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The effect of glycaemic index of high carbohydrate diets consumed over 5 days on exercise energy metabolism and running capacity in males

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Abstract
The aim of this study was to determine whether rates of total fat and carbohydrate oxidation and endurance capacity during running conducted in the fasted state are influenced by the glycaemic index (GI) of high carbohydrate diets consumed over 5 days. Nine healthy males performed three treadmill runs to exhaustion at 65% of maximum oxygen uptake ($\dot{V}O_{2max}$): after a habitual diet (control trial), after 5 days on a high carbohydrate/high glycaemic index diet, and after 5 days on a high carbohydrate/low glycaemic index diet in randomized counterbalanced order. No significant differences in rates of fat and carbohydrate oxidation, concentrations of plasma insulin, glucose, non-esterified fatty acids and glycerol, or time to exhaustion were observed between the high carbohydrate/high glycaemic index and high carbohydrate/low glycaemic index trials. Compared with the control trial, the concentration of plasma glycerol and rate of fat oxidation were lower ($P < 0.05$) and the rate of carbohydrate oxidation higher ($P < 0.05$) in both the high carbohydrate/high glycaemic index diet and high carbohydrate/low glycaemic index trials during the run to exhaustion. In conclusion, the extent by which a high carbohydrate diet consumed over 5 days reduces rate of fat oxidation during subsequent running exercise in the fasted state is not influenced by the glycaemic index of the diet.

Keywords: *Glycaemic index, high carbohydrate diets, exercise metabolism*

Introduction

It is well established that increased dietary carbohydrate intake for several days before endurance events increases muscle glycogen concentration (Rauch et al., 1995, Tarnopolsky et al., 2001) and enhances performance (Brewer, Williams, & Patton, 1988; Rauch et al., 1995). It is also known that optimization of glycogen content with high carbohydrate diets occurs at the cost of diminished availability and contribution of fat towards exercise energy expenditure (Brewer et al., 1988; Coyle, Jeukendrup, Oseto, Hodgkinson, & Zderic, 2001). This compromised fat oxidation, in addition to enhanced pre-exercise muscle glycogen availability, could be expected to enhance the rates of glycogenolysis and glycogen depletion (Arkinstall et al., 2004; Hargreaves, McConell, & Proietto, 1995, Wojtaszewski et al., 2003), a condition known to be accompanied by an impairment in oxidative energy provision (Gibala, Pierce, Constantin-Teodosiu, & Greenhaff, 2002), disturbances in excitation–contraction coupling (Hargreaves, 2004), and thus attenuate the enhancement of exercise performance expected from a high carbohydrate intake.

Several recent studies have suggested that lipid availability and fat oxidation during endurance exercise conducted under conditions of a high carbohydrate intake might be influenced by the glycaemic index. First, there is evidence to suggest that consuming carbohydrates with a low glycaemic index 2–3 h before endurance exercise results in increased availability of plasma free fatty acids and thus a higher rate of total fat oxidation (Febbraio, Keenan, Angus, Campbell, & Graham, 2000; Kirwan, Cyr-Campbell, Campbell, Scheiber, & Evans, 2001; Sparks, Selig, & Febbraio, 1998; Wee, Williams, Gray, & Horabin, 1999; Wu, Nicholas, Williams, Took, & Hardy, 2003; Wu & Williams, 2006). Second, two recent studies have suggested that a low glycaemic index diet consumed during 24 h recovery between bouts of prolonged strenuous

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exercise may also result in greater availability of plasma free fatty acids (Stevenson, Williams, McComb, & Oram, 2005; Trenell, Stevenson, Stockmann, & Brand-Miller, 2008) and sometimes (Stevenson et al., 2005), but not always (Trenell et al., 2008), a higher rate of total fat oxidation during subsequent exercise conducted in the fasted state.

There is some evidence to suggest that availability of fasting free fatty acids could also be influenced by the glycaemic index of moderate carbohydrate diets consumed for an extended period (Kiens & Richter, 1996). However, in contrast to 24-h post-exercise recovery studies (Stevenson et al., 2005, Trenell et al., 2008), Chen et al. (2008) reported no impact of the glycaemic index of a high carbohydrate diet consumed for 3 days on exercise energy substrate utilization and exercise performance. Therefore, further studies are required to determine whether adaptations to the glycaemic index of a high carbohydrate diet consumed for a longer period differ from those seen in shorter intervention studies.

The aim of this study was to investigate the impact of consuming a high carbohydrate diet with either a low or high glycaemic index for 5 days on energy substrate utilization during running conducted in the fasted state. As in previous research (Chen et al., 2008; Febbraio et al., 2000; Sparks et al., 1998; Stevenson et al., 2005; Wee et al., 1999; Wu & Williams, 2006), we also wished to determine whether the glycaemic index of high carbohydrate diets has an impact on exercise capacity.

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Methods

Participants

Nine healthy active males participated in this study. Their mean age, weight, height, body mass index, and maximum oxygen consumption ($\dot{V}O_{2max}$) were 23.9 years ($s = 4.3$), 71.6 kg ($s = 8.2$), 1.79 m ($s = 0.07$), 22.3 kg $\cdot$ m^{-2} ($s = 2.0$), and 59.8 ml $\cdot$ kg$^{-1}\cdot$ min^{-1} ($s = 4.3$) respectively. Six of the participants had been training for distance running and took part regularly in regional and sometimes national competitions, a seventh was a skateboarder, and the remaining two had been training as footballers at local clubs. All participants had been involved in regular endurance training for at least 4 years. None of the participants was a vegetarian or a smoker, and none had any diagnosed cardiovascular or metabolic disease or were consuming medication or drugs known to influence lipid or carbohydrate metabolism. This study was conducted with the approval of the University of Glasgow's Medical Faculty Ethics Committee and the participants provided written consent.

Study design

Each participant, in randomized counterbalanced order, performed three treadmill runs to exhaustion at 65% $\dot{V}O_{2max}$: one after following their habitual diet (control trial), another after 5 days on a high carbohydrate/high glycaemic index diet (HC-HGI trial), and a third after 5 days on high carbohydrate/low glycaemic index diet (HC-LGI trial). The exercise trials were separated by a washout period of a minimum of 11 days. During the 5 days leading up to the first treadmill run, the participants recorded all planned and structured exercise conducted and were asked to replicate this before their second and third runs. For 2 days before the running trials, the participants were asked to limit themselves to activities of daily living and slow walking or cycling for personal transport over short distances and were asked not to consume alcohol. The participants recorded all fluids they consumed during the 24 h leading up to the first running trial and were asked to replicate this before the second and third runs. To ensure euhydration, the participants were instructed to consume about a litre of water the night before and $\sim$500 ml in the morning before each running trial. All running trials were performed under similar experimental and environmental conditions. Two weeks before the main running trial, the participants undertook a familiarization run to ensure that their predicted running speed corresponded to 65% $\dot{V}O_{2max}$ and to allow the participants to become familiar with the experiment protocol.

Preliminary exercise test

Before the familiarization run and treadmill runs to exhaustion, two preliminary exercise tests were conducted to determine the speed that elicited 65% $\dot{V}O_{2max}$ for each participant. In the first, the steady-state relationship between submaximal $\dot{V}O_2$ and treadmill speed was established. In the second, $\dot{V}O_{2max}$ was determined during uphill running at constant speed (range 9.0–11.5 km $\cdot$ h^{-1}).

Main exercise trials

The participants arrived at the laboratory after a 12-h overnight fast, at approximately 08:30 h. They were weighed and a cannula (Venflon 18G, Becton Dickinson Ltd., Helsingborg, Sweden) was inserted in an antecubital vein. Participants then rested in a seated position for 10 min before a baseline blood sample (7 ml collected into a EDTA tube) was drawn and expired air was collected.

After a brief warm-up consisting of 5 min of continuous running at 60% $\dot{V}O_{2max}$ followed by 5 min of stretching, the participants ran to

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exhaustion on the treadmill at a speed equivalent to 65% $\dot{V}O_{2max}$. During the last minute of every 15-min stage throughout the run, expired air samples were collected using the Douglas bag technique (Consolazio, Johnson, & Pecora, 1963), heart rate was monitored using short-range telemetry (Polar S610i, Polar Electro, Finland), and ratings of perceived exertion (RPE) were recorded using the Borg scale (Borg, 1982). These measurements coincided with blood sample collection. After each blood sample, the cannula was flushed with saline solution (0.9% w/v sodium chloride intravenous infusion BP, B. Braun Melsungen AG, Melsungen, Germany) to keep it patent throughout the experiment. During trials, participants were allowed to drink water and an electric fan was used to cool them. Strong verbal encouragement was also given to the participants throughout the run and especially when near to exhaustion. Exhaustion was defined as the point at which the participants were no longer able to maintain the prescribed running speed. When a participant signalled that he could only manage a further 2 min, expired air was immediately collected, heart rate was recorded, and a blood sample was taken.

Development of experimental diets

The energy content of the prescribed diets was based on habitual energy requirements, which were calculated by adding energy expenditure of planned and structured exercise estimated from 5-day physical activity diaries and the compendium of physical activity tables (Ainsworth et al., 2000) to the multiplier of resting metabolic rate (Deltatrac, Datex Instrumention Corporation, Helsinki, Finland) and physical activity level of 1.5. The proportions of energy from carbohydrates, fat, and protein were similar in the prescribed high carbohydrate/high glycaemic index and high carbohydrate/low glycaemic index diets (approximately 70%, 15%, and 15% respectively). The main sources of carbohydrate in the high carbohydrate/high glycaemic index diet were refined breakfast cereals, white rice, wholemeal bread, instant mashed potatoes, biscuits, and Lucozade™, and in the high carbohydrate/low glycaemic index diet All Bran™ cereal, porridge, pasta, basmati rice, rye bread, oatcakes, and apple juice (Table I). Participants were provided with all the food and menus, which informed them of the exact amounts of each food they were required to consume and when during the high carbohydrate/high glycaemic index and high carbohydrate/low glycaemic index trials, together with digital food scales and written instructions explaining how to cook and prepare the prescribed foods. To eliminate any influence of cooking methods on glycaemic response and increased compliance, the menus were based on processed and easy-to-prepare foods. Any deviations from these instructions were recorded by the participants. The researcher kept in close contact with the participants, who were encouraged to contact the researcher if they had any questions concerning the experimental diets. For the control diet, participants performed a 5-day weighed food diary using the digital scales provided and were asked to follow their usual or habitual diet during this period. The glycaemic index of each carbohydrate food in the high carbohydrate/high glycaemic index and high carbohydrate/low glycaemic index diet was taken from Foster-Powell et al.

Table I. Example of prescribed high carbohydrate/high glycaemic index (HC-HGI) and high carbohydrate/low glycaemic index (HC-LGI) meals consumed over 5 days.

Meal	HC-HGI	HC-LGI
Breakfast	Coco Pops™ breakfast cereal (100 g) + semi-skimmed milk (200 g), wholemeal bread (70 g) + jam (30 g) + low-fat spread (8 g), tea (260 g) + semi-skimmed milk (40 g)	All Bran™ breakfast cereal (100 g) + skimmed milk (200 g), Burgen® bread (70 g) + jam (30 g) + low-fat spread (8 g), tea (200 g) + semi-skimmed milk (40 g)
Snack	Apple (100 g), banana (100 g)	Pear (100 g), orange (100 g)
Lunch	Wholemeal bread (140 g) + lean ham (50 g) + low-fat spread (12 g) + cucumber (40 g) + tomatoes (40 g), Lucozade® original (340 g)	White pita bread (120 g) + lean ham (50 g) + low-fat spread (12 g) + cucumber (40 g) + tomatoes (40 g), lentil soup (400 g), unsweetened apple juice (340 g)
Snack	Rice cakes (30 g), Lucozade® original (330 g)	Cheese-flavoured oatcakes (30 g), unsweetened apple juice (330 g)
Evening meal	Instant potato (200 g) + peas (80 g) + chunks of chicken in gravy (300 g), Lucozade® original (330 g), bananas (100 g)	Pasta sauce (200 g) + mince meat in tomato sauce (200 g) + spaghetti (cooked weight 300 g), unsweetened apple juice (330 g), low-fat yogurt (200 g), orange (100 g)
Evening snack	Wholemeal bread (70 g) + low-fat spread (5 g) + jam (15 g), tea (260 g) + semi-skimmed milk (40 g)	Burgen® bread (70 g) + low-fat spread (5 g) + jam (15 g), tea (260 g) + semi-skimmed milk (40 g)

Note: This menu was prescribed to individuals with an energy requirement of approximately 2900 kcal · day^{-1}.

(Foster-Powell, Susanna, & Miller, 2002), Henry et al. (Henry, Lightowler, Strik, Renton, & Hails, 2005), and Aston et al. (Aston, Gambell, Lee, Bryant, & Jebb, 2008), and the glycaemic index of the overall diet was calculated from the weighted means of the glycaemic indexes of the carbohydrate-containing foods (Wolever & Jenkins, 1986). A computerized version of food composition tables (Diet 5^{TM}, Robert Gordon University, Aberdeen) was used for the prescription of the experimental diets.

Dietary analysis, calculation of dietary glycaemic index and glycaemic load

Dietary intake of energy and macronutrients from the participants' habitual dietary records (control trial) as well as from the experimental diets was calculated using a computerized version of food composition tables (Diet 5^{TM}, Robert Gordon University, Aberdeen). Dietary glycaemic index and glycaemic load, which quantifies the overall glycaemic effect of portion of food (Salmeron et al., 1997), were also estimated from the participants' habitual diet records and from the experimental diets based on the following steps. First, the glycaemic index of each carbohydrate food was obtained from the most up-to-date published sources at the time (Aston et al., 2008; Foster-Powell et al., 2002; Henry et al., 2005). Second, the glycaemic load of each carbohydrate-containing food was estimated by multiplying the carbohydrate content of the food consumed by the glycaemic index of that food divided by 100. The glycaemic loads, calculated in this way, for all carbohydrate-containing foods were summed to give the glycaemic load for 5 days, and this value was then divided by 5 to obtain the daily glycaemic load. Finally, to estimate the daily glycaemic index, the daily glycaemic load was divided by total daily carbohydrate intake and then that value multiplied by 100 (Wolever & Jenkins, 1986).

Measurement of substrate oxidation and energy expenditure

Expired air was collected into a Douglas bag over 60 s and immediately analysed for oxygen and carbon dioxide concentrations (Servomex 1440, Crowborough, UK). The expired gas volume was determined using a dry gas meter (Harvard, Kent, UK), and oxygen consumption ($\dot{V}O_2$) and carbon dioxide production ($\dot{V}CO_2$) were calculated using the Haldane transformation. Energy expenditure and substrate oxidation during running were estimated from $\dot{V}O_2$ uptake and $\dot{V}CO_2$ production using indirect calorimetry, neglecting protein oxidation (Ferrannini, 1988).

Anthropometry and body composition

Measurements of body mass and body fat were taken using bioelectrical impedance scales (TBF-300, TANITA, Cranlea, UK), (Jebb, Cole, Doman, Murgatroyd, & Prentice, 2000). Height was determined using standard protocols (Marfell-Jones, Olds, Stewart, & Carter, 2006).

Plasma preparation and analysis

Blood samples were collected into pre-cooled EDTA monovettes and centrifuged at 3000 rev $\cdot$ min^{-1} for 15 min at 4°C. After centrifugation, aliquots of plasma were transferred to labelled 1.5-ml Eppendorf tubes (Eppendorf AG, Hamburg, Germany). The aliquoted plasma was then stored at $-$ 80°C for later analysis of insulin (Mercodia Ultrasensitive Insulin ELISA, Mercodia AB, Uppsala, Sweden), non-esterified fatty acids (Wako Chemicals, Neuss, Germany), glucose (Randox, Northern Ireland, UK), and glycerol (Randox, Northern Ireland, UK).

Statistical analysis

Results are presented as means $\pm$ standard errors (s_x) unless otherwise stated. Reponses during the exercise period were compared by two-factor (trial $\times$ time) repeated-measures analyses of variance (ANOVA), with Tukey *post hoc* tests being used to locate the differences. Differences between baseline values and those at the point of exhaustion, and between dietary profiles were compared by one-factor (trial) ANOVA. Statistical significance was set at $P < 0.05$. Data were analysed using the Statistica software program (Statistica for Windows, version 6).

Results

Dietary intake

Daily dietary intakes for the 5 days preceding the run to exhaustion are presented in Table II. Both the high carbohydrate/high glycaemic index and high carbohydrate/low glycaemic index diets were isocaloric to the habitual diet and provided energy that was very similar to the predicted energy requirements (12.40 $\pm$ 0.34 MJ). Daily intake of available carbohydrates and the percentage of energy provided by carbohydrates were significantly higher ($P < 0.05$) in the two experimental trials than the control trial. There were no significant differences in available carbohydrate and fibre intakes and the percentage of energy provided by carbohydrate between the high carbohydrate/high glycaemic index and high carbohydrate/low glycaemic index trials. The glycaemic

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index and glycaemic load in the high carbohydrate/high glycaemic index trial were significantly higher ($P < 0.01$), and the glycaemic index of the high carbohydrate/low glycaemic index diet was significantly lower ($P < 0.01$), than in the control trial. The glycaemic index and glycaemic load of the high carbohydrate/high glycaemic index diet were significantly higher ($P < 0.01$) than those of the high carbohydrate/low glycaemic index diet. Body mass and body fat percentage before the run to exhaustion were not significantly different between trials (Table III).

Plasma glucose, insulin, non-esterified fatty acids, and glycerol

Concentrations of plasma glucose, insulin, non-esterified fatty acids, and glycerol measured in the fasted state before running (Table III), during the run to exhaustion, and at the point of exhaustion (Figure 1) were not significantly different between the high carbohydrate/high glycaemic index and high carbohydrate/low glycaemic index trials. During the run to exhaustion and at the point of exhaustion, plasma glycerol concentration in the two experimental trials was significantly lower ($P < 0.05$) than in the control trial (Figure 1). At exhaustion, plasma glucose concentration in the high carbohydrate/low glycaemic index trial tended ($P = 0.06$) to be higher than in the control trial, but glucose concentration was similar between the high carbohydrate/high glycaemic index and high carbohydrate/low glycaemic index trials. The concentrations of plasma insulin and non-esterified fatty acids during running and at the point of exhaustion were not significantly different between trials.

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Table II. Daily macronutrient and energy intakes, percentage (%) of energy from macronutrients, glycaemic index, and glycaemic load of habitual (control), high carbohydrate/high glycaemic index (HC-HGI), and high carbohydrate/low glycaemic index (HC-LGI) diets consumed over 5 days before a run to exhaustion at 65% $\dot{V}O_{2max}$ (mean $\pm$ s_x; $n = 9$).

	Control	HC-HGI	HC-LGI
Nutrient intake			
Available carbohydrate (g)	349 ± 27	511 ± 11*	508 ± 12*
Sugar (g)	80 ± 9	65 ± 16	49 ± 14
NMES (g)	96 ± 15	194 ± 15*	195 ± 12*
Starch (g)	186 ± 13	255 ± 12*	266 ± 9*
Fibre (g)	29 ± 4	39 ± 1	39 ± 3
Fat (g)	74 ± 4	47 ± 2*	47 ± 2*
Protein (g)	115 ± 7	102 ± 3	107 ± 2
Carbohydrate ($g \cdot kg^{-1} \cdot day^{-1}$)	4.6 ± 0.5	7.4 ± 0.2*	7.3 ± 0.2*
Energy Intake (MJ)	11.0 ± 0.5	12.5 ± 0.4	12.3 ± 0.3
Energy from carbohydrate (%)	53 ± 2	71 ± 0*	70 ± 1*
Energy from fat (%)	26 ± 2	15 ± 0*	15 ± 0*
Energy from protein (%)	18 ± 1	14 ± 0*	15 ± 0*
Glycaemic index	56 ± 1	71 ± 1*	36 ± 0*#
Glycaemic load	171 ± 17	391 ± 9*	216 ± 6#

Note: NMES = non-milk extrinsic sugars. *Significantly different ($P < 0.01$) from control trial. #Significantly different ($P < 0.01$) from HC-HGI trial.

Table III. Metabolic responses, body mass, and body fat in the fasted state before a run to exhaustion in the control, high carbohydrate/high glycaemic index (HC-HGI), and high carbohydrate/low glycaemic index (HC-LGI) trials (mean $\pm$ s_x; $n = 9$).

	Control	HGI	LGI
Glucose ($mmol \cdot l^{-1}$)	5.02 ± 0.17	4.91 ± 0.13	5.16 ± 0.17
Insulin ($mU \cdot l^{-1}$)	3.51 ± 0.48	3.67 ± 0.33	4.23 ± 0.56
NEFA ($meq \cdot l^{-1}$)	0.41 ± 0.06	0.39 ± 0.06	0.46 ± 0.06
Glycerol ($mmol \cdot l^{-1}$)	0.58 ± 0.01	0.55 ± 0.01	0.60 ± 0.01
TAG ($mmol \cdot l^{-1}$)	0.76 ± 0.40	0.98 ± 0.44*	0.93 ± 0.32*
HDL-cholesterol (mmol/l)	1.55 ± 0.31	1.37 ± 0.38*	1.39 ± 0.39#
Fat oxidation ($g \cdot min^{-1}$)	0.07 ± 0.01	0.06 ± 0.01	0.07 ± 0.01
CHO oxidation ($g \cdot min^{-1}$)	0.19 ± 0.03	0.21 ± 0.02	0.17 ± 0.03
Body mass (kg)	74.1 ± 6.4	74.1 ± 6.9	74.3 ± 6.8
Body fat (%)	9.8 ± 3.4	10.1 ± 6.9	10.1 ± 3.9

*Significantly different ($P < 0.05$) from control trial. #Trend for difference ($P = 0.07$) from control trial.

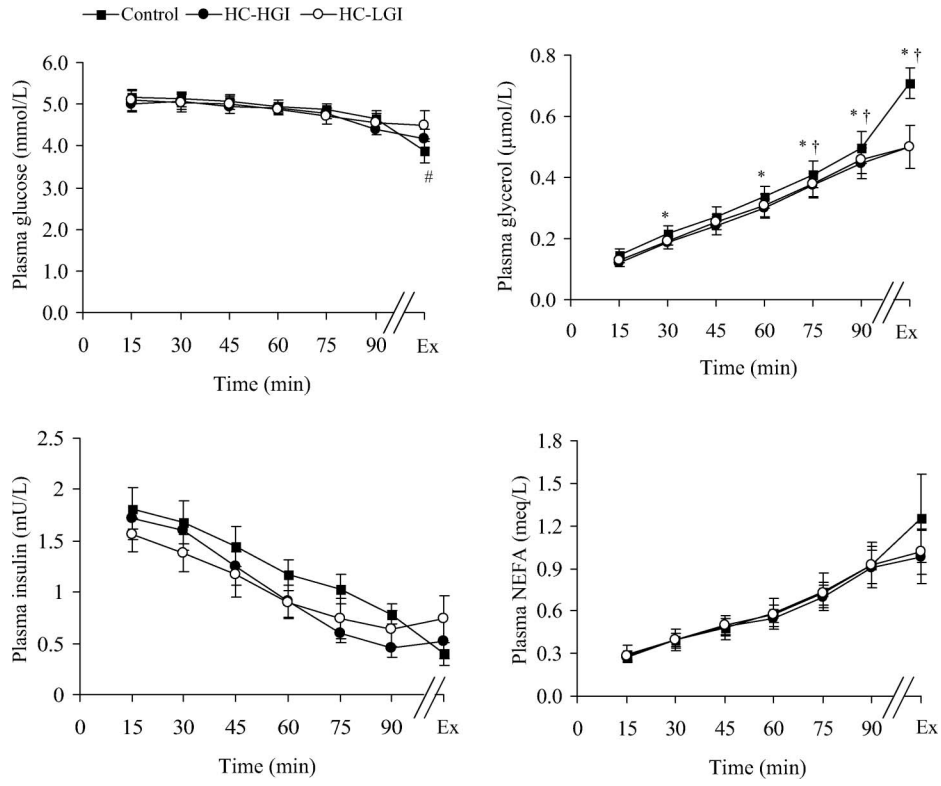

Figure 1. Plasma concentrations of glucose (mmol · l^{-1}), glycerol (mmol · l^{-1}), insulin (mU · l^{-1}), and non-esterified fatty acids (meq · l^{-1}) throughout a run to exhaustion at 65% $\dot{V}O_{2max}$ and at the point of exhaustion (Ex) in the control trial (■), high carbohydrate/high glycaemic index trial (●), and high carbohydrate/low glycaemic index trial (○). Values are means ± s_x. *Significantly different ($P < 0.05$) from high carbohydrate/high glycaemic index trial. †Significantly different ($P < 0.001$) from high carbohydrate/low glycaemic index trial. # Trend for a difference ($P = 0.06$) between the control and high carbohydrate/low glycaemic index trial.

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Fat and carbohydrate oxidation

The rates of fat and carbohydrate oxidation in the fasted state before running (Table III), during the run to exhaustion, and at the point of exhaustion (Figure 2) were not significantly different between the high carbohydrate/high glycaemic index and high carbohydrate/low glycaemic index trials. During the run to exhaustion, the rate of fat oxidation in both experimental trials was significantly lower ($P < 0.05$), and the rate of carbohydrate oxidation higher ($P < 0.05$), than in the control trial (Figure 2). At the point of exhaustion, compared with the control trial the rate of fat oxidation was lower ($P < 0.05$) and the rate of carbohydrate oxidation higher ($P < 0.05$) only in the high carbohydrate/low glycaemic index trial.

Heart rate, ratings of perceived exertion and oxygen consumption

There were no differences in heart rate, ratings of perceived exertion or oxygen consumption during the run to exhaustion and at the point of exhaustion (Table IV) between trials.

Time to exhaustion and running distance

Of the nine participants, one stopped exercising before exhaustion in one of the trials because of a hip problem. Therefore, results for time to exhaustion and running distance are presented for eight participants only. Time to exhaustion (control trial: 114 min, $s = 15$; high carbohydrate/high glycaemic index trial: 107 min, $s = 18$; high carbohydrate/low glycaemic index trial: 110 min, $s = 18$) and distance covered (control trial: 19 km, $s = 3$; high carbohydrate/high glycaemic index trial: 18 km, $s = 5$; high carbohydrate/low glycaemic index trial: 19 km, $s = 5$) by these eight participants were not significantly different between trials.

Discussion

The main finding of the present study is that the extent to which high carbohydrate diets consumed for 5 days reduce the rate of fat oxidation during running in the fasted state is not influenced by the glycaemic index of the diet. We also found that the glycaemic index of high carbohydrate diets consumed for 5 days has no impact on running capacity.

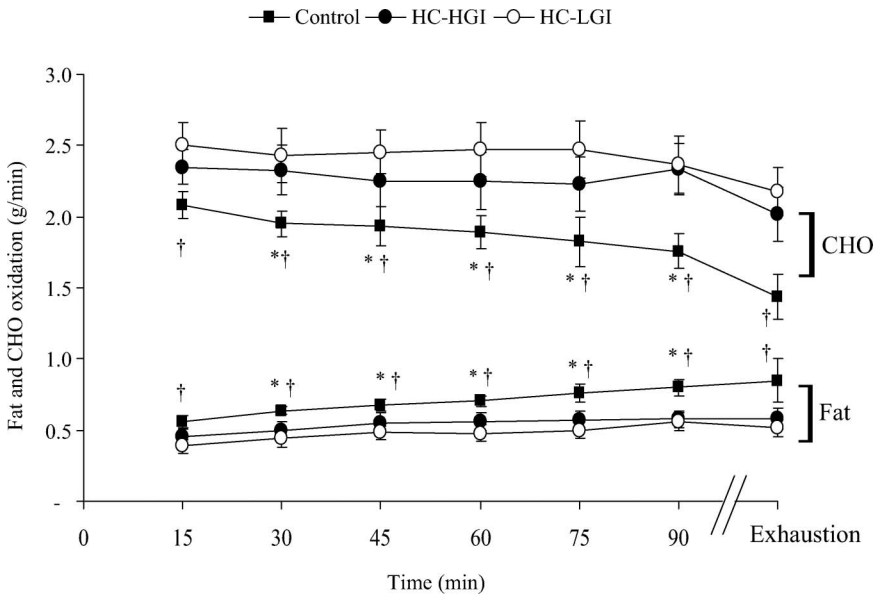

Figure 2. Rates of fat and carbohydrate oxidation ($g \cdot min^{-1}$) throughout the run to exhaustion at 65% $\dot{V}O_{2max}$ and at the point of exhaustion in the control trial (■), high carbohydrate/high glycaemic index trial (●), and high carbohydrate/low glycaemic index trial (○).Values are means ± s_x. *Significantly different ($P < 0.05$) from high carbohydrate/high glycaemic index trial. †Significantly different ($P < 0.001$) from high carbohydrate/low glycaemic index trial.

Table IV. Oxygen consumption ($\dot{V}O_2$; $ml \cdot kg^{-1} \cdot min^{-1}$), ratings of perceived exertion (RPE), and heart rate ($beats \cdot min^{-1}$) during running on the treadmill at 65% $\dot{V}O_{2max}$ to exhaustion in the control, high carbohydrate/high glycaemic index (HC-HGI), and high carbohydrate/low glycaemic index (HC-LGI) trials (mean ± s_x; $n = 9$ for 15–90 min and $n = 8$ at exhaustion).

	15 min	30 min	45 min	60 min	75 min	90 min	Exhaustion
$\dot{V}O_2$							
Control	38.2 ± 0.7	38.9 ± 0.8	39.6 ± 0.9	40.0 ± 0.9	40.8 ± 0.9	41.0 ± 1.2	40.6 ± 1.4
HC-HGI	38.4 ± 0.9	39.5 ± 1.1	40.3 ± 1.1	40.2 ± 1.0	40.4 ± 1.2	41.6 ± 1.3	42.5 ± 2.5
HC-LGI	38.3 ± 1.2	39.0 ± 1.2	40.0 ± 1.1	40.0 ± 1.2	40.5 ± 1.2	41.0 ± 1.2	41.4 ± 1.4
RPE							
Control	11 ± 0	12 ± 0	13 ± 0	13 ± 0	14 ± 1	15 ± 1	17 ± 1
HC-HGI	11 ± 0	12 ± 0	13 ± 0	13 ± 1	15 ± 1	15 ± 1	18 ± 1
HC-LGI	10 ± 1	12 ± 0	12 ± 0	13 ± 0	14 ± 1	16 ± 1	18 ± 1
Heart rate							
Control	148 ± 4	154 ± 4	157 ± 4	159 ± 5	162 ± 5	164 ± 6	167 ± 6
HC-HGI	148 ± 2	155 ± 3	159 ± 4	162 ± 5	164 ± 5	166 ± 5	171 ± 6
HC-LGI	148 ± 4	155 ± 4	160 ± 4	161 ± 4	164 ± 5	167 ± 5	172 ± 6

From a practical perspective, our findings suggest that when high carbohydrate diets are consumed for 3–5 days leading up to an endurance event, consideration of the glycaemic index is not necessary.

As reported previously (Arkinstall et al., 2004; Brewer et al., 1988; Chen et al., 2008; Coyle et al., 2001; Wojtaszewski et al., 2003), the rate of total fat oxidation and thus the contribution of fat to running energy expenditure was lower following both high carbohydrate diets than the control trial. Also, the plasma concentration of non-esterified fatty acids during the run to exhaustion after both high carbohydrate diets was strikingly similar to the concentration measured during the control trial. Thus, the reduced oxidation of fat observed during running after the high carbohydrate diets may be a reflection of the reduced availability and utilization of intramuscular triacylglycerol, the main contributor of non-plasma-derived fatty acids (Roepstorff, Vistisen, & Kiens, 2005; van Loon et al., 2003). This suggestion is supported by evidence that intramuscular triacylglycerol content is modified by dietary macronutrient composition (Roepstorff et al., 2005).

Previous evidence suggests that high carbohydrate/low glycaemic index diets consumed during 24-h recovery periods between bouts of prolonged strenuous exercise may result in greater availability of

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plasma non-esterified fatty acids (Stevenson et al., 2005; Trenell et al., 2008) and sometimes (Stevenson et al., 2005), but not always (Trenell et al., 2008), in a higher rate of fat oxidation during subsequent exercise conducted in the fasted state. Furthermore, a significant increase in the fasting concentration of plasma non-esterified fatty acids was reported after a 3-day moderate carbohydrate diet with a low but not high glycaemic index (Kiens & Richter, 1996). However, in our study, the glycaemic index of high carbohydrate diets consumed for 5 days had no impact on plasma non-esterified fatty acid concentration measured either during rest or during a run to exhaustion. In addition, the rate of total fat and carbohydrate oxidation was not different between the two high carbohydrate trials, which is consistent with the finding of Chen et al. (2008) that the amount rather than the glycaemic index of the carbohydrate consumed during a 3-day isoenergetic carbohydrate loading is the most overriding factor for subsequent exercise energy metabolism. Therefore, when high carbohydrate diets are consumed for a few days before an endurance event, the expected reduction in fat oxidation (Arkinstall et al., 2004; Brewer et al., 1988; Coyle et al., 2001) and thus compensatory increase in rate of muscle glycogen utilization (Arkinstall et al., 2004; Wojtaszewski et al., 2003) can not be prevented by lowering the glycaemic index of the foods consumed.

We found that the glycaemic index of high carbohydrate diets consumed for 5 days had no impact on exercise capacity measured as time to exhaustion during an endurance run in the fasted state. This finding is in line with recent evidence suggesting that the glycaemic index of high carbohydrate diets consumed for 3 days has no impact on the time taken to complete a 10-km run (Chen et al., 2008). Brewer et al. (1988) observed no impact of quality of carbohydrate consumed on exercise performance in their study, in which time to complete a treadmill run to exhaustion was measured in two groups of experienced runners who were required to obtain 70% of energy from carbohydrate for 3 days, either by supplementing their normal diets with complex (synonymous with low glycaemic index carbohydrates) or simple (synonymous with high glycaemic index carbohydrates) carbohydrates,

In the present study, exercise running capacity measured after high carbohydrate diets consumed for 5 consecutive days was not different from that in the control trial. This finding is quite unexpected, since increased dietary carbohydrate intake elevates muscle and liver glycogen concentration (Arkinstall et al., 2004; Burke & Hawley, 1999; Tarnopolsky et al., 2001; Wojtaszewski et al., 2003), which prolongs time to exhaustion in trials over 90 min in duration (Brewer et al., 1988; Hawley, Schabort, Noakes, & Dennis, 1997). During both the high carbohydrate/high glycaemic index and high carbohydrate/low glycaemic index trials in the present study, carbohydrate intake was on average 2.8 $g \cdot kg^{-1} \cdot day^{-1}$ higher that in the control trial and amounted to 7.3–7.4 $g \cdot kg^{-1} \cdot day^{-1}$, which is only slightly lower that the commonly recommended value of 8–10 $g \cdot kg^{-1} \cdot day^{-1}$ (Burke & Hawley, 1999). It should be noted, however, that the diet in the control trial was not strictly controlled and coincided with the participants' habitual diet. Thus, although intake of available carbohydrates in both high carbohydrate trials was significantly higher than in the control trial, the difference in carbohydrate intake between habitual and high carbohydrate diets in some participants may not have been sufficient to promote a reasonable increase in muscle glycogen and thus increase exercise capacity. This may have contributed to the fact that there was no significant difference in exercise capacity between the control and high carbohydrate trials. In addition, since the rate of muscle glycogen utilization and thus sharpness of the end point of exercise is very sensitive to exercise intensity, it is possible that the validity of assessment of exercise capacity was diminished by asking the participants to run at 65% rather than at 70% of $\dot{V}O_{2max}$.

Although the rates of fat and carbohydrate oxidation during running to exhaustion were very similar in all three trials, the rate of fat oxidation at the point of exhaustion in the high carbohydrate/low glycaemic index trial was lower, and the rate of carbohydrate oxidation higher, than in the control trial. This coincided with a tendency for plasma glucose at the point of exhaustion to be higher in the high carbohydrate/low glycaemic index trial than in the control trial. This implies that high carbohydrate diets based on low glycaemic index foods may be better at delaying the point at which availability of carbohydrate stores is limited during consecutive bouts of exercise, and at improving exercise capacity or performance, than high carbohydrate diets based on high glycaemic index foods. Indeed, Chen et al. (2008) found that 3 days of a high carbohydrate diet with low but not high glycaemic index foods reduced the time taken to complete a 10-km run performed after 1 h of steady-state running. It should be noted, however, that Chen et al. (2008) observed significantly higher blood glucose concentrations during the final stages of exercise in both high carbohydrate trials than in their low-carbohydrate trial.

It is widely accepted that substrate selection during exercise is dictated not only by the pre-exercise muscle glycogen concentration (Harvey, Frew, Massicotte, Peronnet, & Rehrer, 2007) but also by

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the availability of intramuscular triacylglycerol (van Loon et al., 2003). Thus, the fact that we found no difference in the rate of fat and carbohydrate oxidation between the high carbohydrate/high glycaemic index and high carbohydrate/low glycaemic index trials does not necessarily imply that the expected increase in muscle glycogen (Arkinstall et al., 2004; Burke & Hawley, 1999; Tarnopolsky et al., 2001; Wojtaszewski et al., 2003) and reduction in intramuscular triacylglycerol (Coyle et al., 2001) were not influenced by the glycaemic index of the two diets. Indeed, it has been reported that after glycogen-depleting exercise, a high carbohydrate/high glycaemic index diet consumed over a recovery period of 24 h results in greater muscle glycogen resynthesis than a high carbohydrate/low glycaemic index diet (Burke, Collier, & Hargreaves, 1993), and that during 3 h of the postprandial period muscle glycogen concentration is increased by 15% after high a glycaemic index meal but remains unchanged after a low glycaemic index meal (Wee, Williams, Tsintzas, & Boobis, 2005). In addition, there is some evidence to suggest that consumption of a high carbohydrate diet with a low glycaemic index may lead to less accumulation (Kiens & Richter, 1996; Trenell et al., 2008) and reduced utilization (Trenell et al., 2008) of intramuscular triacylglycerol during subsequent exercise compared with a high glycaemic index diet. Regardless of the above evidence, the role of the glycaemic index of high carbohydrate diets consumed for several days in modifying the content of intramuscular energy substrates remains unclear and requires further investigation.

As in all dietary intervention studies, it was very important to ensure that the participants complied with the diets prescribed. As in studies in which dietary fat is reduced and replaced with carbohydrate an increase in plasma triacylglycerol concentration and reduction in HDL-cholesterol are observed (Koutsari, Malkova, & Hardman, 2000), we assessed whether the concentrations of these lipids were modified by the high carbohydrate diets consumed in the present study. We found that changes in plasma triacylglycerol and HDL-cholesterol concentrations following high carbohydrate diets were as expected.

This study is not without limitations. First, calculation of the glycaemic index and glycaemic load of the diets was performed using published glycaemic index tables (Aston et al., 2008; Foster-Powell et al., 2002; Henry et al., 2005) rather than measuring the glycaemic index of the foods, meals or diets themselves. Due to concern that foods with contrasting glycaemic indexes do not always induce a proportionally comparable difference in plasma glucose (Galgani, Aguirre, & Díaz, 2006), we evaluated retrospectively whether the diets used in this study could be expected to modified glycaemia differently. Using a crossover design, the blood glucose response (HemoCue AB, Angelholm, Sweden) to a high carbohydrate diet with a low and high glycaemic index was measured in nine physically active healthy participants. The diets were designed based on the approach adopted in the present study and consumed for one whole day. We found that the time-averaged incremental area under the glucose versus time curve (high carbohydrate/low glycaemic index diet: 0.45 ± 0.14 mmol $\cdot$ l^{-1}; high carbohydrate/high glycaemic index diet: 1.06 ± 0.37 mmol $\cdot$ l^{-1}) was significantly higher ($P = 0.008$) when daily meals were based on high glycaemic index than low glycaemic index foods. Thus, the diets prescribed in the present study may be expected to result in a different metabolic response. Furthermore, food intake on the days before the interventions began was not strictly controlled. Thus, although all participants had constant dietary habits and were expected to consume similar diets before all dietary interventions, it is possible that the dietary profile and thus the metabolic status of the participants may have been different before they started the experimental diets.

We conclude that the extent to which a high carbohydrate diet consumed for 5 days reduces the rate of fat oxidation and increases the rate of carbohydrate oxidation during subsequent running exercise in the fasted state is not influenced by the glycaemic index, and that the glycaemic index of high carbohydrate diets commonly consumed during days leading up to an athletic endurance event has no impact on exercise capacity.

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