Effect of Preexercise Meals With Different Glycemic Indices and Loads on Metabolic Responses and Endurance Running

Ya Jun Chen, Stephen H. Wong, Chun Kwok Wong, Ching Wan Lam, Ya Jun Huang, and Parco M. Siu

This study examined the effect of ingesting 3 isocaloric meals with different glycemic indices (GI) and glycemic loads (GL) 2 hr before exercise on metabolic responses and endurance running performance. Eight male runners completed 3 trials in a randomized order, separated by at least 7 days. Carbohydrate (CHO) content (%), GI, and GL were, respectively, 65%, 79, and 82 for the high-GI/high-GL meal (H-H); 65%, 40, and 42 for the low-GI/low-GL meal (L-L); and 36%, 78, and 44 for the high-GI/low-GL meal (H-L). Each trial consisted of a 1-hr run at 70% \( \text{VO}_{2\max} \), followed by a 10-km performance run. Low-GL diets (H-L and L-L) were found to induce smaller metabolic changes during the postprandial period and during exercise, which were characterized by a lower CHO oxidation in the 2 trials (\( p < .05 \)) and a concomitant, higher glycerol and free-fatty-acid concentration in the H-L trial (\( p < .05 \)). There was no difference, however, in time to complete the preloaded 10-km performance run between trials. This suggests that the GL of the preexercise meal has an important role in determining subsequent metabolic responses.

**Keywords:** glycemic index, glycemic load, carbohydrate, preexercise diet

It has become widely accepted for athletes undergoing strenuous daily training or competition to eat a moderate-size high-CHO meal 2–4 hr before exercise for optimal restoration of liver and muscle glycogen (Brooks & Trimmer, 1996; Schabort, Bosch, Welten, & Noakes, 1999). Any large glycemic and insulinemic perturbation accompanying such ingestion, however, might reduce plasma free-fatty-acid (FFA) availability and oxidation (Coyle, Jeukendrup, Wagenmakers, & Saris, 1997; Horowitz, Mora-Rodriguez, Byerley, & Coyle, 1997) during subsequent exercise. Regarding the limitations of carbohydrate (CHO) stores, increasing the oxidation of fat at the expense of CHO oxidation has important implications for endurance-trained athletes (Stevenson, Williams, Mash, Phillips, & Nute, 2006). A body of research has examined different ways to increase the contribution of FFA in exercise fuel metabolism.
One such strategy has been high dietary fat intake (defined as >30% of total calories from dietary fat). The available research on the effect of high-fat diets on endurance exercise is still limited, and the results are equivocal (Cook & Haub, 2007). It has been argued that a high-fat diet might lead to a decline in preexercise muscle glycogen content, especially in untrained individuals, which might defeat the purpose of creating the glycogen-sparing effect in the first place. Lambert, Speechly, Dennis, and Noakes (1994), however, demonstrated enhanced endurance capacity in endurance-trained individuals on a high-fat diet even in the face of diminished preexercise glycogen levels. Another such strategy is to use low-glycemic-index (LGI) CHO foods in preexercise meals (Burke, Collier, & Hargreaves, 1998). As compared with a high-GI (HGI) meal, a LGI CHO meal consumed at different times before prolonged exercise maintained higher blood glucose concentrations (DeMarco, Sucher, Cisar, & Butterfield, 1999; Stannard, Constantini, & Miller, 2000), decreased plasma lactate concentrations during exercise or postexercise (Stannard et al.), increased fat oxidation, and reduced reliance on the body’s limited CHO stores (Wong et al., 2008). Despite the fact that no improvement in exercise performance was found after ingestion of a LGI meal in most studies (Febbraio, Keenan, Angus, Campbell, & Garnham, 2000; Sparks, Selig, & Febbraio, 1998; Wee, Williams, Gray, & Horabin), an enhancement in subsequent exercise performance seemed apparent in some other studies (DeMarco et al.; Earnest et al., 2004; Wong et al.; Wu, Nicholas, Williams, Took, & Hardy, 2003). The results of the two strategies imply that there might be an ideal nutritional method that both provides adequate exogenous FFA to maintain a high rate of FFA oxidation and improves plasma glucose homeostasis.

The GI takes only the type of CHO into account, ignoring the total amount of CHO in a typical serving, although both the type and amount of CHO influence the postprandial glycemic and insulin response to a given food as typically consumed (Jenkins et al., 1981). A recent study demonstrated that the amount of CHO ingested accounted for 66–65% of the variability in glucose response, and the GI of the CHO explained a similar amount (60%) of the variance. Together, the amount and the GI of CHO accounted for ~90% of the total variability in the blood glucose response (Tsintzas, Williams, Wilson, & Burrin, 1996). Glycemic load (GL), defined as the product of the GI value of a food and its CHO content, was subsequently proposed as a measure that incorporates both the quantity and the quality of CHO (Salmeron, Ascherio, et al., 1997; Salmeron, Manson, et al., 1997). By summing the GL contributed by individual foods, the overall glycemic load of a meal or the whole diet can be calculated (Salmeron, Ascherio, et al.; Salmeron, Manson, et al.). Although a mathematical concept, GL has been physiologically validated as a relatively reliable measure of glycemic responses to individual foods across a wide range of portion sizes (Brand-Miller et al., 2003), and it has been suggested that GL would be a much better predictor than CHO amount or percentage or GI alone (Scaglioni, Stival, & Giovannini, 2004).

Compared with a number of studies that have examined the application of GI in sports nutrition, GL, which is primarily applied in epidemiological research (Augustin et al., 2003; Salmeron, Ascherio, et al., 1997; Salmeron, Manson, et al., 1997), has been less studied directly. Furthermore, GL is derived by multiplying the amount of available CHO consumed in the diet by its GI value. Thus, the GL value can be reduced by decreasing the amount of either CHO consumed or...
the dietary GI. Although both of these approaches reduce acute plasma glucose and insulin responses (Chew, Brand, Thorburn, & Truswell, 1988; Indar-Brown, Noreberg, & Madar, 1992), their effect on metabolic and physiological responses during exercise is still unclear.

Therefore, the purpose of this study was to examine the effect of three isoenergetic mixed meals with different GI and GL, by changing either the GI or the amount of the CHO by replacing CHO with fat, on preloaded (1 hr 70% VO2max run) 10-km time-trial (TT) performance and physiological responses during endurance running. It has been suggested that the TT and time-to-exhaustion (TTE) methods did not reliably measure the same effects, and TTE was a less reliable measure of performance with large variability as measured by coefficient of variation (Erlenbusch, Haub, Munoz, MacConnie, & Stillwell, 2005). The pretrial preload enables achievement of a “steady state,” which might be advantageous to researchers measuring gas exchange. Furthermore, preloaded TTs also allow for a lowering of endogenous substrate stores before a TT performance test (Doyle & Martinez, 1998), and this type of testing has been suggested to be an extremely reproducible method in endurance-trained runners, which is important for research assessing the effect of diet on endurance running performance (Doyle & Martinez). We hypothesized that (a) compared with an HGI meal with an equal amount of CHO, consuming an LGI meal 2 hr before exercise would enhance running performance and result in a reduced fluctuation in metabolic responses to exercise, which in turn would allow the maintenance of this metabolic status until the 2-hr recovery period, and (b) ingesting meals of equal GL 2 hr before exercise would produce similar glycemic and insulinemic responses regardless of their GI and CHO content; however, the meal with high fat would produce a higher FFA oxidation during exercise.

**Methods**

**Participants**

Eight healthy male runners (age 24.3 ± 2.2 years, body mass 66.7 ± 2.0 kg, VO2max 55.9 ± 1.9 ml · kg⁻¹ · min⁻¹) volunteered to participate in this study. The procedure in the study was approved by the university clinical research ethical committee.

**Preliminary Test**

To alleviate the participants’ anxiety, they were familiarized with running on a motorized treadmill, the laboratory environment, and the experimental protocols during their first visit to the laboratory. A series of preliminary tests was conducted before the two main trials. The first test determined the participants’ maximum oxygen uptake (VO2max) using a modified protocol of a continuous, incremental, graded uphill treadmill running test to volitional exhaustion, as previously described (Wong & Williams, 2000). The second test determined the relationship between running speed and oxygen uptake on a level treadmill using a 16-min incremental submaximal running protocol. The speeds were chosen with reference to each participant’s training status and were set between 60% and 90% VO2max. Expired-gas samples were collected during the last minute of each 4-min period. The samples were analyzed by a metabolic cart system (MAX-1 Physio-Dyne, New York). From
the results of these two preliminary tests, running speeds equivalent to 70% $\text{VO}_{2\text{max}}$ were determined and used in the main trials. One week before the main trial, the participants completed a 60-min treadmill run to confirm, and adjust as necessary, the running speed for the main trials.

**Dietary and Training Control**

To minimize the variation of dietary intake before each main trial, a 3-day weighed-food record was obtained from each participant before the main trials. Dietary analyses were performed using commercially available software (The Food Processor 8.4, Esha, USA.). The participants were asked to consume the same diet before each trial with the aim of minimizing variation in muscle and liver glycogen concentrations. They reported to the laboratory after a 12-hr overnight fast. This was to ensure that they had an empty stomach and to minimize the effect of a previous meal on gastric emptying rate of the test meals. To maintain a state of euhydration before each experimental test, the participants were instructed to drink approximately 500 ml of water the night before they reported to the laboratory.

During the period of the study, all participants were required to maintain their endurance running training at a frequency of at least three sessions of at least 50 km of accumulated running distance per week. They were also advised to refrain from any strenuous exercise 3 days before each main trial to minimize the effect of heavy training on the study’s findings.

**Prescribed GI and GL Meals**

Three pairs of isocaloric meals (~630 kcal for a 70-kg participant) were used in this study, namely, high-GI and high-GL (H-H), low-GI and low-GL (L-L), and high-GI and low-GL (H-L). Because the GL was a calculated indicator that incorporates the GI and amount of CHO, that is, $\text{GI} \times \text{CHO (g)/100}$, a diet with a low GI and high GL (L-H) was practically unfeasible. Trials were separated by at least 7 days. Available CHO intake (% of energy intake), GI, and GL were, respectively, 66%, 79, and 82 for the H-H; 66%, 40, and 42 for the L-L; and 36%, 78, and 44 for the H-L. The GI and GL of the meal were calculated from a method described by Jenkins et al. (1981). The detailed nutritional composition of the three preexercise meals is shown in Table 1. The H-H and L-L trials both provided 1.5 g CHO/kg body mass, whereas the H-L trial provided only 0.8 g CHO/kg body mass. The water content of all meals was also standardized so that each provided 1,100 ml of fluid. The whole meal had to be consumed within 15–20 min. The participants remained seated in a quiet area of the laboratory, and their activity level was minimal (Thorne, Thompson, & Jenkins, 1983). Blood samples were obtained to determine glucose concentrations, and the perceived ratings of gut fullness were recorded throughout the 2-hr postprandial period at specific time points (15, 30, 45, 60, 90, and 120 min after the test meal). These blood glucose assessments were made using finger-prick sampling and were a separate measurement from the venous blood-sampling measurements indicated in Figure 1. To avoid bias, the specific purpose related to GI foods and the weight of the food were not disclosed to the participants.
Table 1  Nutritional Composition of Preexercise Meals (for a 70-kg Participant)

<table>
<thead>
<tr>
<th>Meal</th>
<th>Contents</th>
<th>Nutritional analysis</th>
<th>Estimated GI</th>
<th>Estimated GL</th>
</tr>
</thead>
<tbody>
<tr>
<td>H-H</td>
<td>275 g potatoes (baked) 200 ml plain soy milk 40 g ham (11% fat) 18 g white granulated sugar 30 g raw egg 2.5 g corn oil</td>
<td>633.6 kcal 66% CHO (104.3 g) 15% protein (22.2 g) 20% fat (14.2 g) 1,100 ml water</td>
<td>79</td>
<td>82</td>
</tr>
<tr>
<td>L-L</td>
<td>150 g apple 50 g ham (11% fat) 6 g corn oil 267 g macaroni (cooked) 0.25 cup tomato sauce</td>
<td>631 kcal 66% CHO (104.1 g) 15% protein (22.8 g) 20% fat (13.6 g) 1,100 ml water</td>
<td>40</td>
<td>42</td>
</tr>
<tr>
<td>H-L</td>
<td>130 g grain white rice (boiled) 18.8 g corn oil 150 g eggs 220 g grapefruit</td>
<td>632 kcal 36% CHO (56.8 g) 15% protein (23.7 g) 49% fat (34.3 g) 1,100 ml water</td>
<td>78</td>
<td>44</td>
</tr>
</tbody>
</table>

Note. GI = glycemic index; GL = glycemic load; H-H = high-glycemic-index/high-glycemic-load; CHO = carbohydrate; L-L = low-glycemic-index/low-glycemic-load; H-L = high-glycemic-index/low-glycemic-load. GI and GL were calculated by a method described in Wolever and Jenkins (1986) with GI values taken from Foster-Powell, Holt, and Brand-Miller (2002).

Experimental Procedure

A standardized preloaded TT (1 hr 70% VO\textsubscript{2max} and then 10-km TT) protocol (Figure 1) was used in this study. A 5-min warm-up at 60% VO\textsubscript{2max} was performed after the 2-hr preexercise rest period. The speed of the treadmill was increased to an intensity of 70% VO\textsubscript{2max} for each participant immediately after the warm-up session. For the first hour (T1), the participants ran at a fixed speed equivalent to 70% VO\textsubscript{2max}. Then they could select their own pace to complete the subsequent 10-km TT run as quickly as possible. To ensure maximal effort during the performance run, strong verbal encouragement was given to the participants throughout the run solely by the chief experimenter, who was blinded to the treatments. The pretrial preload (T1) enables achievement of a “steady state” and also allows for a lowering of muscle glycogen concentration in both fiber types before a TT performance test (Doyle & Martinez, 1998; Tsintzas et al., 1996). The order of these experimental trials was randomized, and the study employed a counterbalanced crossover design.
Figure 1 — Schematic representation of the experimental procedures.
Throughout each run, expired-air samples were collected and analyzed at 20-min intervals during T1, at 2.5-km intervals during the 10-km TT, and at 1-hr intervals during the 2-hr recovery period. From the VO$_2$ and VCO$_2$ values obtained, the substrate oxidation rates and the total CHO and fat oxidized were estimated using the stoichiometric equations of McArdle, Katch, and Katch (1986). Heart rate was monitored continuously using a heart-rate monitor (Sport Tester PE 4000, Polar Electro, Kempele, Finland) and recorded throughout the experimental trials. Ratings of perceived exertion were estimated using the 6–20 Borg scale (Wong & Williams, 2000). Rating of abdominal discomfort was assessed using a 10-point scale on which 1 was completely comfortable and 10 was very uncomfortable (Wong & Williams). To assess thirst, participants chose a number on a 10-point scale on which 1 was not thirsty and 10 was very thirsty (Wong & Williams).

Ten-milliliter samples of venous blood from each participant were drawn from an antecubital vein into three evacuated collection tubes (Vacutainer, Becton Dickinson, Mountain View, CA) at specific time points: premeal, 1 hr preexercise, at 20-min intervals during T1, at 5 km during the 10 km TT, and 1 hr and 2 hr in the recovery period. Blood lactate and glucose concentrations were determined immediately by patented immobilized enzyme technology (lactate analyzer, Model 1500, YSI, Yellow Springs, OH; glucose analyzer, Model 1500 Sidekick, YSI). The sera were separated and stored at –70 °C for later measurement of insulin (Insulin ELISA, Mercodia, Sweden), free fatty acid (FFA 115 kit, Randox Laboratories Ltd, UK), glycerol (GY 105 kit, Randox Laboratories Ltd., UK), and cortisol (Active Cortisol EIA DSL-10-2000,Diagnostic Systems Laboratories Inc., USA) concentrations by using commercially available kits.

Statistical Analyses

The data were examined using a 2 x 2 factorial (Trial x Time of Measurement) ANOVA with repeated-measures design. Any significant F ratios found were assessed using the post hoc Tukey’s test. If a data set was not normally distributed, statistical analysis was performed on the logarithmic transformation of the data. Assumptions of homogeneity and sphericity in the data were checked, and an adjustment in the degrees of freedom for the ANOVA was made. Performance times were analyzed using Wilcoxon’s signed ranks tests for nonparametric data. All data were presented as $M \pm SEM$, with the significance set at $p < .05$.

Results

On the three occasions, the preexercise body mass (H-H vs. L-L vs. H-L: 65.8 ± 1.7 kg vs. 66.8 ± 1.8 kg vs. 66.7 ± 2.1 kg), the laboratory temperature (H-H vs. L-L vs. H-L: 21.0 ± 1.1 °C vs. 20.6 ± 1.0 °C vs. 20.3 ± 1.5 °C), and relative humidity (H-H vs. L-L vs. H-L: 62.2% ± 1.3% vs. 61.8% ± 1.5% vs. 58.8% ± 2.1%) were not different, indicating that the participants started all the experiments under similar experimental and environmental conditions.

There were no differences in the daily energy intake and macronutrient composition of the diet in the 3 days before each main trial (H-H vs. L-L vs. H-L: total energy intake 13.7 ± 1.5 vs. 13.2 ± 1.8 vs. 13.5 ± 1.3 MJ, CHO 63.1% ± 2.3%
vs 64.5% ± 2.0% vs. 62.8% ± 2.5%, protein 18.1% ± 1.2% vs. 17.8% ± 1.0% vs. 16.9% ± 0.9%, and fat 18.6% ± 2.1% vs. 17.5% ± 1.9% vs. 20.3% ± 1.8%).

All participants completed the three trials. There were no differences in time to complete the preloaded 10-km performance run among the three main trials (H-H vs. L-L vs. H-L: 52.6 ± 2.0 min vs. 51.2 ± 2.0 min vs. 52.7 ± 2.0 min, NS; Table 2). There were no differences in the running speed and %VO_{2max} measured at either 20-min intervals during the 1-hr 70% VO_{2max} run or at 2.5-km intervals in the 10-km TT among the three trials (p > .05). The running speed increased to approximately 80% VO_{2max} at the end of the 10 km TT, however.

The average respiratory-exchange rates were higher in H-H (p < .05) than in L-L and H-L throughout the exercise period (except for the 5-km time point) and at the end of the 2-hr recovery period. A higher respiratory-exchange rate on L-L, as compared with H-L, was only found at the end of T1 (60 min) and the end of the 2-hr recovery period (Table 3).

Table 4 shows the substrate oxidation during the postprandial, exercise, and recovery periods. During exercise, the total CHO oxidation was higher (p < .05) in H-H, with a compensatory decrease in fat oxidation (p < .05) compared with L-L and H-L, such that the overall energy expenditure was similar. There were no differences, however, in CHO and fat oxidation between the L-L and H-L trials.

There were no differences in heart rate, rating of perceived exertion, and perceived thirst during the endurance run among the three trials at any time points (Table 5). As expected, the ratings of perceived exertion increased during the exercise in all trials (p < .05). The abdominal-discomfort ratings in the H-L trial at the later stage of 10-km TT were higher than those in the H-H (p < .05 at 7.5 km) and L-L trials (p < .05 at 10 km).

**Blood Glucose**

The postprandial 2-hr incremental area under the blood glucose curve (AUC) using the finger-prick glucose measurements was larger in the H-H trial than in the L-L and H-L trials (H-H vs. L-L vs. H-L: 177.1 ± 18.3 vs. 120.0 ± 15.6 vs. 105.7 ± 11.0 mmol · min⁻¹ · L⁻¹, p < .01). The AUC after the H-H meal was about 1.5 times larger than that after the L-L and H-L meals. The blood glucose concentrations during the three main trials are shown in Figure 2. Compared with the H-H trial, the blood glucose concentrations were equally well maintained during the exercise and recovery periods in the L-L trial. Higher blood glucose concentrations were observed in the L-L trial at 20 min during the 1-hr 70% VO_{2max} run (H-H vs. L-L

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**Table 2** The 10-km Performance Time During the H-H, L-L, and H-L Trials (N = 8, M ± SEM)

<table>
<thead>
<tr>
<th>Trial</th>
<th>Performance Time (min)</th>
<th>Range (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H-H</td>
<td>52.6 ± 2.0</td>
<td>47.9–57.2</td>
</tr>
<tr>
<td>L-L</td>
<td>51.2 ± 2.0</td>
<td>46.5–55.8</td>
</tr>
<tr>
<td>H-L</td>
<td>52.7 ± 2.0</td>
<td>47.9–57.5</td>
</tr>
</tbody>
</table>

Table 3  The Respiratory-Exchange Rate During the H-H, L-L, and H-L Trials (N = 8, M ± SEM)

<table>
<thead>
<tr>
<th></th>
<th>Premeal</th>
<th>20 min</th>
<th>40 min</th>
<th>60 min</th>
<th>2.5 km</th>
<th>5 km</th>
<th>7.5 km</th>
<th>10 km</th>
<th>Post-60 min</th>
<th>Post-120 min</th>
</tr>
</thead>
<tbody>
<tr>
<td>H-H</td>
<td>0.81 ± 0.03</td>
<td>1.00† ± 0.03</td>
<td>0.97† ± 0.03</td>
<td>0.96† ± 0.02</td>
<td>0.94† ± 0.01</td>
<td>0.93 ± 0.02</td>
<td>0.95† ± 0.02</td>
<td>0.96† ± 0.01</td>
<td>0.74 ± 0.02</td>
<td>0.74† ± 0.03</td>
</tr>
<tr>
<td>L-L</td>
<td>0.83 ± 0.02</td>
<td>0.94* ± 0.03</td>
<td>0.92* ± 0.02</td>
<td>0.94† ± 0.02</td>
<td>0.91* ± 0.02</td>
<td>0.91 ± 0.02</td>
<td>0.92* ± 0.02</td>
<td>0.92* ± 0.02</td>
<td>0.72 ± 0.02</td>
<td>0.74† ± 0.03</td>
</tr>
<tr>
<td>H-L</td>
<td>0.80 ± 0.02</td>
<td>0.94* ± 0.02</td>
<td>0.93* ± 0.02</td>
<td>0.91* ± 0.02</td>
<td>0.90* ± 0.02</td>
<td>0.90 ± 0.03</td>
<td>0.91* ± 0.02</td>
<td>0.92* ± 0.03</td>
<td>0.73 ± 0.02</td>
<td>0.71* ± 0.02</td>
</tr>
</tbody>
</table>


*p < .05 from H-H. †p < .05 from H-L.
Chen et al.

vs. H-L: 4.7 ± 0.3 vs. 5.0 ± 0.4 vs. 4.6 ± 0.3 mmol/L, \(p < .05\) and at 60 min into the recovery period (H-H vs. L-L vs. H-L: 4.5 ± 0.4 vs. 5.1 ± 0.4 vs. 4.8 ± 0.3 mmol/L, \(p < .05\)).

**Plasma Insulin**

Serum insulin concentrations increased after consumption of the preexercise test meals in all trials. There were differences in the serum insulin concentrations, however, at 60 min and 120 min in the postprandial period among the three trials (\(p < .05\)). There were no differences in serum insulin concentrations throughout the exercise or during the 2-hr recovery period among trials (Figure 3).

**Serum FFA and Glycerol**

There were no differences in serum FFA and glycerol concentrations during the 2-hr postprandial period among the three trials. Serum FFA concentrations were higher in H-L than in H-H and L-L during the exercise and 2-hr recovery period (H-H vs. L-L vs. H-L: post-60 min 1.03 ± 0.11 vs. 1.27 ± 0.17 vs. 1.55 ± 0.13 mmol/L, post-120 min 1.04 ± 0.10 vs. 1.21 ± 0.18 vs. 1.34 ± 0.16 mmol/L; \(p < .05\); Figure 4). Similar to the FFA, the serum glycerol concentrations were higher in the H-L than in the H-H and L-L throughout the exercise (\(p < .05\)). In addition, glycerol levels were higher than those at premeal in all trials throughout the exercise and 2-hr recovery period (\(p < .01\); Figure 5).

**Blood Lactate**

Exercise lactate concentrations were higher than the preexercise value (\(p < .01\)) in all trials. They remained elevated throughout exercise in the H-H trial as compared with the L-L and H-L trials (\(p < .05\)). There were no differences between trials during the 2-hr recovery period (Figure 6).

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### Table 4  Total Carbohydrate and Fat Oxidized Before, During, and After Exercise During the H-H, L-L, and H-L Trials \((N = 8, M \pm SEM)\)

<table>
<thead>
<tr>
<th>Trial</th>
<th>Postprandial</th>
<th>Exercise</th>
<th>Recovery</th>
<th>Postprandial</th>
<th>Exercise</th>
<th>Recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>H-H</td>
<td>32.9 ± 4.2</td>
<td>252.2 ± 14.3</td>
<td>37.0 ± 3.0</td>
<td>13.0 ± 0.9</td>
<td>24.6 ± 3.9</td>
<td>17.7 ± 4.0</td>
</tr>
<tr>
<td>L-L</td>
<td>28.6 ± 5.2</td>
<td>230.7 ± 10.4*</td>
<td>33.7 ± 8.9</td>
<td>13.8 ± 2.4</td>
<td>32.6 ± 5.2*</td>
<td>18.5 ± 2.1</td>
</tr>
<tr>
<td>H-L</td>
<td>27.7 ± 6.1</td>
<td>225.5 ± 12.1*</td>
<td>30.1 ± 6.0</td>
<td>14.6 ± 1.6</td>
<td>35.2 ± 2.6*</td>
<td>20.3 ± 3.8</td>
</tr>
</tbody>
</table>


*p < .05 from H-H.
Table 5  Heart Rate, Rating of Perceived Exertion (RPE), Abdominal Discomfort (AD), and Perceived Thirst (PT) During the H-H, L-L, and H-L Trials (N = 8, M ± SEM)

<table>
<thead>
<tr>
<th></th>
<th>Premeal</th>
<th>20 min</th>
<th>40 min</th>
<th>60 min</th>
<th>2.5 km</th>
<th>5 km</th>
<th>7.5 km</th>
<th>10 km</th>
<th>Post-60 min</th>
<th>Post-120 min</th>
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<tbody>
<tr>
<td><strong>Heart rate</strong></td>
<td></td>
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<td>(beats/min)</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H-H</td>
<td>55 ± 3</td>
<td>145 ± 4*</td>
<td>153 ± 5*</td>
<td>156 ± 5*</td>
<td>155 ± 5*</td>
<td>159 ± 4*</td>
<td>162 ± 3*</td>
<td>165 ± 3*</td>
<td>78 ± 3</td>
<td>70 ± 3</td>
</tr>
<tr>
<td>L-L</td>
<td>58 ± 2</td>
<td>149 ± 4*</td>
<td>153 ± 5*</td>
<td>155 ± 5*</td>
<td>156 ± 4*</td>
<td>158 ± 4*</td>
<td>161 ± 4*</td>
<td>168 ± 3*</td>
<td>80 ± 2</td>
<td>71 ± 2</td>
</tr>
<tr>
<td>H-L</td>
<td>56 ± 4</td>
<td>146 ± 4*</td>
<td>152 ± 5*</td>
<td>152 ± 5*</td>
<td>155 ± 4*</td>
<td>158 ± 4*</td>
<td>161 ± 4*</td>
<td>166 ± 4*</td>
<td>82 ± 4</td>
<td>68 ± 4</td>
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*p < .01 from premeal. †p < .05 from H-L.
The aim of this study was to observe the effects of three isoenergetic mixed meals with different GI and GL, by changing either the GI or the amount of CHO by replacing CHO with fat, on endurance running performance and metabolic responses during exercise and in a 2-hr short recovery. With these two strategies, we were trying to produce one kind of relatively ideal diet that both provides adequate exogenous fat to maintain high rate of FFA oxidation and improves blood glucose homeostasis without influencing FFA mobilization or hepatic glucose output, thus improving the subsequent endurance performance. The major finding of this study was that preexercise low-GL (H-L and L-L) meals induced smaller metabolic changes during the postprandial period and during exercise than the
Effect of Glycemic Indices and Loads

There was no difference, however, in time to complete the preloaded 10-km TT between trials despite differences in metabolic responses to the different meals.

During the two high-CHO trials (H-H and L-L) in the current study, a higher rate of fat oxidation was observed with the low-GI meal (L-L) than with the HGI meal (H-H) during exercise, which is consistent with the results of some earlier studies (Wee et al., 1999; Wu et al., 2003). Ingesting a low-GI high-CHO meal, with reduced postprandial glycemia and insulinemia, might provide the CHO required during subsequent exercise without depressing fat oxidation to the same extent as is the case when a high-GI CHO meal is consumed (DeMarco et al., 1999; Febbraio et al., 2000; Wee et al., 1999). In the current study, the serum insulin concentrations had not returned to premeal levels before the beginning of the exercise in the high-GI meal. There was no difference, however, in time to complete the preloaded 10-km TT between trials despite differences in metabolic responses to the different meals.

**Figure 3** — Serum insulin concentrations (mU/L) before, during, and after exercise high-glycemic-index/high-glycemic-load (H-H), low-glycemic-index/low-glycemic-load (L-L), and high-glycemic-index/low-glycemic-load (H-L) trials (N = 8, M ± SEM). *p < .01 from premeal. **p < .01 from H-L. ***p < .01 from H-H.
Figure 4 — Serum FFA concentrations (mmol/L) before, during, and after exercise high-glycemic-index/high-glycemic-load (H-H), low-glycemic-index/low-glycemic-load (L-L), and high-glycemic-index/low-glycemic-load (H-L) trials ($N = 8, M \pm SEM$). *$p < .05$ from premeal. **$p < .05$ from H-L.

CHO trial (H-H), which might suggest that the suppression of fat oxidation from the rise in insulin during exercise persisted after the high-GI CHO (H-H) trial. In fact, the delayed effects of insulin on peripheral tissues have been demonstrated in other studies (Montain, Hopper, Coggan, & Coyle, 1991; Wong et al., in press).

The GI concept is based on the incremental area under the blood glucose curve after ingestion of CHO-rich food compared with that of a reference food, either 50 g glucose or white bread (Jenkins et al., 1981). In reality, individuals eat varying portion sizes and a combination of foods, and the GI value of a mixed meal (overall GI) can be calculated using the method described by Wolever and Jenkins (1986). In an effort to improve the reliability of predicting the glycemic response of a given diet, Salmeron, Manson, et al. (1997) have suggested using GL. GL has been physiologically validated to predict the glycemic response to individual foods across a wide range of portion sizes (Salmeron, Ascherio, et al., 1997; Salmeron, Manson, et al.). A recent study investigating the relationships of dietary GL and overall GI with glucose and insulin concentrations in a population of healthy 8-year-old children found that GL might be an effective indicator of the general glucose responses to a diet (Scaglioni et al., 2004). In the current study, the low-GI CHO meal—L-L—induced smaller metabolic changes during both the 2-hr postprandial period and during exercise than a high-GI meal with an equal amount of CHO—H-H. The estimated GL ratio of the two low-GL meals in the current study was 1.0:1.0 (42/40), which is similar to the actual measured value of 1.1:1.0 (120/105).
In addition, as calculated from the GL formula, the H-L and L-L trials had similar insulinemic responses during the 2-hr postprandial period, resulting in lower CHO oxidation during exercise than in the H-H trial. This was partly confirmed by the observed lower blood lactate concentrations during the preloaded 10-km TT in these two low-GL trials, which implied a lower rate of glycolysis.

As previously mentioned, the available research results on the effect of high-fat diets on endurance exercise are still equivocal (Cook & Haub, 2007). It has been reported that a high-fat dietary intake increased muscle triglyceride stores but reduced cycling TT performance compared with a high-CHO diet (Hargreaves, Hawley, & Jeukendrup, 2004). With endurance-trained individuals, however, enhanced endurance capacity was observed in a previous study despite low preexercise glycogen content (Lambert et al., 1994) after ingestion of the high-fat diet. Despite the similar glycemic and insulinemic responses between the two low-GL trials—L-L and H-L in the current study—the H-L meal consisted of much more fat availability (49% of total calories from dietary fat) as the fuel for exercise metabolism than the two high-CHO meals—H-H and L-L (20% of total calories from dietary fat). This might help explain the higher FFA and glycerol concentrations in the H-L trial and the increased fat oxidation in the two low-GL trials. This might be the most interesting finding of the current study: Despite the big difference in micronutrients in the two equally low-GL meals (L-L and H-L),
achieved by changing either the GI or the amount of the CHO by replacing CHO with fat, they both produced similar fat oxidation during exercise. In fact, some similar results have also been reported by Bosher et al. (2004), in which fat and CHO oxidation were not affected despite the significant difference in the concentrations of glucose, insulin, and FFA after resistance training when meals of different macronutrients were consumed.

Both H-H and L-L meals in the current study provided ~104.2 g of CHO; approximately 32.9 g and 28.6 g of CHO were used during the resting period, leaving ~71.3–73.6 g unoxidized CHO from the meals in the two high-CHO trials. The low-CHO trial—H-L—only provided 56.8 g CHO in the meal, so only ~29.1 g CHO was left. This amount of CHO might have been stored as muscle and liver glycogen before the commencement of exercise (Coyle, Coggan, Hemmert, Lowe, & Walters, 1985), whereas some undigested CHO might still be present in the gastrointestinal tract (Thorne et al., 1983) during the early part of the exercise. In addition, the total amounts of CHO oxidized in the low-GL trials—H-L and L-L—were found to be lower than that of the high-GL trial—H-H—during exercise. Therefore, it is reasonable to suggest that the remainder of CHO reserve might be higher in the L-L trial because of the sparing of CHO oxidation during exercise and the higher basal CHO reserve. Thus, it is not surprising that the well-maintained blood glucose concentrations were observed during the first hour of recovery in the L-L trial.

Figure 6 — Blood lactate concentrations (mmol/L) before, during, and after exercise high-glycemic-index/high-glycemic-load (H-H), low-glycemic-index/low-glycemic-load (L-L), and high-glycemic-index/low-glycemic-load (H-L) trials (N = 8, M ± SEM). a p < .05 from premeal. b p < .05 from H-L. c p < .05 from H-H.
The effect of the GI of a preexercise CHO meal on endurance performance has attracted considerable interest in recent years in the area of sports nutrition. Although many differences in metabolic responses have been shown after the ingestion of meals with different GI and GL, there were no differences in the preloaded 10-km TT running performance between trials. It is noteworthy that previous studies have investigated improvements in endurance capacity (TTE), and not exercise performance (TT), after a low-GI diet (DeMarco et al., 1999; Wu & Williams, 2006). It has been argued that the TTE measure is not sufficiently sensitive to detect treatment differences, if any, because endurance competitions often require athletes to complete a set amount of work in the least possible time (Doyle & Martinez, 1998). Consequently, the TT design of the current study was one that required the participants to complete a fixed-distance run in the shortest possible time, which is similar to an actual competitive situation (Doyle & Martinez). The inconsistency in the results might be a result of the difference in the timing of food ingestion, the quantity of CHO ingested, the type of exercise employed, and especially the performance measurement method. In studies that have shown improvements in exercise performance after the ingestion of a low-GI meal, a better maintained glucose concentration and an increased fat oxidation have been suggested to play important roles. Although increased fat oxidation was observed in the two low-GL trials, normal and stable glucose concentrations were present toward the end of exercise in all three trials.

Although no impairment in endurance performance was observed after ingestion of the low-CHO meal in the H-L trial as compared with that in the other two trials, additional fat supplementation is usually regarded as undesirable because endogenous fat stores are adequate (Jeukendrup, Thielen, Wagenmakers, Brouns, & Saris, 1998). In fact, increased abdominal discomfort was reported in the later stage of the 10-km TT in the H-L trial in the current study, which was probably caused by delayed gastric emptying because of the fat content.

We concluded that ingesting the mixed isocaloric meals with equal GL 2 hr before exercise produced similar glycemic and insulin responses regardless of the differences in GI and CHO content. Furthermore, the low-GL meal induced smaller metabolic changes during the postprandial period and during exercise and resulted in lower CHO oxidation during exercise. Nonetheless, a preexercise H-L meal might not be recommended because of the incidence of abdominal discomfort in the later stage of TT, although there was no difference in the preloaded 10-km-run performance between trials. Because of the absence of data on muscle glycogen concentration before exercise and glucose kinetics during the experiment process, it cannot be determined whether the difference in the physiological responses between trials was attributable to the preexercise basal muscle glycogen content or the glucose and FFA metabolism during the whole experimental process.

This is the first study to directly determine the role of preexercise GL on endurance exercise performance, but the concept of GL remains controversial, and the principles underlying it have not been recognized by any governmental or professional entity in any country. Although the estimated GL value is similar to the actual measured value in the current study, not all the foods tested have this good agreement, which implies that GL estimated from GI x available CHO might not be applicable to all foods in all portion sizes. If postprandial glycemia does not respond linearly with varying amounts of food, this suggests that testing the GI of
a food to calculate GL will not always provide a reliable estimate of GL (Venn et al., 2006). Thus, this is another major concern in future research on GL.

References


