLU:FRU ratio we anticipated intestinal glucose transporters (SGLT-1) to become saturated and exogenous CHO oxidation rates to peak at ~ 1.2 g/min (26) during cycling. Indeed, the observed oxidation rates in the CYCLE trial matched these expectations. During the RUN trial similarly high exogenous CHO oxidation rates were detected. This finding is supported by a study of Derman *et al.* (16), which also reported similar oxidation rates during running compared with cycling. But, these results have to be regarded with caution due to limitations in their methodology to measure exogenous CHO oxidation. When the applied ^{14}C tracer is metabolized some of the arising $^{14}\text{CO}_2$ will be temporarily

trapped in the bicarbonate pool, even more so during high-intensity exercise. Over time the turnover of this pool increases several-fold so that a physiological steady state condition will occur relatively rapidly and $^{14}\text{CO}_2$ in the expired air will equilibrate with the $^{14}\text{CO}_2/\text{H}^{14}\text{CO}_2$ pool, respectively. However, complete recovery of $^{14}\text{CO}_2$ will approach only after ~60 min of exercise (34). As the exercise protocol was only ~1 h and was set at relatively high intensities, the interpretation of results from tracer measurements is limited in that study.

One reason why we hypothesized that exogenous CHO oxidation would be different between running and cycling is associated with increased gastrointestinal (GI) distress during running (31, 32). Altered mechanical stress due to the bouncing nature of running has been linked to a higher prevalence of GI distress (8). One factor leading to GI symptoms during running could be altered absorption due to relatively high mechanical stress (19). In contrast to previous research (31, 32), we did not find differences in ratings of GI symptoms between modes of exercise. However, we have to acknowledge that the employed exercise intensities were moderate in the present study, whereas previous research has investigated GI distress during competition (31) or in a laboratory study at higher exercise intensities ($75\%\text{VO}_{2\text{max}}$) over a prolonged period of time (3 h) (31, 32). GI distress is reported to increase with exercise intensity as well as with increasing exercise duration (for review, see (8)) and therefore differences might occur during competition. However, the finding that exogenous CHO oxidation rates were similar between running and cycling suggests that absorption at moderate-intensity exercise is not impaired during running.

Cycling and running elicit very different movement and muscle recruitment patterns (5, 20), hence it is not surprising that differences in energy metabolism have been detected between both modes of exercise (1, 4, 9, 16, 29). Our investigation revealed higher fat oxidation rates during running compared with cycling at ~60% $\text{VO}_{2\text{max}}$, which were significant in the WAT trial, but failed to reach statistical significance in the CHO trial ($p=0.09$; Table 5.1). This finding contradicts a study of Arkinstall *et al.* (4) who did not detect differences in fat oxidation rates during 60 min of continuous cycling and running. In contrast to our investigation, the study by Arkinstall *et al.* normalized exercise intensities at lactate threshold (LT), which elicited a higher percentage of $\text{VO}_{2\text{max}}$ during running compared with cycling (78% and 69% $\text{VO}_{2\text{max}}$, respectively). However, the most complete picture can be derived from studies comparing both modes of exercise with the use of graded exercise protocols (1, 4, 16, 29). For example a study by Achten *et al.* (1) measured substrate oxidation during running and cycling over a wide range of intensities. In support of our data, it was shown that total fat oxidation rates were higher during running compared with cycling between 50 and 80% $\text{VO}_{2\text{max}}$. Accordingly, it has been suggested that a larger muscle mass is involved in the running movement compared with cycling (22). Consequently, it could be speculated that the work rate of a single muscle fibre is greater during cycling and thus, due to the higher exercise intensity that each muscle fibre is working at, a higher reliance on CHO could be expected (1).

Previous research also suggested that CHO ingestion during running results in a more marked elevation in blood glucose and insulin concentrations compared with cycling (4, 36). This difference, however, was not evident in the present study. Similar to the study by Arkinstal *et al.* (4) plasma glucose concentrations were significantly elevated to values ~6.5

mmol/L in the first half hour during both CHO trials. However, plasma glucose concentrations remained elevated throughout exercise in both CHO trials of the present study, whereas plasma glucose concentration gradually declined to levels around baseline (~4.7 mmol/L) in the CHO cycling trial of the study by Arkinstall *et al.* Corresponding to similarly elevated plasma glucose concentrations in the present study, plasma insulin levels were similar between CHO trials. In contrast, the study by Arkinstall *et al.* reported significantly higher insulin concentrations during the running CHO trial after 20 min. The discrepancies between the findings of the two studies could be caused by differences in exercise intensities or by 50% greater CHO ingestion rates in the present study, which potentially maximized the insulin response in both modes of exercise.

A further difference in CHO metabolism that was suggested between running and cycling is a different effect of CHO feeding on muscle glycogen utilization (36). During cycling the majority of studies failed to measure a significant muscle glycogen sparing effect with the ingestion of CHO (7, 12, 17, 18) and only a small number of studies detected a significant attenuation in glycogen usage with CHO intake (21, 35). Due to the fact that studies in runners by Tsintzas *et al.* (37, 38) have reported a ~25% reduction in muscle glycogen utilization, the assumption was made that a glycogen sparing effect with CHO ingestion is greater during running (4, 36). However, caution needs to be taken with this interpretation as the mode of exercise, exercise duration and intensity, the CHO feeding protocol and methods of glycogen measurement were all different between studies. Arkinstall *et al.* (4) directly compared mixed muscle glycogen use during running and cycling at the individual LT and failed to detect a glycogen sparing effect with the ingestion of CHO during both modes of exercise. However, it has to be noted that even though they were unable to detect

a statistically significant difference, muscle glycogen utilization during running was ~20% reduced with CHO feeding. It therefore remains to be established whether muscle glycogen utilization during endurance running is different from cycling. In agreement with previous tracer studies (for review, see (25)) our study detected lower endogenous CHO oxidation rates with CHO ingestion compared with water intake, most probably due to considerably reduced liver glycogen utilization. As a result of higher fat oxidation rates during running, the sparing in endogenous CHO tended to be higher during running compared with cycling.

An important aspect that needs to be reviewed critically, when two modes of exercise are compared, is the influence of variation in exercise intensities. As mentioned before, exercise intensity is one of the most important regulators of substrate oxidation, which can explain equivocal findings when different modes of exercise are compared. In the present study, much care was taken to ensure that subjects exercised at the same relative intensity (~60%VO₂ max) during both trials. This moderate exercise intensity has been chosen, because it was demonstrated that exogenous CHO oxidation rates peak at exercise intensities between 51-65% VO₂max (33). Hence, the influence of exercise intensity on exogenous CHO oxidation rates becomes minimal at intensities of ~60%VO₂max. Furthermore, we had to choose an exercise intensity to ensure subjects could complete 2 h of treadmill running exercise, since due to methodological considerations of carbon retention; we wanted to compare CHO oxidation between modes of exercise in the second hour of exercise. It can therefore be concluded that it is very unlikely that the observed similar exogenous CHO oxidation rates are confounded by differences in exercise intensities and exogenous CHO oxidation rates are indeed similar during running and cycling.

In summary, the present study demonstrates that a GLU+FRC drink was oxidized at similarly high rates of ~ 1.2 g/min during both modes of exercise. Due to similar exogenous CHO oxidation rates and higher fat oxidation rates during running, utilization of endogenous CHO (muscle and liver glycogen) tended to be lower during running compared with cycling. The current study therefore suggests that recommendations for CHO intake, which were previously based on measures of exogenous CHO oxidation during cycling, are indeed transferable to running. However, it has to be considered that high-intensity exercise, especially running, has been linked to increased GI distress and it should therefore be advised that athletes test their tolerance of CHO in hard training sessions.

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Chapter 6

Nutrient and Fluid Intake and Gastrointestinal Problems during Prolonged Endurance Events

6.1 Abstract

There is little information about the actual nutrition and fluid intake habits, and gastrointestinal (GI) symptoms of athletes during endurance events. **Purpose:** To quantify and characterize nutrient intakes during endurance competitions and investigate links to GI symptoms. **Method:** 221 endurance athletes (male and female) were recruited from two Ironman triathlons (IM Hawaii and IM GER), a half-Ironman (IM70.3), a MARATHON, a 100/150 km CYCLE race. Professional cyclists (PRO) were investigated during stage-racing. A standardized post-race questionnaire quantified nutrient intake and assessed 12 GI symptoms on a scale from 0 (no problem) to 9 (worst it has ever been) in each competition. **Results:** Mean CHO intake rates were not significantly different between IM Hawaii, IM GER and IM70.3 (62 ± 26 , 71 ± 25 g/h and 65 ± 25 g/h, respectively), but lower mean CHO intake rates were reported during CYCLE (53 ± 22 g/min, $p=0.041$) and MARATHON (35 ± 26 g/min; $p<0.01$). Prevalence of serious GI symptoms were highest during the IM races ($\sim 31\%$; $p=0.001$) compared with IM70.3 (14%), CYCLE (4%), MARATHON (4%) and in PRO (7%), and correlated to a history of GI problems. In all data sets scores for upper and lower GI symptoms correlated with reported history of GI distress ($r=0.37$ and $r=0.51$, respectively; $p<0.001$). Total CHO intake rates were positively correlated with nausea and flatulence but negatively correlated with finishing time during both IM ($r=-0.55$ and $r=-0.48$; $p<0.001$). **Conclusion:** The present study demonstrated that CHO intake rates vary greatly between events and individual athletes (6-136 g/h). High CHO intake during exercise was related to increased scores for nausea and flatulence, but also to better performance during IM races. GI symptoms were linked to a reported history of GI distress. Altogether the findings suggest a need for more individualized nutritional advice that optimizes CHO and fluid delivery to enhance performance, whilst minimizing GI discomfort.

6.2 Introduction

Popularity of mass participation in endurance and ultra-endurance events is ever increasing. Athletes participating in these events are required to sustain relatively high work rates over a prolonged period of time, which results in high sweat rates and energy expenditure. Fatigue during endurance events is generally not caused by a single factor, but is the result of a multifaceted phenomenon that often coincides with dehydration, hyperthermia, carbohydrate (CHO) depletion, central fatigue and hyperglycaemia (3, 29). In order to delay the onset of fatigue, and optimize prolonged endurance performance, it is recommended to compensate fluid and electrolyte losses as well as to fuel the body with energy from CHOs (1, 2, 6, 7, 24, 25, 45). Since CHO intake has been shown to improve endurance capacity and performance (for review see 9, 24, 25), the current position stand of the American College of Sports Medicine (ACSM) and American Dietetic Association (ADA) advises athletes to consume CHO at rates of 0.7 g/kg bodyweight/h (30-60 g/h) during endurance events (2). An alternative contemporary recommendation (24, 28) suggests higher CHO intake rates of up to 90 g/h for athletes competing in intense (ultra) endurance events. The rationale to recommend higher CHO intake rates, is based on recent research that revealed higher exogenous CHO oxidation rates (23, 26) and superior performance (10, 43), with the ingestion of large amounts of glucose + fructose blends compared with isoenergetic amounts of glucose. However, whether athletes actually manage to meet these recommendations remains to be established.

There is only limited and partly contradicting data available about nutritional intake strategies of athletes during endurance events. A number of studies have investigated CHO and fluid intake of athletes during events (see Table 1.1; Chapter 1). But, excluding

retrospective studies, to the best of our knowledge all previous studies have focused on a single event and the majority were conducted with less than 20 subjects. For example, reported CHO intake rates in professional cyclists range from as little as 25 g/h (12) up to 94 g/h (42). The difference between studies could be due to difficulties measuring nutrient intake during competitions, variation in the methodology, environmental conditions or changing nutritional practices over the years between the studies. Furthermore, a large inter-individual difference in nutritional intake habits has been reported in numerous studies investigating athletes during various events (11, 12, 16, 17, 21, 31, 42) and it is therefore difficult to draw conclusions from small sets of data. It may also be inappropriate to extrapolate findings from one sporting event to another. For example a retrospective questionnaire based study by Peters et al (32) in 422 runners, cyclists and triathletes reported higher liquid and food intakes of triathletes compared with runners. Hence, although current recommendations do not differentiate between runners, cyclists and triathletes (2), it is possible that the nutritional intake strategies employed are very different.

Furthermore, a limitation of nutritional recommendations during exercise is the limited consideration of the negative impact that gastrointestinal (GI) distress can have on exercise performance. The intake of several nutrients, such as fat, fibre and protein, has previously been linked to GI distress during exercise (34). In a number of studies ingestion of CHO, and in particular hypertonic drinks, has been related to GI distress (32, 34, 39). In contrast, a recent series of studies has suggested that the intake of high rates of CHO (~1.4 g/min) in the form of gels is well tolerated from the majority of athletes during simulated 10-mile (16-km) races under mild environmental conditions (37). However, it has to be kept in

mind that the incidence of GI problems increases with exercise time (33) and might be increased under more extreme environmental and competition conditions. Therefore the impact of nutrient intake on GI symptoms during more extreme events with longer duration remains unclear.

Research questions

Therefore, the purpose of the present study was 1) to quantify and characterize the food and fluid intake of athletes during marathon running, road cycling and long distance triathlon using a large subject pool with the same, tightly controlled GI questionnaire methodology and 2) to investigate whether nutrient (especially CHO) intake, fluid consumption, training status and race distance is correlated with the incidence of GI distress. According to previous research we speculated that fat and fibre intake would be correlated with GI distress. We also hypothesized that high CHO intake rates during prolonged exercise would be correlated with increased performance, but under more extreme environmental conditions would cause GI distress, especially of the lower GI tract due to incomplete absorption.

6.3 Methods

Subjects:

For this study different levels of athletes were recruited: amateur and pro triathletes, amateur cyclists, professional cyclists from two different Pro Cycling Teams (both in the top 10 of the International Cycling Union (UCI) ranking) and amateur runners. Athletes were recruited via e-mail or personally approached on the event exhibition. All participants of the study were informed about the purpose of the study, practical details, and risks associated with the procedure before giving their written consent. The study was approved by the School of Sport and Exercise Sciences ethics subcommittee, University of Birmingham, Birmingham, UK.

Events:

Table 6.1 highlights the different events, including subject characteristics and race conditions. All competitions occurred between June and October, in 2009.

Triathlon:

Three different triathlons were investigated, featuring two different race distances: two full distance Ironman (IM), which covers a 3.8 km swim, 180 km bike and 42.2 km run and an Ironman 70.3 (IM 70.3), which covers half of the IM distances (1.9 km swim, 90 km bike and 21.1 km run). Data was collected during the IM European Championships in Frankfurt, Germany (IM GER), the IM World Championships in Hawaii (IM Hawaii) and during the IM Germany 70.3 in Wiesbaden, Germany (IM 70.3).

Table 6.1 Subjects characteristics and ambient conditions for all endurance events (mean \pm SD; $p < 0.05$). a significantly different from all triathlon races. b significantly different from IM 70.3. c significantly different from IM GER. d significantly different from CYCLE.

	Heat index (°C)	Participants (male/female)	Age, y	Height, m	Body weight, kg	Finish time (h:min)	Endurance training experience, yr	Running training h/wk	Cycling training, h/wk	Total training h/wk
IM Hawaii**	29 (26-36)	53 (34/19)	41 \pm 13	171 \pm 26	67 \pm 16	11:40 \pm 2:05 ^{bc}	13 \pm 9	6 \pm 3	11 \pm 4 ^{bc}	19 \pm 8 ^{bc}
IM GER*	25 (15-33)	54 (45/9)	38 \pm 7	176 \pm 26	73 \pm 11	11:09 \pm 1:23 ^b	12 \pm 8	5 \pm 1	12 \pm 1 ^b	17 \pm 6 ^b
IM 70.3 ***	24 (15-34)	43 (36/7)	38 \pm 7	178 \pm 13	75 \pm 13	6:05 \pm 0:44	11 \pm 10	4 \pm 2	7 \pm 3	13 \pm 5
MARATHON	12 (7-14)	28 (22/6)	45 \pm 12	177 \pm 10	71 \pm 13	3:46 \pm 0:34 ^a	13 \pm 9	6 \pm 3	n.a	n.a
CYCLE	20 (15-24)	28 (28/0)	41 \pm 7	185 \pm 8	81 \pm 13	3:32 \pm 0:42 ^a	14 \pm 11	n.a	7 \pm 4	n.a
PRO DL	17 (10-23)	7 (7/0)	31 \pm 5	181 \pm 5	70 \pm 5	5:04 \pm 0:32 ^d	17 \pm 5	n.a	23 \pm 2 ^d	n.a
PRO VUELTA	25 (19-31)	8 (8/0)	29 \pm 3	181 \pm 5	71 \pm 7	5:22 \pm 1:01 ^d	16 \pm 5	n.a	23 \pm 2 ^d	n.a

* Amateur and 3 Pro athletes ** Amateurs and 2 Pro athletes *** Amateurs and 1 Pro athlete; n.a. question was not assessed

Road cycling:

Professional cyclists (PRO) from two different teams were investigated. One professional cycling team was investigated during two flat stages (228 km and 182 km) of the Dauphine Libéré, France. The other professional cycling team was studied during the Vuelta a España (Tour of Spain). Two mountain stages (204.7 km and 188.8 km) and a flat stage (171.2 km) were investigated. Amateur cyclists were investigated at the Vattenfall Cycclassics cycling race, Hamburg, Germany (CYCLE). Half of the participants participated in a shorter 100-km event whereas the other half completed 155 km on a slightly hilly course.

Running:

A city marathon (42.2 km) with a relatively flat course profile was investigated in Munich, Germany (MARATHON).

Experimental design:

Subjects were recruited via e-mail or at the event exhibition and had at least one personal contact with the investigators prior to the event where they were carefully instructed and briefed about the importance of the accuracy in their responses. During the briefing athletes were also given strategies to remember food and fluid consumption during the race, such as for participants with a nutrition plan to remember any deviations from the plan. The participants then filled in one questionnaire before the event in order to assess training history, nutritional habits and history of GI discomfort and one after the event in order to accurately quantify their fluid and food intake and rate their GI discomfort during the event. To ensure accuracy of the data, replies were followed up via e-mail, or in personal communications whenever possible. Professional cyclists were individually interviewed immediately after the race days rather than asked to fill in the questionnaires themselves.

Pre-Race Questionnaire:

One or two days before the events subjects were asked to complete a first questionnaire in order to assess personal characteristics, training history, nutritional habits and history of GI problems (see appendix).

Race day Questionnaire:

In the evening after the races all participants received an e-mail with the second questionnaire (see appendix), reminding them to fill it in as soon as possible, but no longer than two days after the race. Race environmental conditions were collected from local weather stations and are expressed as heat index. The heat index takes increased humidity into account, which can lead to increased heat stress (18). The questionnaire after the race asked the participants to accurately write down what they ate and drank in the morning straight before the race and during the entire race.

The food and fluid intake was assessed by mentioning the available food and fluid options from the event organizer and giving examples on precision of amounts (e.g. water in mL or cups or bottles). For the triathlon races all food and fluid intake at the start (up to 30 min prior to the race) was counted into the swim section of the event, the first and second transition were counted into the cycle and run section, respectively. Afterwards data on food and fluid intake was evaluated by a trained nutritionist using NutritionistProTM (Axxya Systems, Stafford, Texas, USA), following up estimated nutrient intakes in personal or e-mail conversations in case of any doubts. Furthermore, participants were asked to answer questions on GI problems, adapted from previous research (27, 37). The questions about GI symptoms were similar in the pre-race questionnaire, which assessed race occurrence and

history of GI symptoms. The questionnaires were organized in three sections and each section included between four and seven questions. Section one addressed upper abdominal problems (reflux/heartburn, belching, bloating, stomach cramps/pain, nausea, vomiting), section two lower abdominal problems (intestinal/lower abdominal cramps, flatulence, urge to defecate, side ache/stitch, loose stool, diarrhoea, intestinal bleeding) and section three systemic problems (dizziness, headache, muscle cramp, urge to urinate). Each question was assessed on a 10-point scale, ranging from 0 "no problem at all" to 9, "the worst it has ever been".

Statistical analysis:

Nutrient intake data, training details and performance data were approximately normally distributed and evaluated with a parametric statistical approach. Mean values from different events were compared with the use of unpaired sample t-tests. For comparison of mean values between modes of exercise within one triathlon, paired sample t-tests were used. Possible correlations between race performance (finish time) and nutrient intake during the races were analysed using Pearson's correlation coefficient.

To evaluate data on GI symptoms a non-parametric statistical approach was chosen, as scores on GI symptoms were mainly recorded on the low end of the scale and not approximately normally distributed. Mean values were compared with the use of Mann-Whitney tests. To analyse factors which could possibly have influenced GI tolerance (e.g. nutrient intake and training status) data was analysed using a Spearman's correlation coefficient. Since overall 12 GI symptoms were answered after 6 different events, the false positive rate of 5% could be inflated due to multiple tests. In order to reduce multiplicity,

analysis was restricted to data from triathlon events, which revealed the highest frequency for GI symptoms and took place under similar conditions. First, analyses were performed on averages over a section of symptoms (upper and lower abdominal problems). Then, correlations were performed for individual questions during each triathlon. The p-values of those tests were not adjusted for multiple tests. Therefore the p-values serve as a flag in order to indicate interesting results. Furthermore, GI symptoms that were scored >4 , were classified as “serious”. For all test p-values <0.05 were considered significant. All data is reported as means \pm standard deviations (SD). Additionally minimum and maximum scores are reported for nutrient intake data. Statistics were performed using SPSS 15 for Windows (SPSS Inc., 233 S. Wacker Drive, Chicago, Illinois, USA).

6.4 Results

Race conditions and participant characteristics:

Race conditions (ambient temperature, expressed as heat index), participant characteristics, including finishing times of the events and details about training experience are shown in Table 6.1. Reported years of endurance training experience were not significantly different between the different amateur events. Self-reported training h/wk, however, were significantly higher for IM Hawaii compared with IM GER competitors (19.2 ± 7.8 and 16.4 ± 5.5 h, respectively; $p=0.03$). IM 70.3 competitors trained significantly less h/wk compared with competitors of both IM races (13.2 ± 4.8 h; $p<0.05$). PRO cyclists trained significantly more than amateur cyclists ($p<0.001$).

Nutrient intake (CHO, fluid, sodium and caffeine):

An overview of nutrient intakes during the different races is shown in Table 6.2.

CHO intake rates

Mean CHO intake rates were not significantly different between IM Hawaii and IM GER (62 ± 26 , 71 ± 25 g/h, respectively, $p=0.07$) and between both IM and IM 70.3 (65 ± 25 g/h; $p>0.2$, respectively). In contrast to the triathlons, the average CHO intake rate during CYCLE was significantly lower (53 ± 22 g/min, $p=0.041$). The average CHO intake rate of PRO cyclists tended to be higher compared with amateur cyclists (64 ± 20 g/min and 53 ± 22 g/min, respectively; $p=0.06$). The lowest mean CHO intake rates were reported during the MARATHON (35 ± 26 g/min), which was significantly lower than intake rates during CYCLE ($p=0.007$) and all triathlon events ($p<0.001$). Regardless of the event, individual CHO intakes between athletes varied greatly (range of 6 to 136 g/h).

Table 6.2 Nutritional intakes during endurance events (mean \pm SD; $p < 0.05$). a significantly different from all triathlon races. b significantly different from IM 70.3. c significantly different from IM GER. d significantly different from CYCLE

	Fluid (mL/h)	kcal/h	CHO (g/h)	Protein (g/h)	Fat (g/h)	Fibre (g/h)	Sodium (mg/h)	Caffeine (mg/h)
IM Hawaii	794 \pm 309 ^{bc} (146-1617)	258 \pm 96 (117-472)	62 \pm 26 (22-124)	2 \pm 2 (0-6)	1 \pm 1 (0-7)	1 \pm 1 (0-3)	422 \pm 213 (127-1116)	26 \pm 22 (0-78)
IM GER	703 \pm 238 ^b (352-1656)	292 \pm 104 (114-564)	71 \pm 25 (33-126)	2 \pm 2 (0-10)	1 \pm 1 (0-4)	1 \pm 1 (0-2)	444 \pm 216 (69-975)	33 \pm 29 (0-100)
IM 70.3	700 \pm 254 (318-1385)	265 \pm 105 (96-494)	65 \pm 25 (31-122)	3 \pm 3 (0-12)	1 \pm 1 (0-5)	1 \pm 1 (0-4)	403 \pm 193 (91-936)	28 \pm 24 (0-107)
MARATHON	354 \pm 187 ^{ad} (81-918)	146 \pm 102 ^{ad} (18-527)	35 \pm 26 ^{ad} (6-136)	3 \pm 5 (0-16)	1 \pm 1 (0-13)	2 \pm 3 (0-12)	118 \pm 87 (9-321)	23 \pm 32 (0-125)
CYCLE	643 \pm 599 ^a (69-1012)	233 \pm 103 (53-557)	53 \pm 22 ^a (13-114)	3 \pm 3 (0-13)	1 \pm 1 (0-5)	1 \pm 1 (0-4)	208 \pm 183 (15-857)	21 \pm 29 (0-108)
PRO	711 \pm 270 ^d (333-1268)	284 \pm 76 (167-431)	64 \pm 20 (29-107)	4 \pm 2 (0-8)	2 \pm 2 (0-6)	1 \pm 1 (0-2)	311 \pm 156 ^d (164-768)	12 \pm 14 ^d (0-45)

Within the triathlon events, CHO intake rates were significantly higher during the cycling section compared with the run ($p < 0.05$; Figure 6.1). During both IM male participants ingested significantly more CHO compared with female athletes (IM Hawaii: 69 ± 28 and 50 ± 15 g/h, respectively; $p = 0.002$; IM GER: 75 ± 25 g/h and 53 ± 15 g/h, respectively; $p = 0.015$). The difference failed to reach statistical significance during IM 70.3 (67 ± 26 g/h and 54 ± 19 g/h, for male and female respectively; $p = 0.06$). However, after correction for bodyweight the gender difference was no longer significant in any triathlon event ($p > 0.5$).

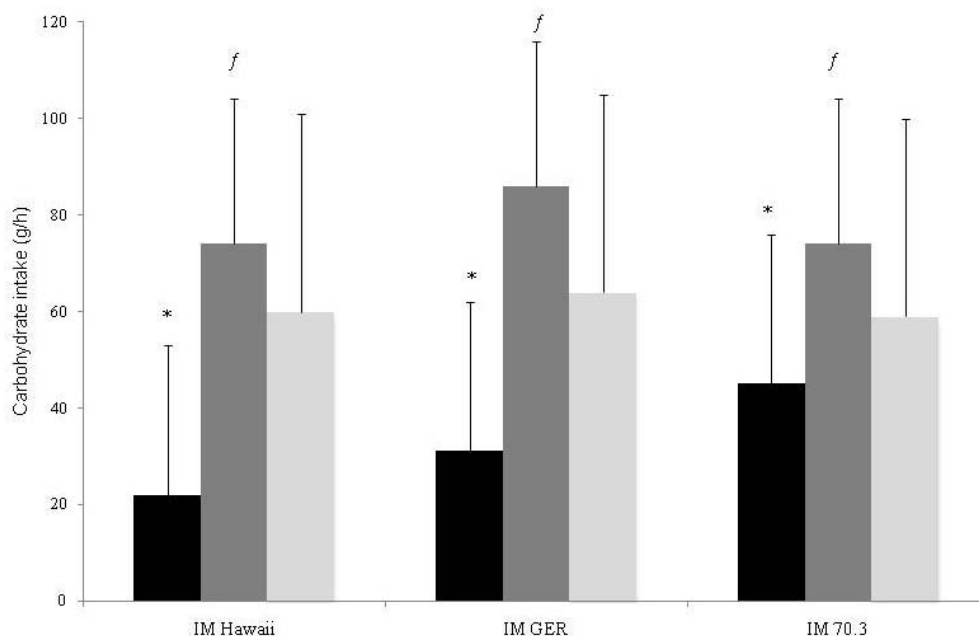


Figure 6.1 CHO intake during IM Hawaii, IM GER and IM 70.3 split into swim (black), cycle (dark-grey) and run (light-grey) section of the event (means \pm SD). Intake up to 30 min before race-start is included into the swim section. * significantly different from cycle and run section. *f* significantly different from run section. $p < 0.05$.

Form of CHO intake

The chosen form of CHO (solid, liquid or gel) was different between both IM and the IM 70.3 (see Figure 6.2). Athletes took in a higher percentage of CHO in the form of liquid during IM Hawaii compared with IM 70.3 ($49 \pm 24\%$ and $40 \pm 14\%$, respectively, $p=0.043$). Less solid CHO was consumed during IM Hawaii than during IM 70.3 ($15 \pm 16\%$ and $24 \pm 20\%$, respectively; $p=0.013$). During IM GER a similar trend to higher % liquid CHO and lower intake of solids compared with IM 70.3 was shown, however, this trend was not significant ($p=0.056$ and $p=0.094$, respectively). Within the triathlon events a significantly higher percentage of the ingested CHO was consumed in the form of solids during cycling compared with running ($p<0.05$). The chosen form of CHO intake was not significantly different between PRO and amateur cyclists. During MARATHON significantly less CHO was ingested in the form of liquids compared with the IM 70.3 ($p=0.035$; Figure 6.2). The percentage of CHO ingested as gel was significantly higher during MARATHON compared with CYCLE ($p=0.34$; Figure 6.2).

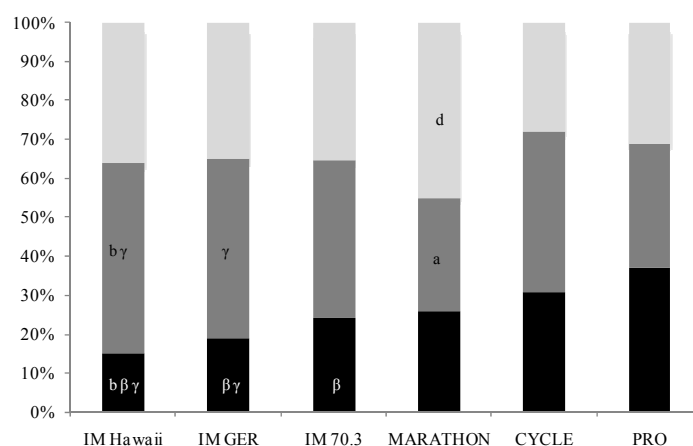


Figure 6.2 The contribution of solid (black), liquid (grey) and gel (light-grey) intake forms to total CHO intake during different events. a significantly different from all triathlon races. b significantly different from IM 70.3. d significantly different from CYCLE. β significantly different from liquid CHO. γ significantly different from CHO gel. $p<0.05$.

When analyzing CHO (from solid, gel and liquid) together with fluid intake rate, an estimate of percent CHO solution consumed was calculated. On average, the percent CHO solution across all six events was $10.6 \pm 6.2\%$. The consumed percent CHO solution was significantly more dilute during IM Hawaii ($8.8 \pm 4.4\%$; $p < 0.05$) compared with all other events. The ingested CHO expressed as percent solution ranged from 3.5 to 27%.

Fluid intake

Fluid intake rates were not significantly different between all triathlon races (794 ± 309 , 703 ± 238 and 700 ± 254 mL/h, for IM Hawaii, IM GER and IM 70.3, respectively; Table 6.2). Fluid intake was higher during the cycle compared with the run section within all three triathlon events (849 ± 339 and 729 ± 377 mL/h, respectively; $p < 0.001$). During CYCLE significantly lower fluid volumes were ingested compared with triathlon (643 ± 599 mL/h; $p = 0.001$). Furthermore, amateur cyclists ingested on average less fluid than PRO (711 ± 270 mL/h; $p = 0.03$). Compared with all other events, the lowest fluid intake rates were reported during the MARATHON (354 ± 187 mL/h; $p < 0.01$).

Within IM Hawaii and IM GER fluid intake tended to be higher within males compared with females (IM Hawaii: 849 ± 280 mL/h and 675 ± 289 mL/h, respectively; $p = 0.03$; IM GER: 729 ± 245 mL/h and 575 ± 216 mL/h, respectively; $p = 0.08$). However, corrected for bodyweight the differences were not significant.

GI symptoms during the races:

Frequency of serious GI problems and ratings of upper and lower abdominal problems during events are displayed in Table 6.3. Significantly more participants reported serious GI problems (GI scores >4) during IM Hawaii and IM GER compared with IM 70.3 (32, 31 and 14% for IM Hawaii, IM GER and IM 70.3, respectively; $p=0.001$). Only 4% of the athletes during CYCLE and the MARATHON and 7% of all PRO cyclists reported serious GI problems. Mean scores for upper abdominal symptoms were not significantly different between all triathlon races (Table 6.3). However, lower abdominal symptoms were rated significantly less problematic during the half distance IM 70.3 compared with IM Hawaii ($p=0.029$) and IM GER ($p=0.034$). Upper and lower abdominal symptoms during CYCLE were on average less ($p<0.001$) compared with all triathlon events. No significant difference in the occurrence of upper and lower abdominal symptoms was reported between amateur and PRO cyclists ($p=0.10$ and $p=0.71$, respectively). During MARATHON mean scores for upper abdominal symptoms and for lower abdominal symptoms were lower compared with all triathlon events ($p<0.001$; Table 6.3). No significant differences in mean scores for upper and lower abdominal symptoms were found between MARATHON and CYCLE.

Table 6.3: GI symptoms during endurance events: Any of the 12 GI symptoms rated >4 were considered as serious. Values for upper and lower GI symptoms are means \pm SD ($p<0.05$). a significantly different from all triathlon races. b significantly different from IM 70.3.

	% Serious symptoms	Upper abdominal symptoms	Lower abdominal symptoms
IM Hawaii	32% ^b	0.89 \pm 1.00	0.72 \pm 0.80 ^b
IM GER	31 % ^b	1.12 \pm 1.18	0.70 \pm 1.02 ^b
IM 70.3	14%	0.84 \pm 0.90	0.41 \pm 0.54
MARATHON	4% ^a	0.33 \pm 0.48 ^a	0.19 \pm 0.27 ^a
CYCLE	4 % ^a	0.20 \pm 0.31 ^a	0.18 \pm 0.27 ^a
PRO	7% ^a	0.20 \pm 0.41 ^a	0.25 \pm 0.23 ^a

Factors correlated with GI symptoms:*History of GI problems:*

During all events scores for upper and lower abdominal symptoms were positively correlated with the reported history of upper and lower abdominal symptoms ($r=0.37$ and $r=0.51$, respectively; $p<0.001$; Figure 6.3).

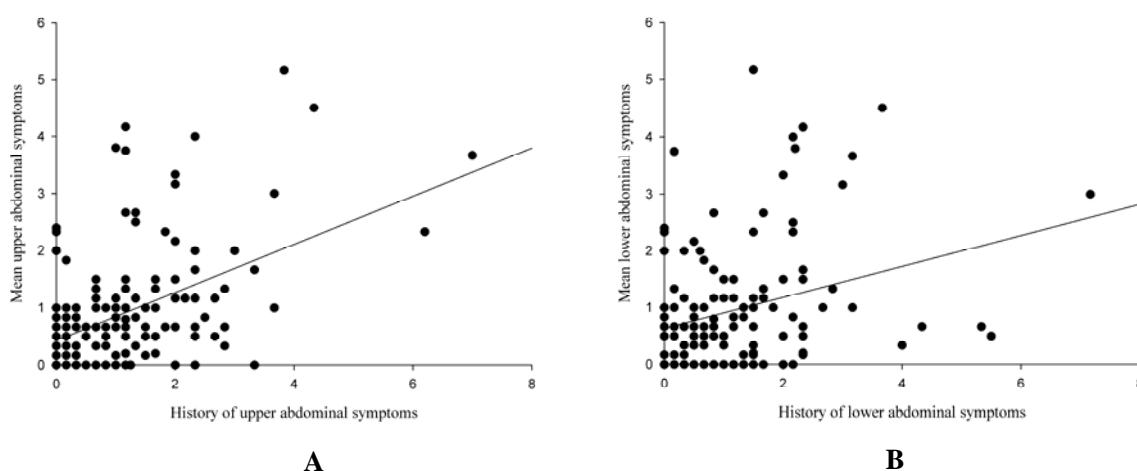


Figure 6.3A/B Correlation between mean scores for upper (A) and lower (B) abdominal problems during the triathlon races and the reported history of symptoms. ($r=0.39$ and $r=0.51$, respectively; $p<0.001$)

Nutrient intake

All correlations between nutrient intake and GI symptoms are displayed in Table 6.4. Mean scores for upper and lower abdominal problems were not correlated with CHO, fluid, sodium, caffeine, protein, fat or fibre intake rates in any of the triathlon events.

When scores for single GI symptoms were evaluated some significant, low to moderate correlations were detected. However, none of these individual GI symptoms were corrected for multiple tests. Nausea and flatulence was correlated with CHO intake rate in two data sets ($r=0.33$ and $r=0.34$ for nausea; $r=0.34$ and $r=0.35$ for flatulence during IM Hawaii and

IM 70.3 respectively, $p < 0.05$). High fibre intake was also correlated with higher scores for flatulence during IM 70.3 and IM Hawaii ($r = 0.35$ and $r = 0.34$, respectively, $p < 0.01$). When triathletes were divided into subjects experiencing serious GI problems and subjects with mild or without GI problems, CHO intake rates were not significantly different between both groups (65 ± 25 g/h and 69 ± 27 g/h, respectively; $p = 0.49$).

Personal characteristics, training habits and environmental conditions:

No significant difference between upper and lower abdominal problems of male and female athletes has been detected. Within data from IM Hawaii lower abdominal problems were negatively correlated with years of endurance training experience ($r = -0.37$; $p = 0.008$). Lower abdominal problems were negatively correlated to training h/wk during IM 70.3 ($r = -0.30$; $p = 0.005$). Mean upper and lower GI scores were significantly ($p < 0.001$) correlated with heat index of the different events ($r = 0.29$ and $r = 0.33$, respectively).

Table 6.4 Correlations (r values) between GI symptoms and nutrient intake rates during the three triathlon races. * significant $p < 0.05$. ** significant $p < 0.001$.

		CHO (g/h)	Sodium (g/h)	Fluid (L/h)	Protein (g/h)	Fat (g/h)	Fibre (g/h)	Caffeine (mg/h)	% Solid CHO	% liquid CHO	% CHO gel
Upper GI symptoms	IM Hawaii										
	IM GER							- 0.34*			
	IM 70.3										
Lower GI symptoms	IM Hawaii										
	IM GER										
	IM 70.3										
Reflux	IM Hawaii										
	IM GER										
	IM 70.3										
Belching	IM Hawaii										
	IM GER							- 0.35**			
	IM 70.3	0.33*					0.32*				
Bloating	IM Hawaii										
	IM GER			- 0.42**							
	IM 70.3										
Stomach cramps	IM Hawaii	0.32*		0.35*				0.35*			
	IM GER										
	IM 70.3										
Nausea	IM Hawaii	0.33*		0.39**							
	IM GER										
	IM 70.3	0.35*									
Vomiting	IM Hawaii										
	IM GER										
	IM 70.3										
Abdominal cramps	IM Hawaii										
	IM GER										
	IM 70.3		0.31*								
Side ache	IM Hawaii										
	IM GER										
	IM 70.3							0.37*			
Flatulence	IM Hawaii	0.34*					0.35*				
	IM GER										
	IM 70.3	0.35**	0.36*				0.33*				
Urge to defecate	IM Hawaii										
	IM GER										
	IM 70.3										
Diarrhoea	IM Hawaii										
	IM GER										
	IM 70.3									0.37*	

Race performance

During both IM events and the MARATHON faster finish times were correlated ($r=-0.55$, $r=-0.45$ and $r=-0.49$; $p<0.01$) with high CHO intake rates (Figure 6.4). A negative correlation with high caffeine intake rates was detected during IM Hawaii and MARATHON ($r=-0.33$ and $r=-0.41$, respectively, $p<0.05$). Furthermore, faster finish times were correlated with high sodium intake rates during IM Hawaii and IM GER ($r=-0.32$ and $r=-0.45$, respectively; $p<0.05$).

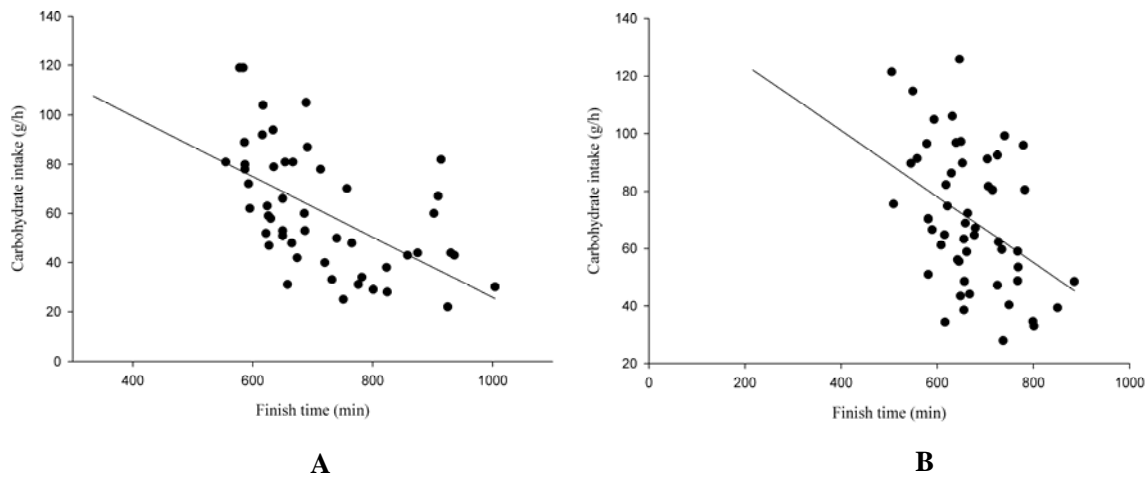


Figure 6.4A/B Correlation between finishing time and CHO intake rate during IM Hawaii (A; $r=-0.55$; $p<0.001$) and IM GER (B; $r=-0.45$; $p<0.001$).

6.5 Discussion

In the present study food and fluid intake habits of athletes have been quantified with the use of the same standardized GI questionnaire methodology and a large subject pool (221 athletes) during different endurance events. A major finding of the present study was that CHO intake rates varied greatly between running, cycling and triathlon events, but also between individual athletes. Previously recommended high CHO intake rates (up to 90 g/h) (24) were achieved by ~50% of the triathletes, 30% of the cyclists and 15% of the marathon runners. High CHO intake rates were not associated with higher average scores for upper or lower GI symptoms, but appeared to be a risk factor for nausea and flatulence. However, high CHO intake rates were significantly correlated with faster finishing times and it appears reasonable to advise athletes to aim for a relatively high CHO intake as tolerated by the individual.

CHO and fluid intakes during endurance events

The highest CHO intake rates within the present study have been reported in ultra-endurance triathlon events. In agreement with a previous study by Kimber *et al.* (31) average CHO intake rates during IM and IM 70.3 (67 g/h) exceeded ACSM recommendations (2). During the amateur cycling event (CYCLE) significantly lower average CHO intake rates (53 g/h) were reported. However, the lowest average CHO intake rates (35 g/h) were found during MARATHON. Consequently, 73% of marathon runners failed to meet the comparatively low ACSM recommendations. Altogether it has to be recognized that the inter-individual differences in intake rates are large (6-136 g/h) and a substantial number of athletes ingested less or more CHO than recommended. The average fluid intakes during the events were between 354 mL/h (MARATHON) and 794 mL/h (IM

Hawaii). Interestingly, the average resulting CHO solution was 10.6%, with individual % CHO solution ranges from 3.5 to 27%. The lowest average CHO concentration (8.8% during IM Hawaii) still exceeds general recommendations for the composition of sports drinks of 4-8% (2, 15). Strategies to achieve CHO and fluid intake rates generally consisted of a mixed intake of CHO forms (solid, semi-solid and liquid) and only 1% of athletes ingested CHO solely from solutions. In support of the strategy to ingest different CHO forms, several recent studies have shown similar exogenous CHO oxidation rates between fluids, semi-solid gels (35) and solid bars (36).

Factors influencing CHO and fluid intakes

Regardless of the sport, variability between races existed in a number of factors that might have influenced food and fluid intakes. For example, ambient conditions were different between events with hot conditions (24-29°C) during the triathlon events compared with moderate temperatures during MARATHON (12°C). Previous studies have shown that hot conditions lead to high voluntary fluid intake rates (16) and our data supports this. The highest proportion of CHO ingested in the form of liquid (49%) was found during the hottest event (IM Hawaii), while the lowest percentage CHO intake (29%) in the form of liquid was reported during the coolest event (MARATHON). Additionally, the investigated events varied in average race duration between 3.5 h up to 11.7 h. From previous studies it could have been expected that nutritional intake will be higher during a longer race (11, 17). However, in the present study no difference between IM and IM 70.3 was detected and no difference between intakes of athletes cycling 100 km or 150 km during CYCLE. Finally, CHO intake rates seem to vary with the level of athletes. In agreement with a study by Havemann *et al.* (21), which reported an association of athlete's level and CHO intake

rates, the present study reported ~20% higher CHO intakes of PRO compared with amateurs. Furthermore, in this and previous studies, CHO intake rates have been correlated to faster finishing times (31), indicating that either CHO intake improved endurance performance, faster athletes tend to ingest more CHO compared with slower athletes, or faster athletes have a greater ability to ingest and absorb larger quantities of CHO.

Differences in CHO and fluid intakes between sports

Even though some variation in nutritional intakes can be explained by different environmental conditions and personal characteristics, a substantial variation remains between the different sports. CHO intake rates during all triathlons were considerably higher compared with MARATHON and CYCLE. This finding is in line with the results of a retrospective questionnaire based study by Peters *et al.* (32) where triathletes reported to take in more liquids and food during competition than runners. Furthermore, CHO and fluid intake rates during MARATHON were substantially lower compared with CYCLE and triathlon. Part of this difference might be explained by the considerably colder weather during MARATHON compared with all other events. However, the difference in CHO and fluid intake rates between running and cycling also persists within the triathlon events (Figure 6.1). A similar nutrition pattern has been reported in a study by Kimber *et al.* (31) and the authors suggested that the lower nutrient intakes during running are due to practical difficulties ingesting large fluid volumes or solid foods. A preference for the ingestion of semi-solid or liquid CHO forms while running has been present in all triathlon events of the present study, whereas comparatively more CHO was ingested in solid form during the cycling section. It could be speculated that, due to a higher prevalence of GI distress during

running compared with cycling (32, 33), athletes self-adapt their nutrition and select a nutrient and fluid intake profile (amount and type) which they tolerate well.

Prevalence of gastrointestinal (GI) symptoms

A further aspect of our study was to investigate GI distress, which is common during ultra-endurance events (30, 32, 41). In the present study a high prevalence for serious GI distress (~30%) was reported during the IM races. Significantly lower frequencies of serious complaints were reported during IM 70.3 (14%), MARATHON (4%) and CYCLE (4%). It is known that prevalence for GI distress is augmented with increasing exercise duration (33), possibly caused by increasing dehydration and decreased blood supply to the GI tract (14). Furthermore, hot conditions have previously been linked to a higher prevalence of GI symptoms (5, 13), most likely due to increased cutaneous blood flow and associated restricted blood flow to the GI tract (14). In the present study, environmental conditions were more extreme during all triathlons compared with MARATHON and CYCLE and, accordingly, heat index correlated with scores of upper and lower GI symptoms. Therefore, the combined effects of exercise duration and hot environmental conditions are most likely the causes for significantly increased GI distress during both IM races compared with IM 70.3 and for higher levels of GI distress during IM 70.3 compared with MARATHON and CYCLE.

As mentioned earlier, running is related with a higher prevalence for GI distress compared with cycling (32, 33), possibly due to the more dynamic bouncing nature of running and associated mechanical stress on the GI tract. However, in the present study no difference between reported GI symptoms during MARATHON and CYCLE was found. The MARATHON took place under considerably colder weather conditions and with the

relatively small number of subjects within those events we might have failed to detect a statistically significant difference.

Personal characteristics correlated with GI symptoms

A number of factors such as athlete's age, gender, training status etc. are thought to influence prevalence of GI distress (32). In the present study no association between age or gender and prevalence of GI distress was observed. Training experience and years of training were linked to lower prevalence of GI distress. This link is in agreement with previous research (32) and it could be speculated that more experienced athletes are also more experienced in their nutritional strategy and have developed their personal strategy through trial and error. Also, selection bias cannot be excluded as those athletes who suffer more from GI distress may drop out of the sport sooner than those who do not. It has also been suggested that the GI tracts can adapt to exercise (14). For example, trained individuals have been reported to empty their stomachs significantly faster than controls, both at rest and during exercise (20). Furthermore, trained individuals are reported to have a greater heat tolerance than untrained individuals, potentially leading to less restricted blood flow to the GI tract (14).

However, the most important factor that influenced GI problems within our study was an individual predisposition and history of GI distress among athletes. Independent of the event, we detected a positive correlation between GI symptoms during the races and reported history of GI distress. This finding is consistent with our previously published data (37) and suggests an individual predisposition for GI distress during exercise.

CHO intake and GI symptoms

The ingestion of CHO, especially the excessive consumption of hypertonic drinks, has previously been linked to altered GI distress (39). It has been speculated that hypertonic drinks cause GI distress via water retention in the intestines (39). Furthermore large amounts of CHO can lead to incomplete absorption (40) and residual CHO in the intestine has been linked to GI problems in studies at rest (8, 38). In contrast to previously reported links between CHO intake and GI distress, a recent series of studies has suggested that the intake of high rates of CHO (~1.4 g/min) in the form of glucose + fructose gels is well tolerated from the majority of athletes during ~70 min endurance running under mild environmental conditions (37). However, it has to be kept in mind that the incidence of GI problems increases with exercise time (33) and might be increased under more extreme weather and race conditions. In the present study we detected no clear relationship between CHO intake rates and GI distress. Mean upper and lower abdominal symptoms were not associated with CHO intake rates. Furthermore, mean CHO intake rates were not different between athletes with and without serious GI symptoms. However, we detected correlations between scores for nausea and flatulence with high CHO intake rates in more than one data set (IM Hawaii and IM 70.3). This confirms the finding of a previous study where we reported higher scores for nausea with high (1.4 g/min) compared with lower CHO intake rates (1 g/min) during a 16-km outdoor run (37). Similarly, in a study by van Nieuwenhoven *et al.* (44), flatulence was previously linked to CHO consumption when the ingestion of a CHO sports drink was compared with water intake. Altogether, this data suggests that CHO intake can indeed be a risk factor for nausea and flatulence during exercise. However, those more minor symptoms are less likely to impair performance

compared with symptoms such as diarrhoea or stomach cramps (27) and high CHO ingestion rates were correlated with faster finishing times.

Protein, fat and fibre intake and GI symptoms

Further nutrients that have previously been linked to GI distress during exercise are fat, protein and fibre (5). Those nutrients are associated with delayed gastric emptying rates (4, 19, 22) which might be one cause of GI discomfort while exercising. Contrary to our *a priori* hypothesis, in the present study we detected no correlation between high fat or protein intake and GI distress. However, it has to be recognized that athletes ingested less than 10% energy from fat or protein. At those low intake rates fat and protein might not have any influence on the GI tract. A correlation of high fibre intake and flatulence has been detected in more than one data set and it seems logical that high fibre intakes can lead to increased gas production in the gut due to its indigestibility and the property to be metabolized by human gut bacteria.

Benefits and limitations of measurements

One aspect that has to be recognized with all dietary measurements is the difficulty to estimate food and fluid intakes, even more so when subjects are exercising. Direct measurement of food and fluid intake on the race course is not possible with the large number of investigated subjects. Hence, the measures rely on the memory of athletes, which is a challenge especially regarding correct estimates of fluid intake during prolonged races. However, all athletes received detailed instructions before the event and were supplied with strategies to remember their race intake such as to recall where the actual intake deviated from a pre-race nutrition plan. Furthermore, any answers which caused doubt, such as very low or high fluid intakes, were directly followed up with individual

athlete interviews after the race. Consequently, this is the only study utilizing strict subject and dietary control that features more than 200 subjects and six different competitions.

Conclusions

In summary, the present study showed that CHO intake rates vary greatly between events, but also between individual athletes (6-136 g/h). The incidence of serious GI distress was quite variable in the present study (4-32%) and correlated with the duration and environmental conditions of the given event. High CHO intakes were linked to higher scores of nausea and flatulence, but at the same time a significant positive correlation to improved finishing times during IM events. Moreover, a correlation between reported GI symptoms and history of GI distress has been reported in this study and previous research (37), suggesting an individual predisposition for GI distress. Altogether the findings of the present study suggest a need for more individualized nutritional advice for endurance athletes, where each athlete finds their unique balance between the ergogenic effects of optimal CHO and fluid intake, and the potential ergolytic effects of substantial CHO intakes causing GI distress.

Acknowledgements

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Chapter 7

General Discussion

7.1 CHO intake during exercise

It is generally recommended that athletes should ingest CHO during endurance exercise (1, 6, 7, 23, 24). A widely used and cited recommendation for athletes is the position stand of the American College of Sports Medicine (ACSM) (1, 2). This recommendation advises athletes, competing in endurance events (>1 h), to consume CHO at a rate of 0.7 g/kgBW/h (~30-60 g/h). In contrast, a contemporary and alternative recommendation suggests that endurance athletes should take in more CHO (up to 90 g/h), especially in the form of CHO blends such as glucose + fructose (GLU+FRC), when competing in events exceeding 2 h. The rationale for recommending such high CHO doses is based on studies that revealed higher exogenous CHO oxidation rates (19, 21, 25, 41) and superior performance (10, 37) with the ingestion of GLU+FRC compared with GLU alone. However, such effects were observed only when large amounts of CHO were ingested (19, 21, 25, 41) and not at lower intakes (17).

In order to achieve such high ingestion rates, studies investigating the oxidation of CHO during exercise in the laboratory have used concentrated CHO solutions between 10% and 20%. In reality, it seems to be common practice to consume CHO in the form of 4-6% CHO solutions alongside other forms of CHO (CHO gels and energy bars) (15). Several practical questions related to these new recommendations were the topic of investigation in this thesis.

7.2 Exogenous CHO oxidation from different CHO forms

It is documented that solid food that also contains fat and fibre can reduce gastric emptying rates considerably (14, 16). Although it is not thought that gastric emptying rates determine exogenous CHO oxidation rates of CHO solutions (24), gastric emptying rates could determine the delivery of CHO available for absorption from solids. Hence, the hypothesis of **Chapter 4** was that exogenous CHO oxidation rates from a solid bar (BAR) would be lower than from a drink (DRINK) due to slower CHO delivery to the small intestine. Previous research on the gastric emptying rates of semi-solid gels has shown equivocal results. The addition of gel-forming fibre, such as guar gum, to CHO solutions was demonstrated to delay gastric emptying rates compared with CHO alone (28, 29, 35). In contrast, a study by Leiper *et al.* (27) reported faster gastric emptying rates from a gel-forming GLU polymer compared with an isocaloric, low-viscosity GLU solution. Furthermore, it has been described that the stomach empties in layers, holding back solid and more concentrated foods in the sinus of the stomach (for review, see (34)). Thus, it would have been possible that a CHO gel plus water would lead to differences in CHO concentrations in the gut and therefore result in different rates of intestinal absorption and subsequent oxidation. The hypothesis of **Chapter 3** was that differences would be small and that exogenous CHO oxidation from a GEL would be similar to that of a DRINK.

The study described in **Chapter 3** confirmed that the intake of a GLU+FRC mixture in the form of a semi-solid CHO gel combined with plain water leads to similar exogenous CHO oxidation rates compared with a CHO solution. The intake of GLU+FRC at an ingestion rate of 1.8 g/min during 3 h of moderate intensity cycling (~60% VO_2max) resulted in similar peak exogenous CHO oxidation rates of 1.44 ± 0.29 g/min and 1.42 ± 0.23 g/min for

GEL and DRINK, respectively. Importantly, the % of ingested CHO that was oxidized (oxidation efficiency) was ~70% for both CHO treatments, indicating that most of the ingested CHO was oxidized.

Somewhat surprisingly, the ingestion of a solid CHO BAR also resulted in high exogenous CHO oxidation rates (>1 g/min) and high oxidation efficiencies (**Chapter 4**). In the study described in **Chapter 4**, ingestion of a solid GLU+FRC BAR was compared with a GLU+FRC solution. A similar exercise protocol as that used in **Chapter 3** was employed; however, a lower CHO intake rate of 1.55 g/min was chosen, to ensure good tolerance of the associated large volume with the intake of high CHO doses in solid form. The mean exogenous CHO oxidation rates and oxidation efficiencies in this study were high and not significantly different between CHO forms. Lower CHO oxidation rates from the BAR were reported between 2 and 2.5 h. At the end of 180 min exercise, both treatments reached similarly high peak exogenous CHO oxidation rates (1.25 ± 0.15 g/min and 1.34 ± 0.27 g/min for BAR and DRINK, respectively). Oxidation efficiency was also high in both treatments ($66 \pm 2\%$ vs. $73 \pm 4\%$, respectively, $p=0.19$) and the difference was not statistically significant.

To summarize, results from **Chapters 3** and **4** suggest that CHO ingested either in semi-solid or solid form are both effectively oxidized. This implies that athletes can choose a mixed intake of different CHO forms as an effective method of CHO delivery to the muscle.

7.3 Exogenous CHO oxidation during running

Most research studies have used cycling as the mode of exercise while very few studies have been conducted in running. Recommendations for running are often extrapolated and derived from findings in cycling studies. However, there are clear differences between both types of exercise, such as movement and muscle recruitment patterns (4, 13). It has been documented that gastrointestinal (GI) problems are more prevalent during running compared with cycling (30, 31). Among other reasons, it was suggested that altered absorption due to relatively high mechanical stress could be a cause for enhanced GI distress during running (12). This led to the hypothesis that exogenous CHO oxidation rates would be different during running and cycling. Studies comparing both modes of exercise are scarce, and therefore in **Chapter 5**, we directly compared exogenous carbohydrate oxidation during running and cycling.

In that study, we demonstrated that exogenous CHO oxidation rates from ingested GLU+FRC solutions at intake rates of 1.5 g/min resulted in similarly high exogenous CHO oxidation rates (~1.2 g/min) during running and cycling at the same relative intensity (~60% of the exercise specific $\text{VO}_{2\text{max}}$). Subjects with a similar training background in running and cycling were chosen. In agreement with previous research in similarly trained subjects, the $\text{VO}_{2\text{max}}$ values were ~4% higher during running compared with cycling (3, 8). Exercise intensity was set at ~60% $\text{VO}_{2\text{max}}$, because it has been shown that exogenous CHO oxidation rates peak between 51-65% $\text{VO}_{2\text{max}}$ (32). Hence, the variation in exogenous CHO oxidation rates with exercise intensity was expected to be small at the chosen intensity.

In line with previous research from our laboratory (25) and equivalent to **Chapter 4**, exogenous CHO oxidation rates in **Chapter 5** reached a peak value of 1.19 ± 0.08 g/min during cycling. Interestingly, during running at the same relative intensity, a similar peak exogenous CHO oxidation rate of 1.25 ± 0.10 g/min was reached. Furthermore, the oxidation efficiency proved to be similar (~74%) in both exercise trials. The findings of this study are supported by a previous study by Derman and co-workers (11) who reported similar exogenous CHO oxidation rates during running compared with cycling at 80% $\text{VO}_{2\text{max}}$. Interpretation of the findings from that study, however, is difficult, because of methodological issues related to the relatively high exercise intensity and short exercise duration (~1 h) of the experimental trials. Conclusions from the tracer methodology (^{14}C) are limited within the first hour of exercise and can be problematic at higher exercise intensities due to a temporary fixation of CO_2 in the bicarbonate pool. A more recent study by Couture *et al.* (9) has also measured exogenous CHO oxidation during running but at an exercise intensity of 70% $\text{VO}_{2\text{max}}$ over 120 min. Reported exogenous CHO oxidation rates from the ingestion of GLU at rates of 2 g/min were very high (1.2 g/min) during running, but no direct comparison with cycling was made in that study. The reported exogenous CHO oxidation rates, however, are similar to results from a cycling study during moderate intensity cycling, with GLU ingestion of 2.4 g/min (20). This supports our finding that exogenous CHO oxidation rates are similar for different modes of exercise and suggests that previous findings from studies investigating exogenous CHO oxidation during cycling studies can also be extrapolated to running (at least at moderate exercise intensities).

In line with previous studies, we measured higher fat and lower total CHO oxidation rates during running compared with cycling at the same relative exercise intensity. The lower

total CHO oxidation rates combined with similar exogenous CHO oxidation rates during running resulted in a trend to reduce endogenous CHO usage (muscle and liver glycogen). It has previously been suggested that muscle glycogen usage is lower during running compared with cycling (38). However, this theory was based on indirect evidence from studies that measured muscle glycogen utilization during running or cycling with the use of different methodologies and exercise protocols. To date, no study has compared muscle glycogen use during running and cycling over a prolonged period of time (>1 h), and it remains to be established whether glycogen utilization is different for different modes of endurance exercise.

7.4 Variation of exogenous CHO oxidation with bodyweight

An alternative to the ACSM recommendation (1), which is based on CHO intake according to bodyweight (0.7 g/kg bw/h), suggests CHO intake in absolute terms (23). One could argue that a CHO intake recommendation according to bodyweight would be more suitable, considering the potential large variation in bodyweight and energy expenditure of athletes. However, it was argued that the variations in measures of exogenous CHO oxidation in previous research are generally small (18, 19, 21, 22, 25, 41), suggesting that only small differences in CHO utilization exist among athletes. Even though it was not the purpose of the present doctoral thesis, data taken from **Chapter 3** and **Chapter 4** indicates that no correlation between bodyweight and exogenous CHO oxidation rates exists (see Figure 7.1A and B, respectively).

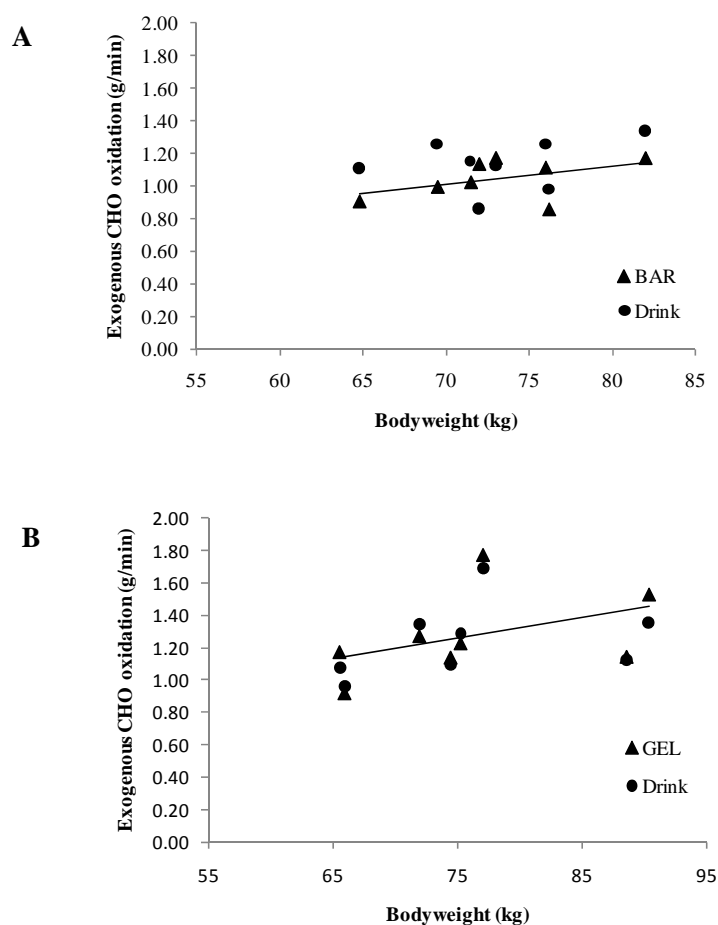


Figure 7.1A/B Data from Chapters 3 (A) and 4 (B) is presented: Exogenous CHO oxidation rates are shown in relation to the subject's bodyweight. No correlations between bodyweight and exogenous CHO oxidation rates were observed.

In each study, only 8 subjects were tested with relatively similar bodyweights. However, the results are in agreement with a large number of measurements obtained over many years in our laboratory (unpublished findings). A larger scale study currently being conducted, measuring exogenous CHO oxidation rates over a wide range of bodyweights, also seems to confirm these results. The recommendation by ACSM per kg bodyweight is not based on scientific evidence and should be replaced with advice in absolute amounts of CHO.

7.5 Gastrointestinal (GI) tolerance of high CHO intake rates

An obvious criticism of recommendations derived from laboratory research is whether high CHO intake rates (~1.5 g/min; (23)) are possible to achieve and are tolerated in a field situation. The intake of CHO, and especially the ingestion of hypertonic drinks, has been linked to altered GI distress (30, 33), which can ultimately impair performance (5, 36).

In **Chapter 2**, the tolerance of two different doses of CHO was tested during a 16-km simulated running competition. In a randomized cross-over design, 34 well-trained runners ingested a moderate (MOD; 1 g/min, 60 g/h) or a high CHO dose (HIGH; 1.4 g/min, 90 g/h) in the form of a gel. Overall, no dose-response effect on GI distress was detected for the treatments. The only symptom that occurred more often with the HIGH dose was nausea.

This finding was later confirmed in data from triathlon events. In **Chapter 6**, we evaluated the nutrient intake and GI distress of a total of 221 athletes during 2 Ironman triathlons (IM), a half-distance Ironman (IM 70.3), a marathon (MARATHON) and an amateur cycling race (CYCLE) and professional (PRO) stage racing. GI distress was reported frequently during the IM (31%) and IM 70.3 (14%). Consequently, this data was evaluated for possible links between nutrient intake and GI distress. In agreement with the dose-response study of **Chapter 2**, we reported no clear link between the CHO intake rate and GI distress. Accordingly, high CHO intake rates during the events were correlated with increased levels of nausea. Furthermore, flatulence was reported to correlate with high CHO intake rates. A study by van Nieuwenhoven (39) already linked this symptom with CHO consumption when the ingestion of a CHO sports drink was compared with water

intake. Altogether it appears that CHO intake is linked to nausea and flatulence, those symptoms, however, can be rated as less severe compared with symptoms such as diarrhoea or stomach cramps (26, 33). Interestingly, high CHO intake rates, although associated with nausea and flatulence, were correlated with faster finish time during the IM races. One explanation for why CHO intake rates correlated with finishing times could be that nutrient intake habits vary among different levels of athletes. Higher-class athletes may be more educated and have a more advanced nutrition strategy. However, another reason could be that higher CHO intakes provided a benefit in performance. Furthermore, GI symptoms during the events were correlated to a reported history of GI distress in all studies of the present thesis. In conclusion, it seems reasonable to advise athletes to test their tolerance of high CHO doses during hard training sessions, ideally under similar conditions to the races they aim to compete in.

One theory that has linked CHO intake with altered GI distress is the possibility that excess CHO, which is not absorbed, remains in the lower intestine (40). As described earlier in this thesis, superior exogenous CHO oxidation rates from CHO blends such as GLU+FRC compared with GLU alone are largely attributed to different absorptive properties in the small intestine. This led to the hypothesis that less remaining CHO in the GI tract with the ingestion of GLU+FRC could result in improved tolerance of those CHOs compared with GLU. Consequently, a second study described in **Chapter 2** compared tolerance of high CHO intake rates (1.4 g/min) delivered in the form of GLU or GLU+FRC gel with the use of a similar study design as the dose-response study. In contrast to the hypothesis, no overall difference between treatments was detected, however, some individuals showed more symptoms with one or the other gel.

One reason that no better tolerance of GLU+FRC was shown could be that GI tolerance is not exclusively influenced by absorption and residual CHO in the intestine. As discussed in **Chapter 1**, factors such as reduced blood flow to the gut or mechanical stress from running can be involved in the etiology of GI distress. In addition, a superior effect of faster absorption of different CHOs would be expected later in exercise. Higher exogenous CHO oxidation from a GLU+FRC blend compared with GLU starts to occur after ~45 min of exercise (21, 41), and an average duration of ~70 min might have been too short to detect differences caused by residual CHO in the GI tract. A superior tolerance of GLU+FRC compared with single GLU might exist later in exercise and future research in this area is needed.

An interesting finding in all experimental trials in **Chapter 2**, which was also confirmed in **Chapter 6**, was a correlation between GI symptoms during the trials with a reported history of GI symptoms. This finding suggests an individual predisposition for GI distress during exercise, which implies that personal advice and individual testing of food and drink intake during exercise are vital. Furthermore, a link between training experience and GI distress was reported in **Chapter 6** and has been documented previously (30). It could be speculated that more experienced athletes are more likely to adapt a suitable nutritional strategy. Another explanation could be that training, especially with the ingestion of CHO, can train the GI tract, leading to a better tolerance of high CHO intake rates. However, this possible link has yet to be established.

7.6 Nutritional intake of athletes during endurance events

Knowledge about the nutritional intake habits of recreational and elite athletes during competitions is scarce. To give appropriate advice, however, recognizing athletes' habits

and understanding possible limitations of nutrient intake in the field are important. Therefore, a large-scale study, involving a total of 221 athletes, was designed to quantify and characterize nutrient (especially CHO) intake during endurance running, cycling and triathlon competitions (**Chapter 6**). The study revealed that CHO intake rates varied greatly between events as well as between individual athletes (6 to 136 g/h). The highest average CHO intake (65 g/h) rates exceeded the ACSM recommendations (1) and were reported during ultra-endurance triathlon events. During the amateur cycling event (CYCLE), lower average CHO intake rates (53 g/h) were reported. The lowest average CHO intake rates (35 g/h) were found during MARATHON, where 73% of the marathon runners failed to meet the relatively low ACSM recommendations.

Differences in CHO intakes were not associated with the duration of the races but varied with the mode of exercise. Running has been linked to low CHO and fluid intake rates, not only between different events but also within each triathlon. Interestingly, high CHO intake rates were correlated with faster finish times. CHO and fluid intake rates were higher in professional cyclists compared with amateur cyclists, suggesting that higher-level athletes are more likely to take in higher amounts of CHO and fluid.

The investigated events clearly showed that solid and semi-solid CHO forms are important fuels for athletes, highlighting the relevance of **Chapter 3** and **4** of this thesis. Similar to the very different CHO intake rates, the preferred CHO intake form varied among individual athletes. A clear pattern of preferred CHO forms among different sports, level of athletes and personal characteristics was not shown. There is some indication that environmental race conditions partly influence the choice of CHO delivery form. For example, the highest proportion of CHO ingested as solution was found during the hottest

event (IM Hawaii), while the lowest % CHO intake in the form of liquid was reported during the coolest event (MARATHON). A preference for semi-solid or liquid CHO forms while running was present in all triathlon events, whereas comparatively more CHO was ingested in solid form during the cycling section.

Overall, the study gives important insight into athletes' habits during endurance events and highlights the need for individualized nutritional advice for athletes, due to the large inter-individual differences.

7.7 Conclusions

A number of conclusions, both scientific and practical, can be drawn from this doctoral thesis.

Studies investigating exogenous CHO oxidation (**Chapters 3, 4 and 5**) revealed the following:

- 1) CHO ingested as semi-solid gel results in similar exogenous CHO oxidation rates compared with a CHO drink during prolonged moderate intensity cycling.
- 2) GLU+FRC ingested in the form of a solid bar is effectively oxidized during moderate-intensity cycling and results in high mean and peak exogenous CHO oxidation rates (>1 g/min).
- 3) Exogenous CHO oxidation rates of a CHO solution are similarly high during running and cycling at the same relative (moderate) intensity. Because fat oxidation rates were higher during running compared with cycling, this resulted in a trend to lower endogenous CHO oxidation rates during the running trials.

Studies investigating GI distress (**Chapters 2 and 6**) showed the following:

- 4) High CHO intake rates (1.4 g/min) in gel form are well tolerated by the majority of runners during ~70 min running under mild environmental conditions. However, high CHO intake is linked to the occurrence of nausea and flatulence.
- 5) CHO ingested as GLU+FRC gel does not result in superior GI tolerance compared with GLU gel during ~70 min of running.
- 6) GI distress during events is correlated with a history of GI distress, suggesting that an individual predisposition to GI problems exists.

The study about athletes' nutritional intake habits (**Chapter 6**) showed the following:

- 7) Athletes' nutritional intake habits vary greatly among running, cycling and triathlon events. While the average CHO intake rates during triathlons exceeded ACSM recommendations (63 g/h), 73% of runners failed to meet those recommendations and ingested on average only 35 g/h.
- 8) A large variation in nutritional intake was reported among individual athletes, with CHO intake rates ranging from 6 to 136 g/h.
- 9) High CHO intake rates were correlated to faster finish times during IM races and the MARATHON, indicating a performance benefit of high CHO intake rates or a difference among athletes of different levels.
- 10) Solid and semi-solid CHO sources are indeed frequently consumed during endurance events and provide on average between 15-45% of the CHO intake.

7.8 Future directions

The present doctoral thesis answered several questions related to the practicability and relevance of previous laboratory studies for athletes in the field. Although this thesis has made a significant contribution to our understanding within this area of research, there are several follow-up questions, including the following:

- 1) Is CHO ingested in the form of GLU+FRC tolerated differently compared with ingested GLU during prolonged endurance exercise (>2 h)?
- 2) Is it possible to train the intestinal tract and get accustomed to high CHO intakes?
- 3) What are the physiological differences of the GI tract of athletes with and without a history of GI distress?
- 4) Are exogenous CHO oxidation rates dependent on bodyweight?
- 5) Is muscle glycogen utilization different between running and cycling over prolonged exercise durations (>1 h)?
- 6) As mentioned in the introduction, a clear dose-response relation between exogenous CHO oxidation and improvements in performance has not been established. Hence, a study investigating exogenous CHO oxidation and endurance exercise performance with the ingestion of different CHO doses is warranted.

Furthermore, a standardized approach is necessary for studies investigating GI distress during exercise. A standardized questionnaire with a consistent statistical approach would offer the chance to compare data between different studies and add greatly to a better understanding of GI distress during exercise.

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Training Questionnaire (Triathlon)

General Information

Name:	<input type="text"/>	Date:	<input type="text"/>
First name:	<input type="text"/>	Sex:	Male <input type="checkbox"/> Female <input type="checkbox"/>
Date of birth:	<input type="text"/>	Age:	<input type="text"/>
Address 1:	<input type="text"/>	Telephone:	<input type="text"/>
Address 2:	<input type="text"/>	E-mail:	<input type="text"/>
Post code:	<input type="text"/>	Mobile:	<input type="text"/>
City:	<input type="text"/>	Race number:	<input type="text"/>
Weight:	<input type="text"/>	Height:	<input type="text"/>

Please confirm that you fully understood the instructions about the study, how we intend to use the data you provide, and that you are willing to take part in the study.

☐ yes, I confirm

Please confirm that you are happy for us to contact you by e-mail during the study in case we have any questions.

☐ yes, I confirm

Training History

1. How many Ironman have you done before? <input type="text"/>	2. Have you done any other competitive sports in the past? <input type="checkbox"/> yes <input type="checkbox"/> no If so which sports and at what level? <input type="text"/>
3. How many years ago have you started to compete in triathlon? <input type="text"/> years ago	4. How many years have you been involved in endurance sports? <input type="text"/> years
5. What are your personal bests for the following distances (if applicable; within last 5 years)?	6. What is your expected finishing time for this race?
Sprint Triathlon <input type="text"/> (h:min:s)	<input type="text"/> I don't know
Olympic Distance Triathlon <input type="text"/> (h:min:s)	<input type="text"/> (h:min:s)
70.3 Triathlon <input type="text"/> (h:min:s)	
Ironman <input type="text"/> (h:min:s)	
Marathon <input type="text"/> (h:min:s)	
Comments: <input type="text"/>	
7. Approximately, how many HOURS per WEEK are you RUNNING (average for last 2 months)? <input type="text"/>	8. Approximately, how many KM per WEEK are you RUNNING (average for last 2 months)? <input type="text"/>
9. Approximately, how many HOURS per WEEK are you CYCLING (average for last 2 months)? <input type="text"/>	10. Approximately, how many KM per WEEK are you CYCLING (average for last 2 months)? <input type="text"/>
11. Approximately, how many HOURS per WEEK are you SWIMMING (average for last 2 months)? <input type="text"/>	12. Approximately, how many KM per WEEK are you SWIMMING (average for last 2 months)? <input type="text"/>



Habitual nutrient intake

13. What do you normally drink during **TRAINING**?

	Never	Rarely	Regularly	Always
Water	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Fruit juice	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Sports drink	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Coke	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Others	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Please specify				

14. What do you normally drink during **COMPETITION**?

	Never	Rarely	Regularly	Always
Water	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Fruit juice	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Sports drink	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Coke	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Others	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Please specify				

15. What do you normally eat during **TRAINING**?

	Never	Rarely	Regularly	Always
Gel	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Sports bar	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Fruit (banana)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Jelly beans/gummy bears	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Others	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Please specify				

16. What do you normally eat during **COMPETITION**?

	Never	Rarely	Regularly	Always
Gel	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Sports bar	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Fruit (banana)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Jelly beans/gummy bears	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Others	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Please specify				



17. Which of the following nutrition supplements do you currently take or have taken in the last 2 months?

	Never	Rarely	Regularly	Always
Vitamins and minerals	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Probiotics (e.g.in yoghurt)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Protein shakes	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Amino Acids (tablets or ampoules)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
L-Carnitine	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Creatine	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
HMB	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Beta-alanine	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Ginseng	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Fish oil/ omega-3	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
CLA	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Other	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Please specify				

History of GI problems during RACING

18. Do you have any food allergies?

☐ yes

☐ no

☐ I don't know

19. Are you lactose intolerant?

☐ yes

☐ no

☐ I don't know

If yes, please specify

20. Do you suffer from any abdominal problems during rest?

☐ yes, very often

☐ yes, often

☐ yes, sometimes

☐ no

21. Please tell us if you have one of the following medical conditions diagnosed?

☐ Irritable bowel syndrome

☐ Morbus Crohn

☐ Colitis Ulcerosa

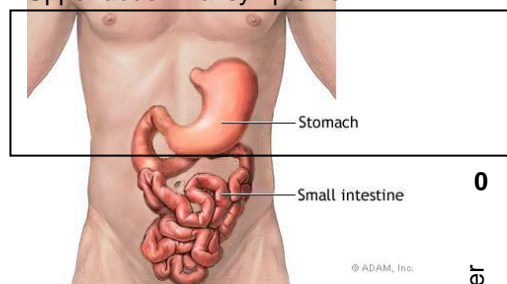
☐ Coeliac disease / gluten sensitivity

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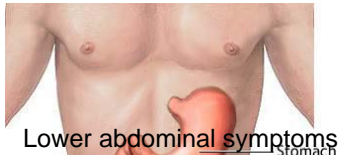
Upper abdominal symptoms



22. Please rate how often you experience the following UPPER ABDOMINAL SYMPTOMS during COMPETITIONS?

	0	1	2	3	4	5	6	7	8	9
	Never	Rarely	Occasionally	Sometimes	Quite often	Fairly frequently	Frequently	Very frequently	Almost always	Always

Reflux/Heartburn	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Belching	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Bloating	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Stomach pain/cramps	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Nausea	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Vomiting	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>



Lower abdominal symptoms

23. Please rate how often you experience the following LOWER ABDOMINAL SYMPTOMS during COMPETITIONS?

	0	1	2	3	4	5	6	7	8	9
--	---	---	---	---	---	---	---	---	---	---

Intestinal/ lower abdominal cramps	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Flatulence	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Urge to defecate	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Side ache/stitch	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Loose stool	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Diarrhoea	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Intestinal bleeding	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>



24. Please rate how often you experience the following SYMPTOMS during COMPETITIONS?

	0	1	2	3	4	5	6	7	8	9
Dizziness	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Headache	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Muscle cramp	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

25. How often have GI problems affected you race outcome?

☐ always
 ☐ often
 ☐ rarely
 ☐ never

Preparation for your race

26. How often have you consumed the following foods in the 3 DAYS BEFORE THE RACE?

Food	Not at all	1 x day	2 x day	3 x day	>3 x day
Sausages (not low fat)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Hamburgers	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Fries (Chips)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Bacon	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Salad dressing (not low fat)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Fish (e.g. salmon, mackerel, herring)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Fat meat (e.g. minced, pork belly, pork hock)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Mayonnaise (full fat)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Margarine/butter	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Sauces (e.g. hollandaise, cheese, cream, meat sauce)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Pizza	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Crisps	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Crackers	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Fried foods	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Pastry, Croissant	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Cookies	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Doughnuts	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Cake	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Ice cream	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Chocolate	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Cream (incl. double cream, crème Fraîche etc.)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Cream Cheese	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

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Cheese (<20% fat)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Cheese (>20% fat)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Whole milk	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Semi skimmed milk (~2%)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Low fat milk	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Yoghurt (full fat)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Yoghurt (low fat)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Buttermilk	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Other dairy products	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Fruit (fresh or canned)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Fruit juice (pure fruit)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Vegetable juice/tomato juice	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Vegetables	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Green salad	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Beans, lentils	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Seeded bread	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Wholemeal bread	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Breakfast cereals (e.g. muesli, shredded wheat, bran flakes)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Alcoholic drinks	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

27. Do you have a structured plan what you intend to eat and drink during the race?

☐ yes, I have a detailed plan ☐ yes, I have an idea ☐ no, I have no plan

28. If yes, where did you mainly get the nutrition information from (please tick the most important source)?

☐ nutritionist/dietician
☐ trainer
☐ personal experience
☐ other athletes
☐ scientific papers
☐ magazines please specify which
☐ websites please specify which
☐ other please specify



Race Questionnaire (Triathlon)

General Information

Name: Date:
First name: Sex: Male ☐ Female ☐
Date of birth: Race No:
E-mail:

Did you know before the race, that you would need to remember what you ate and drank? yes ☐ no ☐
Did you get a personal briefing from the investigators about the study? yes ☐ no ☐

Preparation for the race

1. Did you have breakfast before the race?

☐ yes ☐ no

If yes, how many hours before the race did you have breakfast?

If you had breakfast, what did you eat exactly (please specify foods and quantities exactly, e.g. 2 table spoons cereal (Alpen), 100g yoghurt, 2 thick slices white toast)

2. Did you eat anything else after breakfast (before the race)?

☐ yes ☐ no




If yes, please specify when and what

3. What (and how much exactly) did you drink in the morning before the race?

Food intake during the race

4. How much food (exactly) have you ingested during the race?

Please try to recall your intake as accurate as possible. It is important for us to know exactly what you consumed (type, brand and flavour of a product) and how much (e.g. 1 "GoBar" (65g, ½ Banana, 1 hand full gummy bears).




	Swim (just before) 	Bike (+ Transition 1) 	Run (+ Transition 2) 
Energy Bars:			
Power Bar Performance bars (as supplied)	<input type="text"/>	<input type="text"/>	<input type="text"/>
Other Energy bars	<input type="text"/>	<input type="text"/>	<input type="text"/>
Type: <input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
Type: <input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
Type: <input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
Energy gels:			
PowerBar gels (as supplied)	<input type="text"/>	<input type="text"/>	<input type="text"/>
Other gels	<input type="text"/>	<input type="text"/>	<input type="text"/>
Type: <input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
Type: <input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
Other Food (from aid stations):			
Bananas	<input type="text"/>	<input type="text"/>	<input type="text"/>
Apples	<input type="text"/>	<input type="text"/>	<input type="text"/>
Oranges	<input type="text"/>	<input type="text"/>	<input type="text"/>
Lemon	<input type="text"/>	<input type="text"/>	<input type="text"/>
Dried fruit, please specify: <input type="text"/>	<input type="text"/> hand full	<input type="text"/> hand full	<input type="text"/> hand full
Cake	<input type="text"/>	<input type="text"/>	<input type="text"/>
Other foods: (please specify exactly: Type, brand...)			
Jelly beans/gummy bears	<input type="text"/> hand full	<input type="text"/> hand full	<input type="text"/> hand full
<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>



Fluid intake during the race

5. How much fluid (exactly) have you ingested during the race?

Please try to give accurate amounts of fluid ingested (ml, l, cups or bottles – but please tell us what bottle size you used). It is easiest to count how many bottles/cups you consumed on the way. But please subtract the fluid you spilt, poured over your head etc.

	Swim (just before) 	Bike (+ Transition 1) 	Run (+ Transition 2) 
Water	<input type="text"/>	<input type="text"/>	<input type="text"/>
Power Bar sports drink (from feed stations)	<input type="text"/>	<input type="text"/>	<input type="text"/>
Sports drink (own mixture) Type of Sports drink:			
<input type="checkbox"/> according to instructions (on package)	<input type="text"/>	<input type="text"/>	<input type="text"/>
<input type="checkbox"/> less concentrated			
<input type="checkbox"/> more concentrated			
Home made sports drink (please specify exact ingredients + amounts) <input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
Coke	<input type="text"/>	<input type="text"/>	<input type="text"/>
Red bull	<input type="text"/>	<input type="text"/>	<input type="text"/>
Other soft drink please specify: <input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
Fruit juice, please specify:	<input type="text"/>	<input type="text"/>	<input type="text"/>
Other fluids Please specify: <input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>

6. If you used the sports drink at the feed stations, how would you rate this provided mixture?

☐ according to instructions
 (on package)
 ☐ less concentrated
 ☐ more concentrated

7. If you used your own bottles, how big was the bottle size exactly?

ml

8. If you used drink cups from the feed stations, how much fluid did you get from 1 cup?

ml

9. Have you used any foods or drinks during the race, which you have not used before (during training or competition)?

☐ yes
 ☐ no

Please specify

10. If you had a plan for your nutrient and fluid intake, did you match the intake?

☐ yes
 ☐ no
 Please specify, what was different

Intake of other supplements

11. Have you consumed any of the following caffeinated products (please give amounts)?

Caffeinated Gel (e.g. PowerBar Green apple, Black Currant)	<input type="text"/>
Caffeinated Bars (e.g. PowerBar Raspberry Cream, Coconut Crisp, Cola)	<input type="text"/>
Caffeine tablets (e.g. proplus, NoDoz)	<input type="text"/>
Other caffeinated products	<input type="text"/>

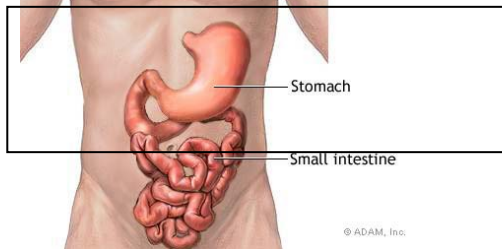
12. If you took in one of the following supplements, please specify how much.

	Amount used immediately BEFORE race	Amount used DURING the race
Salt or electrolyte tablets (Sodium, Na ⁺ ; Potassium K ⁺ , Chloride, Cl ⁻)	<input type="text"/>	<input type="text"/>
please specify amount of sodium/tablet <input type="text"/>		
Mineral Tablets (eg. Magnesium) please specify <input type="text"/>	<input type="text"/>	<input type="text"/>
Vitamin tablets please specify <input type="text"/>	<input type="text"/>	<input type="text"/>
H ₂ blockers (e.g. Tagamet, Pepcid, Zantac)	<input type="text"/>	<input type="text"/>
Pain killer (e.g Aspirin, Paracetamol, Ibuprofen)	<input type="text"/>	<input type="text"/>
Others: please specify <input type="text"/>	<input type="text"/>	<input type="text"/>



GI problems during the RACE

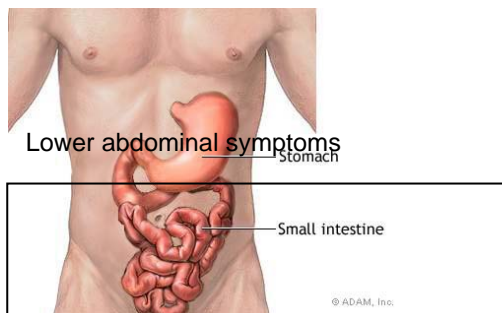
Upper abdominal symptoms



10. Please rate if you experienced any of the following symptoms DURING THIS RACE:

	0	1	2	3	4	5	6	7	8	9
	no problem at all	Very, very minor problems	very minor problems	minor problems	moderate problems	serious problems	severe	very severe	Very, very severe	the worst it has ever been
A Upper abdominal symptoms										
Reflux/Heartburn	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Belching	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Bloating	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Stomach pain / cramps	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Vomiting	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Nausea	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

Lower abdominal symptoms



	0	1	2	3	4	5	6	7	8	9
B Lower abdominal symptoms										
Intestinal / lower abdominal cramps	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Side ache /stitch	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Flatulence	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Urge to defecate	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Diarrhoea	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Intestinal Bleeding	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

Post-race Questionnaire



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	0	1	2	3	4	5	6	7	8	9
C Other symptoms										
Dizziness	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Headache	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Muscle cramp	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Low blood sugar / hypoglycaemia	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

13. Was your performance impaired by gastrointestinal problems?

☐ yes

☐ no

14. How many times did you urinate?

13. Did you finish the race today?

☐ yes

☐ no

If not, can you tell us the reason why?