

# Influence of high-carbohydrate mixed meals with different glycemic indexes on substrate utilization during subsequent exercise in women<sup>1,2</sup>

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## ABSTRACT

**Background:** Few data exist on the metabolic responses to mixed meals with different glycemic indexes and their effects on substrate metabolism during exercise in women.

**Objective:** We examined the effects of preexercise mixed meals providing carbohydrates with high (HGI) or low glycemic index (LGI) on substrate utilization during rest and exercise in women.

**Design:** Eight healthy, active, eumenorrheic women [aged 18.6 ± 0.9 y; body mass: 59.9 ± 7.1 kg; maximal oxygen uptake ( $\dot{V}O_2$ max): 48.7 ± 1.1 mL · kg<sup>-1</sup> · min<sup>-1</sup>] completed 2 trials. On each occasion, subjects were provided with a test breakfast 3 h before performing a 60-min run at 65%  $\dot{V}O_2$ max on a motorized treadmill. Both breakfasts provided 2 g carbohydrate/kg body mass and were isoenergetic. The calculated GIs of the meals were 78 (HGI) and 44 (LGI).

**Results:** Peak plasma glucose and serum insulin concentrations were greater after the HGI breakfast than after the LGI breakfast ( $P < 0.05$ ). No significant differences in substrate oxidation were reported throughout the postprandial period. During exercise, the estimated rate of fat oxidation was greater in the LGI trial than in the HGI trial ( $P < 0.05$ ). Similarly, plasma free fatty acid and glycerol concentrations were higher throughout exercise in the LGI trial ( $P < 0.05$ ). No significant differences in plasma glucose or serum insulin were observed during exercise.

**Conclusion:** Altering the GI of the carbohydrate within a meal significantly changes the postprandial hyperglycemic and hyperinsulinemic responses in women. A LGI preexercise meal resulted in a higher rate of fat oxidation during exercise than did an HGI meal. *Am J Clin Nutr* 2006;84:354–60.

**KEY WORDS** Females, fat oxidation, exercise, hyperinsulinemia, hyperglycemia

## INTRODUCTION

Although the glycemic index (GI) was originally devised to aid diabetics control the glycemic effect of their diet (1), the concept now has a wider utility. The GI has been extensively used in sports nutrition to aid athletes in the selection of appropriate carbohydrates to consume before, during, and after exercise. More recently, diets composed of low glycemic index (LGI) carbohydrates have also been promoted as an effective weight-loss strategy.

Several studies have reported that the preexercise ingestion of LGI carbohydrates results in an increased rate of fat oxidation during exercise compared with when HGI carbohydrates are

consumed (2–10). The large glycemic and insulinemic perturbations accompanying the consumption of HGI foods increases carbohydrate oxidation and blunts the mobilization and oxidation of free fatty acids (FFAs) (11, 12). Increasing the oxidation of fat at the expense of carbohydrate oxidation has important implications both for endurance-trained athletes and for those who are aiming to reduce body fat mass for health purposes. However, many of the previous studies in this area have provided single foods in the hour before exercise (3, 6, 8, 9, 13) which is unlikely to reflect normal dietary behavior. Athletes are recommended to consume a high-carbohydrate meal 3–4 h before exercise (14), and many recreational athletes will exercise at lunchtime 3–4 h after consuming breakfast.

In a recent study from our laboratory, male subjects were provided with a HGI or a LGI high-carbohydrate breakfast 3 h before exercise (5). Although concentrations of plasma glucose and serum insulin had returned to baseline by the start of exercise, the calculated amount of fat oxidized was significantly higher during exercise after the LGI breakfast than after the HGI breakfast.

Interestingly, most research done in this area has used male subjects. This is despite the fact that many women exercise to reduce body fat mass or may use the GI to select appropriate carbohydrates to consume before training and competition. Several studies have reported that sex differences exist in the relative contribution from carbohydrate and fat to oxidative metabolism during exercise (15–20). In contrast, others have reported that no differences exist in the total amount of fat and carbohydrate oxidized by men and women but that different sources of lipid are used (21, 22). Nevertheless, sex differences in the metabolic responses to HGI and LGI meals during rest and subsequent exercise may exist. Therefore, the aim of the present study was to investigate the metabolic responses to HGI and LGI meals during rest and subsequent exercise in women.

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## SUBJECTS AND METHODS

### Subjects

Eight healthy, eumenorrheic women participated in this study. Their mean  $\pm$  SD age, height, body mass (BM), and maximal oxygen uptake ( $\dot{V}O_{2\max}$ ) were  $18.6 \pm 0.9$  y,  $166.0 \pm 3.0$  cm,  $59.9 \pm 7.1$  kg, and  $48.7 \pm 1.1$  mL  $\cdot$  kg<sup>-1</sup>  $\cdot$  min<sup>-1</sup>, respectively. None of the subjects had used oral contraceptives for >6 mo before the study or were they pregnant or lactating. None of the subjects reported any medical conditions. All trials were carried out during the early follicular phase of the menstrual cycle (3–6 d after the first day of menses). A further criterion for inclusion in the study was that participants ran regularly and were able to run for 1 h continuously at  $\approx 65\%$   $\dot{V}O_{2\max}$ . Loughborough University Ethical Advisory Committee approved the protocol, and all subjects gave their written informed consent.

### Preliminary measurements

After familiarization with treadmill running and experimental procedures, subjects undertook 2 preliminary tests to determine 1) the relation between running speed and oxygen uptake by using a 16-min incremental test and 2) their  $\dot{V}O_{2\max}$  by using an uphill incremental treadmill test to exhaustion. All preliminary tests were conducted according to procedures previously described (23). On the basis of the results of the 2 preliminary tests, the running speed equivalent to 65% of each subject's  $\dot{V}O_{2\max}$  was determined.

### Test meals

Subjects were provided with a breakfast consisting of either HGI or LGI carbohydrates. Both meals provided 2 g carbohydrate/kg BM (Table 1). The nutritional content of each meal was calculated from information provided by the manufacturer. Foods were carefully chosen so that each diet was matched for protein and fat; therefore, both diets consisted of 72% carbohydrate, 11% fat, and 17% protein. The breakfasts were not however matched for fiber content with the HGI breakfast providing 1.5 g fiber and the LGI breakfast providing 6.5 g fiber (both values based on a breakfast for a 60-kg person). The energy density of the 2 breakfasts was 1.2 kcal/g and 0.8 kcal/g for the HGI and the LGI breakfasts, respectively. The GI values for the individual foods were taken from the *International Table of Glycemic Index and Glycemic Load Values: 2002* (24). The GI of the total diets was calculated from the weighted means of the GI values for the component food (25). The calculated GIs for the HGI and LGI breakfasts were 78 and 44, respectively.

### Experimental protocol

All subjects completed 2 experimental trials in a randomized crossover design. For 2 d before the first trial, the subjects recorded their diet and exercise routine so that it could be repeated before trial 2 to minimize differences in pretesting intramuscular substrate concentrations between experimental trials. Subjects were advised to maintain their normal training schedule during the study but to abstain from any vigorous exercise in the 24-h period before the 2 experimental trials. During this period they were also instructed to avoid alcohol and caffeine.

On the day of the experiment, subjects arrived in the laboratory at 0800 after an overnight fast. The subjects completed the necessary health and consent forms and were then asked to void

TABLE 1

Characteristics of the test meals (for a 60-kg person)

	HGI breakfast <sup>1</sup>	LGI breakfast <sup>1</sup>
Content		
Corn flakes <sup>2</sup> (g)	62	—
Muesli (g)	—	86
Skimmed milk (mL)	257	257
White bread (g)	80	—
Margarine <sup>3</sup> (g)	10	—
Jam (g)	20	—
Carbonated glucose drink <sup>4</sup> (mL)	155	—
Apple (g)	—	67
Canned peaches (g)	—	103
Yogurt (g)	—	128
Apple juice (mL)	—	257
Macronutrient content		
Energy (kJ)	3054	3063
Carbohydrate (g)	139	139
Fat (g)	10	9
Protein (g)	20	23
Fiber (g)	1.5	6.5
GI <sup>5</sup>	78	44

<sup>1</sup> HGI, high glycemic index; LGI, low glycemic index.

<sup>2</sup> Kellogg's Corn Flakes (Manchester, United Kingdom).

<sup>3</sup> Flora Light margarine spread (Unilever, Bedford, United Kingdom).

<sup>4</sup> Lucozade Original drink (GlaxoSmithKline, London, United Kingdom).

<sup>5</sup> Calculated by the method described in Wolever and Jenkins (25) with GI values taken from Foster-Powell et al (24).

before BM was obtained (Avery, England). A cannula (Venflon 18G; Becton Dickinson Ltd, Helsingborg, Sweden) was then inserted into an antecubital vein while the subject was lying on an examination couch. The cannula was kept patent by flushing with sterile saline solution (0.9%) after blood sampling. Basal blood and gas samples were collected, and then the subjects were provided with their test breakfast. They were asked to consume the breakfast within 30 min, and the 3-h postprandial period began immediately after the subject had consumed the entire breakfast provided. During the postprandial period, subjects remained at rest in the laboratory and were instructed not to eat anything other than the food provided for them. No extra drinks, apart from water, were permitted. Water was available ad libitum during the postprandial period throughout the first trial; however, the volume consumed was measured and recorded and matched during trial 2.

After the 3-h postprandial period, subjects were weighed and then changed into running attire. A short-range telemeter (Technogym, Gambettoio, Italy) heart rate monitor was then attached to the subject to monitor heart rate. Subjects completed a 5-min warm-up at 60%  $\dot{V}O_{2\max}$ , and then the treadmill speed was increased to a speed that represented 65% of the person's  $\dot{V}O_{2\max}$ . All subjects then completed 60 min running at this speed. Throughout the run, water was again available ad libitum during trial 1; however, the volume was measured and recorded and matched in trial 2. At the end of the run, subjects removed surface sweat and were weighed in minimal clothing.

All trials were performed at the same time of day and under similar experimental and environmental conditions. The same treadmill was also used throughout the experiment (Run Race Treadmill 47035; Technogym, Gambettoio, Italy). Ambient



temperature and relative humidity were recorded every 30 min by using a hygrometer (Zeal, London, United Kingdom) during the main trials. Temperature was maintained between 17 °C and 21 °C, and humidity was between 48% and 56%.

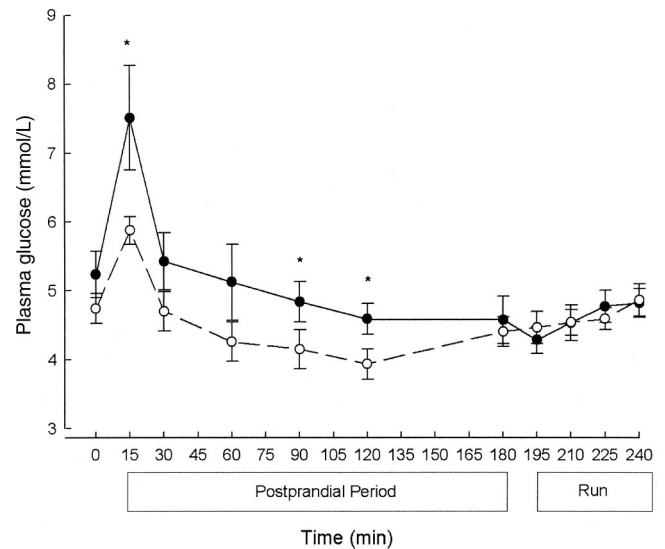
### Sample collection and analysis

Samples of expired air were collected for 5 min at the following times: before meal and 15, 30, 60, 90, 120, and 180 min during the postprandial period. One-minute expired air samples were collected every 15 min during exercise and analyzed as previously described (23). The subjects remained seated for all expired air samples throughout the postprandial period. Substrate oxidation rates were calculated from  $\dot{V}O_2$  and  $\dot{V}CO_2$  values by using stoichiometric equations (26). Total carbohydrate and fat oxidation was estimated from the area under the rate of oxidation versus time curve for each subject. During each expired air collection, perceived gut fullness was recorded by using a 6–20 scale. The scales used were adapted from the Borg Scale (27) such that the anchor terms on each 6–20 scale ranged from “not full” to “very, very full.” The rating of perceived exertion (27) was also recorded every 15 min during exercise.

At each sampling point, 10 mL blood was also collected, and 5 mL whole blood was immediately dispensed into an EDTA-coated tube. Hemoglobin concentration was determined by using the cyanmethemoglobin method (Boehringer Mannheim, Mannheim Germany) ( $2 \times 20 \mu\text{L}$ ), and hematocrit values were determined in triplicate on samples of whole blood by microcentrifugation (Hawksley Ltd, Lancing, Sussex, United Kingdom). Changes in plasma volume were estimated from changes in hemoglobin concentrations and hematocrit values, as described by Dill and Costill (28). Blood lactate concentration was measured by a photometric method by using a spectrophotometer (Shimadzu mini 1240; Shimadzu Corp, Kyoto, Japan) according to the method described by Maughan (29). Plasma samples were obtained by centrifugation of the remaining whole blood for a period of 10 min at  $2000 \times g$  and 4 °C. The plasma was divided into aliquots and was then stored at  $-85 \text{ }^\circ\text{C}$  for later analysis of FFAs (ASC-ACOD kit; Wako, Neuss, Germany), glucose (GOD-PAP kit; Randox Laboratories Ltd, Antrim, Ireland), and glycerol (Randox) by using an automatic photometric analyzer (Cobas-Mira plus; Roche, Basel, Switzerland). The remaining whole blood sample was dispensed into a tube without anticoagulant and left to clot for 45 min. Serum samples were then obtained after centrifugation at  $2000 \times g$  for 10 min at 4 °C. The serum was divided into aliquots, stored at  $-85 \text{ }^\circ\text{C}$ , and later measured for insulin (Coat-A-Count Insulin; ICN Ltd, Eschwege, Germany) by radioimmunoassay by using a gamma counter (Cobra 5000; Packard Ltd, Boston, MA). Pretrial urine samples were measured for osmolality by using a cryoscopic osmometer (Gonometer 030; Gonotec, Berlin, Germany), and adequate hydration was assumed for osmolality values  $< 900 \text{ mosmol/kg}$  (30).

### Statistical analysis

SPSS software (version 10; SPSS, Chicago, IL) was used for data entry and analysis. All data are presented as mean  $\pm$  SEM. The peak glucose concentrations recorded under each treatment were used to estimate that a sample size of 8 has an 83% power to detect a difference in means of 1.63 mmol/L, with a SD of differences of 1.59, when using a paired *t* test with a one-sided



**FIGURE 1.** Effect of high glycemic index (HGI; ●) and low glycemic index (LGI; ○) meals on mean ( $\pm$ SEM) plasma glucose concentrations during the postprandial period and during exercise ( $n = 8$ ). Two-factor ANOVA showed a significant GI  $\times$  time interaction,  $P < 0.05$ . Bonferroni correction was used to analyze significance at specific time points. \*Significantly different from the LGI trial,  $P < 0.05$ .

significance level. Analysis of variance for repeated measures on 2 factors (experimental treatment and time) was used to analyze differences in the physiologic and metabolic responses in both trials. If a significant interaction was obtained, a Holm-Bonferroni stepwise post hoc test was used to determine the location of the variance. Differences were considered significant at  $P < 0.05$ .

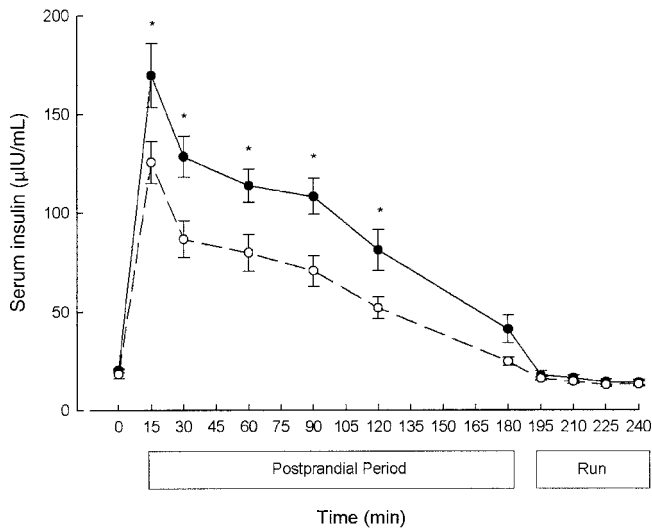
## RESULTS

### Plasma glucose and serum insulin

After ingestion of both breakfasts, plasma glucose concentrations rapidly increased and peaked at 15 min during the postprandial period. The peak concentration was higher in the HGI trial than in the LGI trial ( $7.51 \pm 0.71$  and  $5.88 \pm 0.19 \text{ mmol/L}$  in the HGI and LGI trials, respectively;  $P < 0.05$ ; **Figure 1**). After this peak, plasma glucose concentrations declined in both trials, and concentrations fell below fasting values after the first hour of the postprandial period. Plasma glucose concentrations were higher in the HGI trial than in the LGI trial at 90 min and 120 min during the postprandial period ( $P < 0.05$ ). Throughout exercise, plasma glucose concentrations were maintained at  $\approx 4.5 \text{ mmol/L}$  in both trials.

Serum insulin concentrations peaked 15 min after breakfast in both trials; however, the peak concentration was higher in the HGI trial than in the LGI trial ( $169.6 \pm 16.2$  and  $125.6 \pm 10.8 \mu\text{IU/mL}$  in the HGI and LGI trials, respectively;  $P < 0.05$ ; **Figure 2**). Serum insulin concentrations then declined throughout the remainder of the postprandial period in both trials but remained higher in the HGI trial than in the LGI for the first 2 h of the postprandial period ( $P < 0.05$ ). During exercise, serum insulin concentrations fell below fasting values in both trials. No differences between the trials were observed.

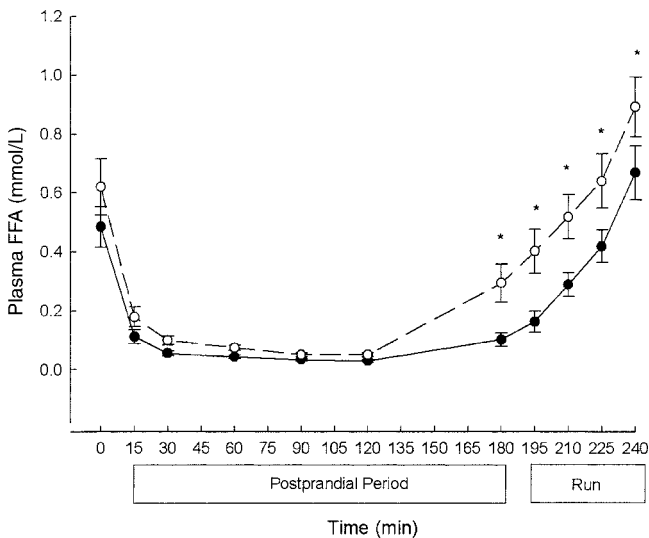




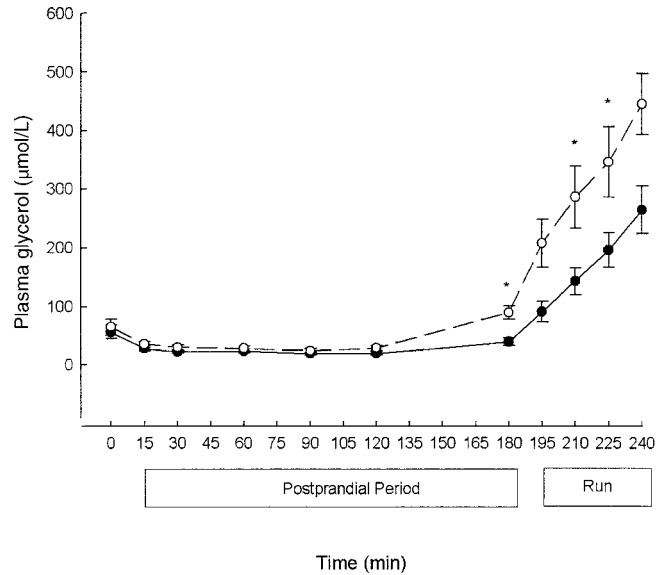
**FIGURE 2.** Effect of high glycemic index (HGI: ●) and low glycemic index (LGI: ○) meals on mean ( $\pm$ SEM) serum insulin concentrations during the postprandial period and during exercise ( $n = 8$ ). Two-factor ANOVA showed a significant GI  $\times$  time interaction,  $P < 0.05$ . Bonferroni correction was used to analyze significance at specific time points. \*Significantly different from the LGI trial,  $P < 0.05$ .

**Plasma free fatty acid and glycerol concentrations**

After both breakfasts, a rapid decline was observed in plasma FFA (Figure 3) and glycerol (Figure 4) concentrations from fasting values ( $P < 0.05$ ), and they remained suppressed throughout the first 2 h of the postprandial period. By the third hour of the postprandial period, concentrations of both metabolites had begun to increase, and concentrations were higher in the LGI trial than in the HGI trial ( $P < 0.05$ ). Throughout exercise, a progressive increase was observed in both plasma FFA and glycerol concentrations with time in both trials; however, FFA concentrations were higher throughout the LGI trial than in the



**FIGURE 3.** Effect of high glycemic index (HGI: ●) and low glycemic index (LGI: ○) meals on mean ( $\pm$ SEM) plasma free fatty acid (FFA) concentrations during the postprandial period and during exercise ( $n = 8$ ). Two-factor ANOVA showed a significant GI  $\times$  time interaction,  $P < 0.05$ . Bonferroni correction was used to analyze significance at specific time points. \*Significantly different from the HGI trial,  $P < 0.05$ .

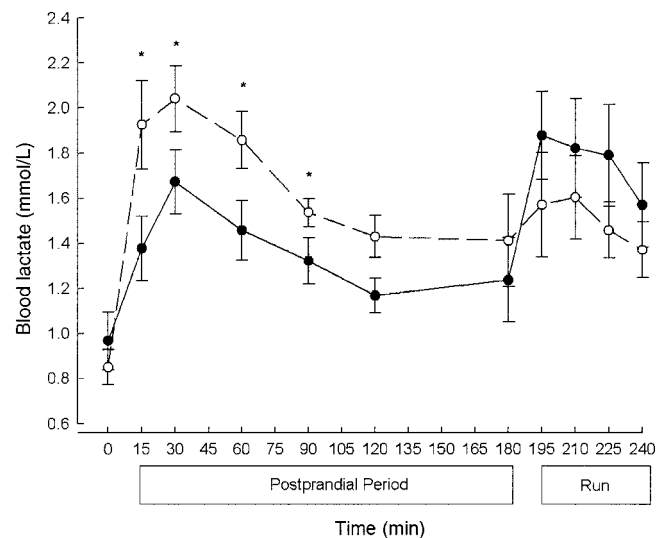


**FIGURE 4.** Effect of high glycemic index (HGI: ●) and low glycemic index (LGI: ○) meals on mean ( $\pm$ SEM) plasma glycerol concentrations during the postprandial period and during exercise ( $n = 8$ ). Two-factor ANOVA showed a significant GI  $\times$  time interaction,  $P < 0.05$ . Bonferroni correction was used to analyze significance at specific time points. \*Significantly higher than the HGI trial,  $P < 0.05$ .

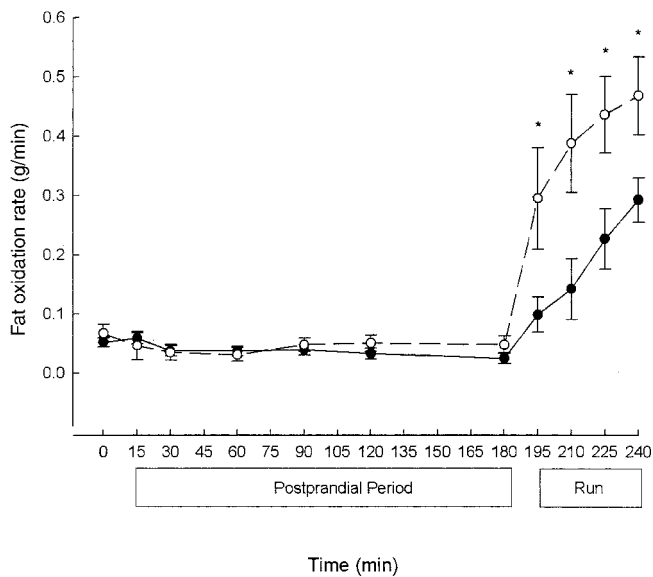
HGI trial at all time points ( $P < 0.05$ ). Plasma glycerol concentrations were higher at 30 min and 45 min in the LGI trial than in the HGI trial ( $P < 0.05$ ).

**Blood lactate concentrations**

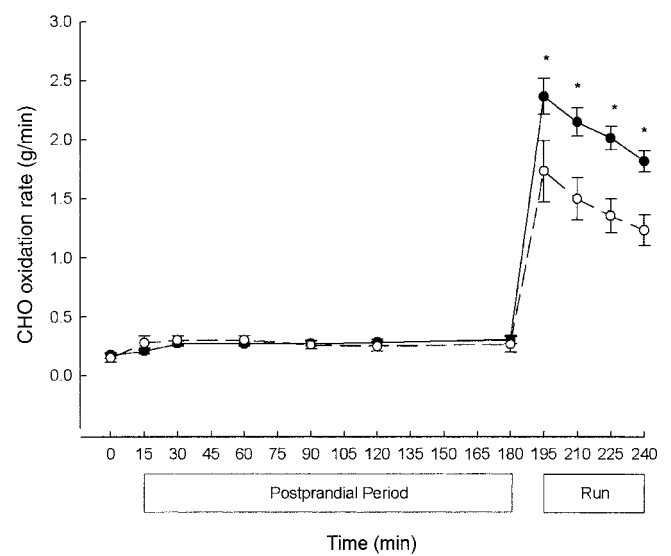
After ingestion of the HGI and LGI breakfasts, blood lactate concentrations increased significantly and peaked at 30 min during the postprandial period ( $P < 0.05$ ; Figure 5). Throughout the first 2 h of the postprandial period, blood lactate concentrations



**FIGURE 5.** Effect of high glycemic index (HGI: ●) and low glycemic index (LGI: ○) meals on mean ( $\pm$ SEM) blood lactate concentrations during the postprandial period and during exercise ( $n = 8$ ). Two-factor ANOVA showed a significant GI  $\times$  time interaction,  $P < 0.05$ . Bonferroni correction was used to analyze significance at specific time points. \*Significantly higher than the HGI trial,  $P < 0.05$ .



**FIGURE 6.** Effect of high glycemic index (HGI: ●) and low glycemic index (LGI: ○) meals on the mean ( $\pm$ SEM) estimated rate of fat oxidation during the postprandial period and during exercise ( $n = 8$ ). Two-factor ANOVA showed a main effect of trial and a significant GI  $\times$  time interaction,  $P < 0.05$ . Bonferroni correction was used to analyze significance at specific time points. \*Significantly different from the HGI trial,  $P < 0.05$ .



**FIGURE 7.** Effect of high glycemic index (HGI: ●) and low glycemic index (LGI: ○) meals on the mean ( $\pm$ SEM) estimated rate of carbohydrate (CHO) oxidation during the postprandial period and during exercise ( $n = 8$ ). Two-factor ANOVA showed a main effect of trial and a significant GI  $\times$  time interaction,  $P < 0.05$ . Bonferroni correction was used to analyze significance at specific time points. \*Significantly different from the LGI trial,  $P < 0.05$ .

were higher in the LGI trial than in the HGI trial ( $P < 0.05$ ). During exercise, no differences were observed in blood lactate concentrations between trials.

#### Estimated rate of carbohydrate and fat oxidation

No differences were observed in substrate oxidation during the postprandial period between the trials. During exercise, the estimated rate of fat oxidation was significantly higher in the LGI trial than in the HGI trial ( $P < 0.05$ ; **Figure 6**), and carbohydrate oxidation was higher in the HGI trial ( $P < 0.05$ ; **Figure 7**). The total amount of fat oxidized throughout the run was  $8.3 \pm 2.2$  g/h in the HGI trial and  $18.7 \pm 4.5$  g/h in the LGI trial ( $P < 0.05$ ). The total amount of carbohydrate oxidized throughout the 60-min run was  $101.5 \pm 12.0$  g/h in the HGI trial and  $70.5 \pm 10.2$  g/h in the LGI trial ( $P < 0.05$ ).

#### Perceived gut fullness

After consumption of both breakfasts, ratings of gut fullness significantly increased; however, a main effect of trial for ratings was observed to be higher after the LGI breakfast ( $P < 0.05$ ). Throughout the postprandial period, ratings of gut fullness remained higher in the LGI trial than in the HGI trial ( $P < 0.05$ ). No differences in perceived gut fullness were reported during exercise (**Table 2**).

#### Plasma volume changes and hydration status

No significant differences were observed in urine osmolality at the start of each trial. By using a cutoff point of 900 mosmol/kg, none of the values suggested that any of the participants began the trials in a dehydrated state ( $672 \pm 78$  mosmol/kg and  $594 \pm 68$  mosmol/kg in the HGI and LGI trials, respectively). No significant differences were observed in plasma volume between trials.

#### Heart rate and rate of perceived exertion

No differences were observed in heart rate during the 60-min run between trials (**Table 2**). Also, no differences were observed in ratings of perceived exertion.

#### DISCUSSION

The main finding of the present study was that the GI of a preexercise carbohydrate meal significantly altered substrate oxidation during subsequent exercise in women. The total amount of fat oxidized during exercise was greater when subjects consumed a LGI breakfast 3 h before exercise than when a HGI breakfast was consumed. The results of this study therefore extend to women the findings of numerous studies that have reported a higher fat oxidation rate during exercise after a LGI preexercise meal or food when using male subjects (2, 4, 5, 7, 9).

It was recently reported that, when a LGI breakfast is consumed 3 h before exercise, less carbohydrate is stored as muscle glycogen than when a HGI breakfast is consumed (31). A 15% increase in muscle glycogen concentration was reported at the end of a 3-h postprandial period after the HGI breakfast; however, only a small nonsignificant increase in muscle glycogen was reported after the LGI breakfast. This was accounted for by the low glycemic and insulinemic responses to the LGI meal (secondary to slow digestion and absorption of the ingested foods). Although the LGI meal contributed less carbohydrates to muscle glycogen synthesis in the postprandial period, a sparing of muscle glycogen during subsequent exercise was observed in the LGI trial, most likely as a result of better maintained fat oxidation. Therefore, the lower rate of carbohydrate oxidation during the LGI trial in the present study could be entirely explained by a lower rate of muscle glycogen utilization.

The GI concept is based on blood glucose responses to a test food that provides 50 g available carbohydrate compared with 50 g glucose as assessed by the incremental area under the curve



TABLE 2

Heart rate (HR), rating of perceived exertion (RPE), and gut fullness during the postprandial period and during exercise in the high glycemic index (HGI) and low glycemic index (LGI) trials<sup>1</sup>

	Postprandial period meal 1							Exercise period			
	Fasting	15 min	30 min	60 min	90 min	120 min	180 min	15 min	30 min	45 min	60 min
HR (beats/min)											
HGI	—	—	—	—	—	—	—	154 ± 5	162 ± 4	165 ± 5	168 ± 5
LGI	—	—	—	—	—	—	—	156 ± 4	162 ± 4	164 ± 4	165 ± 3
RPE <sup>2</sup>											
HGI	—	—	—	—	—	—	—	12 ± 0	12 ± 0	13 ± 0	13 ± 0
LGI	—	—	—	—	—	—	—	12 ± 1	13 ± 1	13 ± 1	14 ± 1
Gut fullness <sup>3</sup>											
HGI	8 ± 1	14 ± 1	13 ± 1	13 ± 1	12 ± 1	11 ± 1	10 ± 1	9 ± 1	10 ± 1	9 ± 1	9 ± 1
LGI	8 ± 1	15 ± 0	15 ± 1	14 ± 1	12 ± 1	12 ± 1	11 ± 1	10 ± 1	10 ± 1	8 ± 1	8 ± 1

<sup>1</sup> All values are  $\bar{x} \pm \text{SEM}$ ;  $n = 8$ . Two-factor ANOVA showed a main effect of trial for gut fullness to be higher in the LGI trial than in the HGI trial,  $P < 0.05$ .

<sup>2</sup> Measured with the Borg Scale (27) that uses a 6–20 scale, ranging from “very, very light” to “very, very hard.”

<sup>3</sup> Adapted from the Borg Scale (27) that uses a 6–20 scale, ranging from “not full” to “very, very full.”

(1). However, because foods are rarely eaten individually, an area of much discussion has been the ability to predict glycemic responses to mixed meals from the GIs of the constituent foods. In the present study, the breakfasts were composed of a variety of HGI and LGI foods that would commonly be part of a habitual Western diet. The meals provided nutrients in proportions that would be realistic to the dietary practices of professional or recreational athletes. Significant differences in the glycemic and insulinemic responses to the HGI and LGI meals were achieved without changing the overall composition of the diet in terms of fat, protein, carbohydrate, and energy content. The GI of the meal was calculated by using a method described by Wolever and Jenkins (25). The estimated GI ratio of the 2 test breakfasts was 1.77:1.00 (78/44) and the actual measured ratio of the incremental area under the blood glucose curve was 1.82:1.00 (71 mmol/L  $\times$  180 min/39 mmol/L  $\times$  180 min). Similar results were recently reported when male subjects consumed the same test meals as used in this study (32). The results of this study therefore provide additional evidence that the GI concept can successfully be applied to mixed meals and provides further support for the calculations proposed by Wolever and Jenkins (25).

Although female subjects were used in some intervention trials that investigated the effects of the GI on health and disease risk (33–35), no studies have specifically investigated the metabolic responses to HGI and LGI meals in female subjects while controlling for menstrual cycle phase and the use of oral contraceptives. Synthetic steroids used as oral contraceptives were reported to alter glucose metabolism and insulin sensitivity in women at rest (36, 37) and during exercise (38). In the present study, none of the subjects had used oral contraceptives for  $\geq 6$  mo before the study commenced. Oral contraceptives are however widely used by both sedentary and sports women, and few investigators have evaluated the affects of these exogenous ovarian steroids on the metabolic responses to physical exercise. Further research is therefore required to investigate whether oral contraceptive users show similar metabolic responses to HGI and LGI preexercise meals as do nonusers.


As previously mentioned, a higher rate of fat oxidation was observed during the LGI trial in the present study. Increasing fat oxidation during exercise is beneficial for those who are exercising to lose body fat mass. Although exercise in the fasted state

promotes optimal fat oxidation, many find it difficult or impractical to exercise while fasted. Consuming a LGI breakfast may therefore be a good compromise. Although the chronic effects of a LGI diet cannot be predicted from observations over a single day, it would not be unreasonable to assume that a LGI diet combined with regular exercise may be an effective and healthy way to optimize the loss of body fat mass. In the present study, subjects completed a 60-min run at 65%  $\dot{V}O_2\text{max}$ . It is recognized that both the duration and intensity of this exercise may not be suitable for many persons, however; clear differences in the rate of fat oxidation were obvious after only 15 min of exercise between the trials. Further research is required to investigate whether differences in fat oxidation still exist when exercising at a lower intensity (ie, walking) and for different durations.

As well as promoting fat oxidation at the expense of carbohydrate oxidation, LGI foods are hypothesized to promote weight regulation by promoting feelings of satiety (39). In the present study, feelings of gut fullness were recorded throughout the postprandial period and during exercise. Higher ratings of gut fullness were reported during the postprandial period in the LGI trial than in the HGI trial, despite the 2 meals being isoenergetic and matched for carbohydrate, protein, and fat content. It is important to note however that the 2 meals were not matched for energy density and fiber content. The LGI breakfast provided 5 g more fiber than the HGI breakfast (for a 60-kg woman) and had a lower energy density (0.8 kcal/g and 1.2 kcal/g in the LGI and HGI meals, respectively). It is therefore possible that the higher fiber content of the LGI meal is responsible for the increased feelings of satiety. However, the exact relation between glycemic carbohydrates and satiety remains unclear because few studies have made concurrent measurements of blood glucose, appetite, and food intake over extended periods. The available literature contains contradictory information on the relation (40); therefore, further studies are required to delineate the role of glycemic carbohydrates and their mechanisms of action in determining satiety (40).

In conclusion, the GI of the carbohydrates consumed as part of a mixed meal had a significant effect on the degree of hyperglycemia and hyperinsulinemia during the postprandial period in female subjects. The total amount of fat oxidized during exercise was greater when the LGI mixed meal was consumed 3 h before



than when the HGI mixed meal was consumed. Further research is required to investigate whether this phenomenon occurs during exercise at different intensities and of shorter duration and also in older women and oral contraceptive users. 

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EJS produced the original study design, performed the laboratory investigations and biochemical analysis, undertook the statistical data analysis, and wrote the first draft of the manuscript. MLN, LEM, and BP assisted with the laboratory investigations and biochemical analysis. CW supervised the data collection, contributed to the data interpretation, and revised the manuscript. None of the authors had a conflict of interest.

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