

Metabolism and performance during extended high-intensity intermittent exercise after consumption of low- and high-glycaemic index pre-exercise meals

Christine B. Bennett¹, Philip D. Chilibeck², Trevor Barss², Hassanali Vatanparast², Albert Vandenberg³ and Gordon A. Zello^{1*}

¹College of Pharmacy and Nutrition, University of Saskatchewan, Saskatoon, SK, Canada

²College of Kinesiology, University of Saskatchewan, Saskatoon, SK, Canada

³Department of Plant Sciences, University of Saskatchewan, Saskatoon, SK, Canada

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Abstract

The metabolic and performance benefits of prior consumption of low-glycaemic index (GI) meals *v.* high-GI meals were determined in extended high-intensity intermittent exercise. Participants (ten males and four females, aged 25.8 (SD 7.3) years) completed two testing days (each consisting of back-to-back 90-min intermittent high-intensity treadmill running protocols separated by 3 h) spaced by at least 7 d. Using a randomised counterbalanced cross-over design, low-GI, lentil-based meals (GI about 42) or high-GI, potato-based meals (GI about 78) matched for energy value were consumed 2 h before, and within 1 h after, the first exercise session. Performance was measured by the distance covered during five 1-min sprints (separated by 2.5 min walking) at the end of each exercise session. Peak postprandial blood glucose was higher by 30.8% in the high-GI trial compared with the low-GI trial, as was insulin ($P=0.039$ and $P=0.003$, respectively). Carbohydrate oxidation was lower by 5.5% during the low-GI trials compared with the high-GI trials at the start of the first exercise session ($P<0.05$). Blood lactate was significantly higher (6.1 *v.* 2.6 mmol/l; $P=0.019$) and blood glucose significantly lower (4.8 *v.* 5.4 mmol/l; $P=0.039$) at the end of the second exercise session during the high-GI trial compared with the low-GI trial. Sprint distance was not significantly different between conditions. A low-GI meal improved the metabolic profile before and during extended high-intensity intermittent exercise, but did not affect performance. Improvements in metabolic responses when consuming low-GI meals before exercise may be beneficial to the long-term health of athletes.

Key words: Carbohydrates: Tournaments: Sports nutrition: Fatigue

Since carbohydrates (CHO) have been established as the most important dietary factor in athletic performance, research has focused on determining the optimal quality and timing of CHO intake. Glycaemic index (GI) of meals consumed before steady-state exercise has been previously evaluated^(1–6); however, the effects of pre-exercise meal GI on metabolism and performance during high-intensity intermittent intensity exercise has received far less consideration^(7–9).

In a recent review comparing meals of different GI consumed before exercise, we found that of twenty studies, seven demonstrated improved performance with low-GI pre-exercise meals, one demonstrated improved performance with high-GI pre-exercise meals, and twelve studies reported no difference between treatments⁽¹⁰⁾. Studies commonly show lower pre-exercise blood glucose and insulin response, and, as a consequence, lower CHO oxidation, higher fat oxidation and

reduced muscle glycogen utilisation during exercise following low-GI pre-exercise meals⁽¹⁰⁾. Low-GI pre-exercise meals result in the slow release of glucose into the blood throughout running, cycling and high-intensity intermittent exercise, potentially reducing the reliance on muscle glycogen later in exercise^(5,9–11). High rates of glycogenolysis during exercise increase production of lactate and deplete glycogen, both of which may lead to fatigue⁽⁸⁾. Low-GI pre-exercise meals result in a smaller increase in blood insulin levels above the pre-meal state⁽²⁾. A lower blood insulin level favourably alters substrate utilisation to increase fatty acid oxidation, reduce CHO oxidation, and sustain muscle glycogen during subsequent exercise^(1,5).

Field strategy sports, such as soccer, require a balance between endurance and sprinting ability. On average, adult elite midfield soccer players cover between 8 and 12 km in

Abbreviations: CHO, carbohydrate; GI, glycaemic index; RPE, rating of perceived exertion; V_{\max} , maximum treadmill velocity; $V_{O2\text{peak}}$, peak V_{O2} .

* **Corresponding author:** Dr Gordon Zello, fax +1 306 966 6377, email gordon.zello@usask.ca

one game through multiple high-intensity intermittent sprints punctuated by low- and moderate-intensity walking and jogging⁽¹²⁾. CHO demands are increased and muscle glycogen is depleted at a greater rate during intermittent high-intensity exercise⁽¹³⁾. We have recently investigated the effects of pre-exercise meal GI on a single simulated soccer game^(7,9). High-GI meals impaired fat oxidation⁽⁷⁾, and increased release of hormones that stimulate glycogenolysis, while low-GI meals resulted in a lower rating of perceived exertion (RPE) and tended to preserve glycogen to a greater degree during the soccer game⁽⁹⁾. Despite these greater metabolic benefits of the low-GI meal, no differences in performance after consuming low- *v.* high-GI meals were found^(7,9). Erith *et al.*⁽⁸⁾ evaluated the effects of high- and low-GI meals on recovery in a tournament setting performance over 2 d. Low- or high-GI meals were consumed over 24 h between two bouts of high-intensity intermittent exercise. No difference in performance was apparent between the low-GI trial and high-GI trial for the second bout; however, no pre-exercise meal was given before the second bout and it was performed in the fasted state. The authors suggested that while high-GI meals result in greater muscle glycogen replenishment after exercise, the low-GI recovery meals promote an up-regulation of fat oxidation during exercise, compensating for a lower muscle glycogen⁽⁸⁾.

No studies have evaluated exercise performance with repeated bouts of extended high-intensity intermittent exercise performed in a single day, as might be practised by field sport athletes during the pre-season. The protocol of the present experiment was designed to determine the effects of low- and high-GI pre-exercise meals on such extended intermittent exercise. Based on previous research findings, we propose that the greatest differences between low- and high-GI pre-exercise meals would be exposed during extended intermittent exercise due to extensive endurance challenges. To complete this objective, a single-blind, randomised and counterbalanced cross-over experiment was used. Based on the metabolic effects of low-GI meals and physiological demands of intermittent, high-intensity exercise, we hypothesised that consumption of low-GI meals would result in improved sprint performance, maintain higher blood glucose levels later in exercise performance, decrease CHO oxidation, and increase fatty acid oxidation in comparison with high-GI meals.

Methods

Participants

A total of twenty-two individuals were initially recruited to participate in the study. All were recreational soccer players. Of those recruited, five participants (four females, one male) withdrew from testing due to previous injuries exacerbated during the study and one female withdrew from the study after extensive fatigue during the treadmill familiarisation trial. Finally, two males withdrew from the study after severe leg muscle cramping during testing. Thus, ten males and four females completed the study protocol (Table 1). Subjects were included in the study based on: (a) appropriate response to the Physical Activity Readiness Questionnaire inquiring about health problems that

Table 1. Participant age, body weight, height, BMI, $V_{O_{2max}}$, maximum heart rate (HR_{max}) and maximum treadmill velocity (V_{max})* (Mean values and standard deviations)

Variable	Males (n 10)		Females (n 4)	
	Mean	SD	Mean	SD
Age (years)	27.2	8.0	22.5	4.4
Body weight (kg)	68.3	7.6	63.3	8.8
Height (cm)	174.8	2.0	169.5	5.1
BMI (kg/m ²)	22.2	1.6	21.9	1.8
$V_{O_{2max}}$ (ml/kg per min)	55.8	5.5	54.6	4.8
HR_{max} (bpm)	191	16	191	13
V_{max} (km/h)	17.0	1.9	16.3	1.0

bpm, Beats per min.

* For all parameters, mean values for the two sexes were not significantly different.

may be exacerbated by exercise⁽¹⁴⁾; (b) previous participation in competitive soccer or previous cardiovascular training involving running at intermittent intensities; (c) athletic ability to perform two consecutive 90-min high-intensity intermittent running simulations separated by a 3 h break, identified as a minimum relative peak V_{O_2} ($V_{O_{2peak}}$) of 45 and 50 ml/kg per min for females and males, respectively; and (d) healthy, non-diabetic, normo-insulinaemic response to CHO and exercise. The study procedure was approved by the University of Saskatchewan Biomedical Research Ethics Board. Written, fully informed consent was obtained from all subjects before participation.

Experimental design

The study protocol included five visits to the laboratory. The first three visits consisted of a $V_{O_{2peak}}$ test, treadmill familiarisation and meal familiarisation. After initial testing and familiarisation, participants completed two experimental trials separated by at least 7 d in a randomised counterbalanced cross-over design. Each trial involved performance of two back-to-back high-intensity intermittent exercise sessions, separated by 3 h. Subjects received either a low-GI meal or an isoenergetic, high-GI meal 2 h before each high-intensity intermittent session. Experimenters measuring performance were unaware of the test meals consumed on that day. Participants were not informed of the study hypothesis.

Expired gas samples were collected during the exercise sessions to determine CHO and fat oxidation. Fingertip blood samples were collected to determine blood concentrations of glucose and lactate. A subsample of ten participants (seven males and three females) provided venous blood samples for assessment of serum insulin and NEFA. The subsample was ascertained by access to a trained phlebotomist. Performance was assessed during the last 15 min of each exercise session by the maximal distance covered during five 1-min sprints, each separated by 2.5 min of walking^(7,9).

Preliminary testing

On initial visit to the laboratory, participants completed an incremental speed treadmill run to determine $V_{O_{2peak}}$ and

maximum treadmill velocity (V_{max}) as previously described by Harling *et al.*⁽¹⁵⁾. After a 5-min warm-up, subjects began the test running at 10 km/h and increased speed at 1 km/h until volitional fatigue. Throughout testing, V_{O_2} was measured by open-circuit indirect calorimetry (Vmax Series 29; SensorMedics). Heart rate was measured continuously using a Polar 610i heart rate monitor (Polar Electro Oy). $V_{O_{2peak}}$ was calculated as the highest 10 s mean for V_{O_2} and maximum heart rate was calculated using the highest 5 s mean. Each subject's peak V_{max} was taken as the highest treadmill speed maintained for 1 min⁽¹⁵⁾.

At least 7 d after the initial visit, participants performed a familiarisation trial on a treadmill. The familiarisation trial was established to practise a single session of high-intensity intermittent running that was informed by a study of the activity pattern common to soccer (see detailed description in the High-intensity intermittent exercise sessions section). A meal familiarisation, completed at least 7 d before experimental testing, was used to introduce lentils (i.e. low-GI meal) to the diet before trial testing and to ensure that participants could consume the meal.

Experimental meal conditions

The low-GI, lentil-based meal (estimated $GI_{glucose}$ about 36, determined glycaemic-response_{whitebread} = 46) was comprised of red lentils (SaskCan Pulse Trading), Saskatoon berries (Moonlake Saskatoon Berry Farm) and liquid honey (Laprell's Beehive Products). These ingredients were chosen because of their low GI and to improve palatability and compliance. The present study is part of a larger programme of research that is examining the effects of lentils on exercise performance with the end goal of developing prepackaged foods containing lentils as the main ingredient. The addition of honey and Saskatoon berries was intended to simulate ingredients that might go into these prepackaged foods (for example, energy bars). The low-GI pre-exercise meal was developed to supply 1.5 g/kg body weight of available CHO based on the recommended amount for optimising subsequent endurance exercise performance⁽¹⁶⁾. The high-GI meal was matched as closely as possible for available CHO (i.e. 1.5 g/kg; Table 2). The high-GI potato-based

meal (estimated $GI_{glucose}$ = 76, $GI_{whitebread}$ = 114; Table 2) was based on instant mashed potatoes (Idahoan Instant Mashed Potatoes; Idahoan Foods LLC) and white bread (Safeway White Bread Texas Toast; Canada Safeway Limited). A second interim meal, with the exact composition of the first meal, was consumed within 1 h of completing the first session. The portions of the interim meal were provided based on recommendations of 30 g CHO to be consumed for every 1 h of endurance activity (1.5 h × 30 g CHO) to replace any CHO losses during the first session and provided 2.0 g CHO/kg body weight, as recommended CHO for upcoming exercise⁽¹⁶⁾.

The GI of the meals was determined during a pilot study using the methodology described by Jenkins *et al.*⁽¹⁷⁾ and calculated using the area under the blood glucose response curve described by Wolever & Jenkins⁽¹⁸⁾. The GI of both meals was calculated using values from Foster-Powell *et al.*⁽¹⁹⁾ and the weighted average method described by Wolever *et al.*⁽²⁰⁾. The energy content of the two meals was computed using Canadian Nutrient File⁽²¹⁾ data and United States Department of Agriculture nutrient intakes from food⁽²²⁾.

High-intensity intermittent exercise sessions

The extended high-intensity intermittent exercise protocol was informed by a study of the activity pattern common to soccer games⁽²³⁾ which has been used by our research group^(7,9). The protocol consisted of two 90-min high-intensity intermittent exercise sessions separated by a 3 h break. The two sessions, exactly analogous to each other, each consisted of two 45-min halves. A 15-min intermittent treadmill speed protocol was repeated three times to simulate the first 45 min half of a soccer game. After a 15-min 'half-time' break, participants completed a second 45 min half comprised of two more 15-min intermittent treadmill protocols followed by 15 min of performance testing. The simulation provides intervals of time at different exercise intensities performed by high-level soccer mid-fielders: 7% standing, 56% walking, 30% jogging, 4% running, and 3% sprinting. The treadmill speeds of exercise intensity were customised for each participant, based on the V_{max} reached during their incremental $V_{O_{2peak}}$ test. A primary goal of the full-day, repeated high-intensity intermittent exercise sessions was to induce the high levels of fatigue and muscle glycogen depletion observed during extended intermittent exercise. For six of the fourteen participants, the second exercise session was reduced in speed by 0.5 km/h for the walking and jogging speeds and by 1.0 km/h for the running and sprinting speeds as these participants exhibited extensive fatigue during the first exercise session. The performance measure was distance travelled over five 1-min sprints each separated by a 2.5-min break during the last 15 min of each exercise session, with the goal of placing a significant demand on glycogenolysis. Sprints were pre-empted by walking at an easy pace, treadmill speed was increased continuously by research personnel to reach V_{max} , at which point the timer was started for 1 min. The subject was allowed to adjust the speed of the treadmill by verbally instructing a researcher to increase or decrease the speed. The participants were kept blind to the speed and distance

Table 2. Test meal characteristics for a 70 kg participant*

	Low-GI meal	High-GI meal
Description	444 g red lentils, 24 g honey, 156 g Saskatoon berries (620 g total)	303 g instant mashed potatoes, 133 g white bread (436 g total)
Energy		
kcal	646	646
kJ	2703	2703
CHO (g)	105	92
Fat (g)	3	13
Protein (g)	36	16
Fibre (g)	24	7
GI†	36	75

GI, glycaemic index; CHO, available carbohydrates.

*Macronutrient breakdowns for each meal were calculated using manufacturers' information and cross-referenced with Canadian Nutrient File data⁽²¹⁾.

†GI calculated according to Wolever & Jenkins⁽¹⁸⁾ using GI values from Foster-Powell *et al.*⁽¹⁹⁾.

during the sprints but were allowed to see the elapsed time. A researcher informed the participant after 15, 30, 45 and 50 s and counted down the last 5 s of each sprint. The treadmill was stopped at the end of each sprint and the subject stood still for 15 s and then walked at 5 km/h for 2.5 min before the speed was increased again for the next sprint. Pilot testing indicated that participants were generally able to complete 1-min sprints at a speed slightly above their V_{\max} , making individual V_{\max} an ideal speed for standardising the start of the sprints. Performance was determined by the distance covered over the five sprints. We have previously shown that this performance measure has good reproducibility, with a CV of 3.3% for tests that were repeated 1 week apart⁽⁷⁾.

Study day protocol

Both trials were conducted using the same treadmill (model 13622; Vacu Med). Subjects arrived at the exercise laboratory between 06.00 and 07.00 hours after a 12 h fast. Baseline measurements of capillary blood glucose and blood lactate were obtained from a fingertip immediately using commercial meters (AccuCheck Compact Plus and Accutrend GC; Roche Diagnostics). Gastrointestinal symptoms were determined using a five-point scale with word anchors (0 = no symptoms, 1 = mild symptoms, 2 = moderate symptoms, 3 = moderately severe symptoms and 4 = severe symptoms). Subjects then consumed the test meal. Capillary blood samples were again taken postprandially at 15, 30, 60, 90 and 120 min and gastrointestinal symptoms were measured at 60 and 120 min after meal consumption. A venous blood sample was obtained from the median cubital vein by venepuncture 120 min after the test meal was consumed. Subjects were then fitted with a heart rate monitor and completed a 5-min running warm-up on the treadmill at 8 km/h followed by 3 min of stretching. Subjects then completed part 1 of exercise session 1, a 45-min simulation (0 to 45 min), followed by a 15-min break (45 to 60 min), and then part 2 of exercise session 1, which included another 30-min simulation (60 to 90 min). For the last 15 min of the first exercise session (90 to 105 min), subjects completed five 1-min maximal sprints separated by 2.5 min rest periods to determine performance at the end of the session.

After the first high-intensity intermittent exercise session was over, subjects were given 1 h (105 to 165 min) to consume a second test meal of identical composition to the first meal. Subjects then rested for 2 h (165 to 285 min). Before the start of the second high-intensity intermittent exercise session, capillary blood glucose and lactate, a venous blood sample and gastrointestinal symptoms were taken. Subjects were again fitted with a heart rate monitor and provided 5 min of running warm up and 3 min of stretching. A second high-intensity intermittent exercise session was then completed following the identical protocol as the first exercise session.

During both exercise sessions, capillary blood glucose and lactate were measured at 15, 45, 90 and 105 min. Venous blood samples were taken at 45 and 105 min in addition to baseline. Breath-by-breath analysis of carbon dioxide production (V_{CO_2}) and V_{O_2} , and heart rate were recorded at 3 to 10 min, 33 to 40 min, and 63 to 70 min during each exercise

session. Gastrointestinal symptoms were determined using a five-point scale, between 0 (no symptoms) to 4 (severe), and were measured at the capillary blood sample intervals. Last, RPE was measured every 15 min throughout each exercise session (15, 30, 45, 75, 90 and 105 min) using the Borg fifteen-point scale (i.e. 6 to 20, where 6 corresponds to very, very easy, and 19 corresponds to very, very hard)⁽²⁴⁾.

Blood and respiratory sample analysis

A trained phlebotomist performed all venous blood sampling using 10 ml tubes (BD Vacutainer SST). Samples were treated as per the manufacturer's directions and stored at -70°C . Insulin values were determined using an ELISA according to the manufacturer's directions (Insulin EIA; Alpco Diagnostics). The serum NEFA assay was performed in duplicate using a protocol with an oleic acid standard solution and a ninety-six-well plate as per the manufacturer's directions (NEFA-HR(2); Wako Diagnostics). The CV for the insulin and NEFA assays were $\leq 10\%$.

Expired gas samples were collected for 7-min segments during the first, third and fifth 15-min segment of high-intensity intermittent exercise sessions. V_{O_2} , carbon dioxide output (V_{CO_2}) and RER were measured breath-by-breath using open-circuit indirect calorimetry (Vmax Series 29; Sensor Medics). CHO and fat oxidation rates were based on calculations by Jeukendrup & Wallis for moderate to high-intensity exercise⁽²⁵⁾.

Dietary and physical activity controls

Subjects completed a detailed 48 h activity and dietary intake record before the first trial day and duplicated their activity and food intake for the second trial day. Subjects were asked to abstain from strenuous physical activity during the 24 h before a trial. During the trials, subjects were not allowed to consume foods other than those provided for the study. Water was provided throughout the first trial *ad libitum* and intake was duplicated as closely as possible for the second trial day.

Statistics

All statistical analyses were performed using SPSS for Windows software (version 14.0; SPSS, Inc.). A three-factor ANOVA with one between-groups factor for sex and two repeated measures (treatment and time) was used to assess differences in blood glucose, blood lactate, RER, CHO oxidation, fat oxidation, heart rate, expired gases, serum insulin, serum NEFA, RPE and sprint performance. Baseline levels for blood glucose and blood lactate between the two treatments were compared using a paired *t* test. Outliers were excluded when values fell more than 2 SD away from the mean value. Where significance was noted, a least significant difference *post hoc* test was used to determine where significant differences existed. Level of significance was set at $P \leq 0.05$. All results are reported as mean values and standard deviations.

Results

For all results with the exception of NEFA, no significant sex \times treatment or sex \times treatment \times time interactions were found, so all remaining analyses were carried out with men and women combined.

Blood sample analysis

Baseline blood glucose was not different at the start of the low-GI and high-GI trials ($P = 0.67$). Blood glucose showed a treatment \times time interaction ($P < 0.001$, $n = 14$; Fig. 1). *Post hoc* analysis showed that blood glucose was significantly higher in the high-GI trial compared with the low-GI trial during the postprandial period at 30, 60 and 90 min. Blood glucose was significantly higher during the low-GI trial, in comparison with the high-GI trial, at 375 min, near the end of the second high-intensity intermittent exercise session, just before the second set of sprints. In our subject group where serum insulin was obtained, a treatment \times time interaction for serum insulin values was evident ($P = 0.003$, $n = 9$; Fig. 2). Insulin levels for the high-GI trial were significantly higher than for the low-GI trial before beginning the first high-intensity intermittent exercise session (*post hoc* analysis; $P = 0.001$). Values for one participant were excluded as four of six samples fell outside 2 SD from the group mean.

Baseline blood lactate did not vary between treatments ($P = 0.93$). A treatment \times time interaction was noted for blood lactate levels ($P = 0.019$, $n = 12$; Fig. 3). *Post hoc* analysis showed that the low-GI meal elicited a significantly higher lactate response in comparison with the high-GI meal during the postprandial period at 30 and 60 min. In contrast, blood lactate was higher near the end of the second high-intensity intermittent exercise session, before the second set of sprints (at 375 min) for the high-GI meal. A sex \times treatment \times time interaction ($P = 0.025$) existed for NEFA. For the last time point (i.e. after sprints at the end of the second exercise session) females on the high-GI treatment had higher NEFA than on the low-GI treatment ($P < 0.001$; Fig. 4).

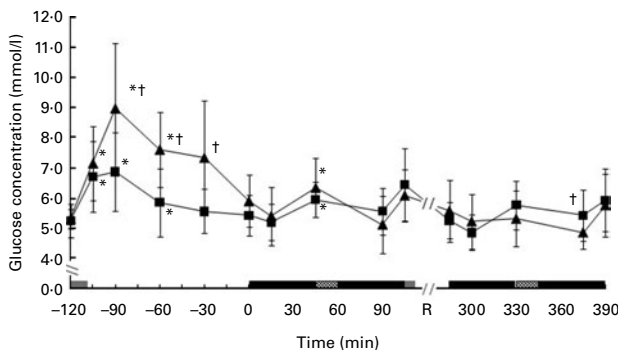


Fig. 1. Blood glucose concentration v. time, at: baseline (-120 min), postprandially (-105 to 0 min) and during exercise (0 to 105 min; 285 to 390 min; ■) with the ingestion of high-glycaemic index (HGI; $-\triangle-$) and low-glycaemic index (LGI; $-\square-$) meals (■). Values are means ($n = 14$), with standard deviations represented by vertical bars. Time R represents a 3 h rest (□). * Mean value was significantly different from that at baseline (-120 min) ($P < 0.05$). † Mean value was significantly different for the LGI condition compared with the HGI condition ($P < 0.05$). (■), Half-time.

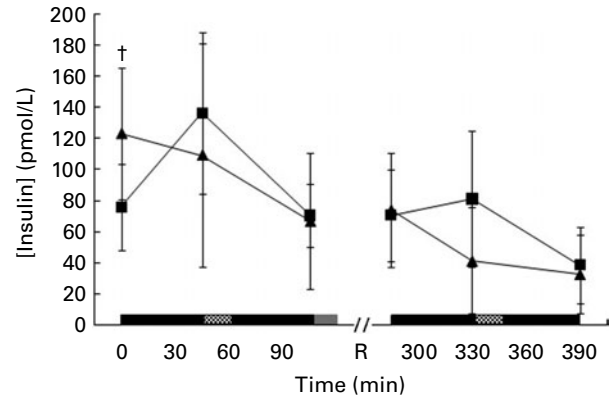


Fig. 2. Serum insulin concentrations v. time before (0 , 285 min), at half-time (45 , 330 min; ■) and after (105 , 390 min) each exercise session (■) with the ingestion of high-glycaemic index (HGI; $-\triangle-$) and low-glycaemic index (LGI; $-\square-$) meals (■). Values are means ($n = 9$), with standard deviations represented by vertical bars. Time R represents a 3 h rest (□). † Mean value was significantly different for the LGI condition compared with the HGI condition ($P < 0.05$).

Substrate oxidation

A treatment \times time interaction for CHO oxidation was evident ($P = 0.039$, $n = 14$; Fig. 5). The high-GI trial elicited a significantly higher CHO oxidation from 3 to 10 min of the first high-intensity intermittent exercise session. Fat oxidation rates increased over time during both trial days ($P < 0.001$, $n = 12$; Fig. 6) with no difference between high- and low-GI conditions. No treatment \times time interaction was evident for the RER in the trials (high-GI = 0.96 (SD 0.02), low-GI = 0.95 (SD 0.03); $P = 0.28$, $n = 14$). The RER did decrease over time in both trials ($P < 0.001$; data not shown).

Sprint performance, rating of perceived exertion and heart rate

Sprint performance (i.e. group mean distance of all five sprints) at the end of each high-intensity intermittent exercise session

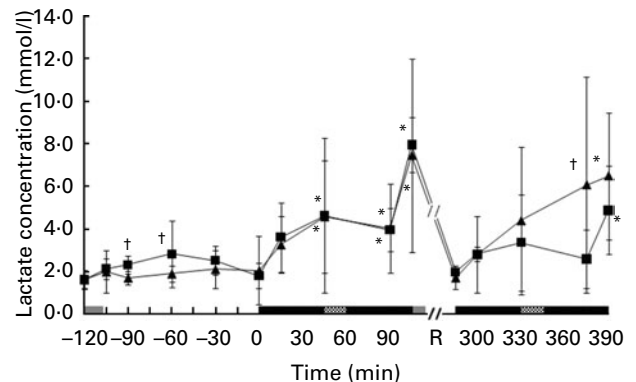


Fig. 3. Blood lactate concentration v. time at: baseline (-120 min), postprandially (30 to 120 min) and during exercise (0 to 105 min; 285 to 390 min; ■) with the ingestion of high-glycaemic index (HGI; $-\triangle-$) and low-glycaemic index (LGI; $-\square-$) meals (■). Values are means ($n = 12$), with standard deviations represented by vertical bars. Time R represents a 3 h rest (□). * Mean value was significantly different from that at baseline (-120 min) ($P < 0.05$). † Mean value was significantly different for the LGI condition compared with the HGI condition ($P < 0.05$). (■), Half-time.

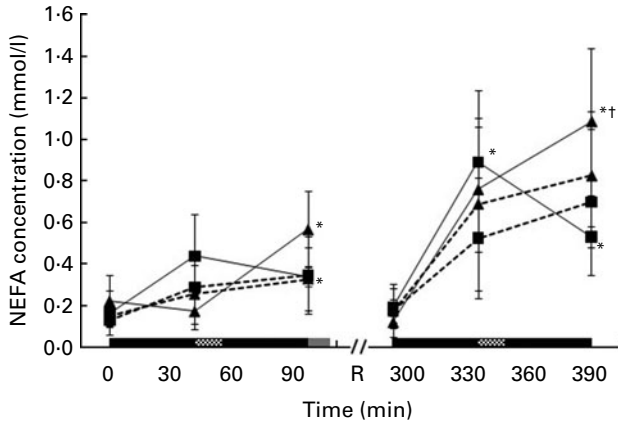


Fig. 4. Serum NEFA concentrations *v.* time, collected before (0, 285 min), at half-time (45, 330 min; ■) and after (105, 390 min) each exercise session (■) with the ingestion of high-glycaemic index (HGI) meals in males (---▲---) and in females (---▲---) and low-glycaemic index (LGI) meals in males (---■---) and females (---■---). Values are means (*n* 10), with standard deviations represented by vertical bars. Time R represents a 3 h rest (□). * Mean value was significantly different from that at time 0 ($P < 0.05$). † Mean value was significantly different for the LGI condition compared with the HGI condition in females ($P < 0.05$).

was not significantly affected by the GI of the pre-exercise test meal (low-GI exercise session 1 total distance = 1328 (SD 141) m; high-GI exercise session 1 total distance = 1333 (SD 100) m; low-GI exercise session 2 total distance = 1283 (SD 128) m; high-GI exercise session 2 total distance = 1303 (SD 210) m; $P = 0.27$). A main effect for time ($P < 0.001$) was observed at the end of the second exercise session, with the distance covered during the third, fourth and fifth sprints lower than for the other sprints.

RPE data collected throughout both trials showed a significant time main effect, increasing over time during both high-intensity intermittent exercise sessions ($P < 0.001$; data not

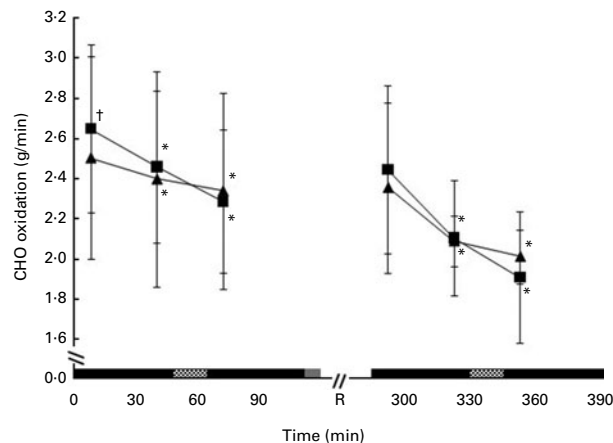


Fig. 5. Average rate of carbohydrate (CHO) oxidation *v.* time, from gas collected for 7-min periods at the beginning (3 to 10 min) before half-time (■) (33 to 40 min) and after half-time (63 to 70 min) for each exercise session (■) after ingestion of high-glycaemic index (HGI; ---■---) and low-glycaemic index (LGI; ---▲---) meals (■). Values are means (*n* 14), with standard deviations represented by vertical bars. Time R represents a 3 h rest (□). * Mean value was significantly different from that at time 1 ($P < 0.05$). † Mean value was significantly different for the LGI condition compared with the HGI condition ($P < 0.05$).

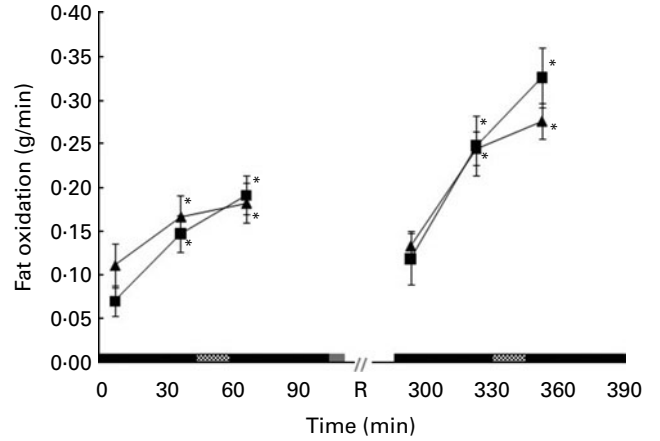


Fig. 6. Average rate of fat oxidation *v.* time, from gas collected for 7-min periods at the beginning (3 to 10 min) before half-time (■) (33 to 40 min) and after half-time (63 to 70 min) for each exercise session (■) after ingestion of high-glycaemic index (HGI; ---■---) and low-glycaemic index (LGI; ---▲---) meals (■). Values are means (*n* 14), with standard deviations represented by vertical bars. Time R represents a 3 h rest (□). * Mean value was significantly different from that at time point 1 (3 to 10 min) ($P < 0.05$).

shown). The peak response for RPE, recorded at the end of the second session sprints, was 17.4 (SD 0.6) and 17.7 (SD 0.5) for the high- and low-GI trials, respectively, indicating that the exercise was rated between ‘very hard’ and ‘very, very hard’. RPE was not influenced by meal GI, with a mean response of 14.1 (SD 0.3) and 14.2 (SD 0.3) for the high- and low-GI trials, respectively ($P = 0.867$). There were no significant differences in heart rate between trials or over time (data not shown).

Gastrointestinal symptoms rating scale and water consumption

Baseline ratings of fullness, hunger, bloating, nausea and abdominal cramps were similar between both trials ($P = 0.44$). After meal consumption, perceived hunger was significantly lower during the low-GI trial compared with the high-GI trial (low-GI exercise session 1 average = 0.7; high-GI exercise session 1 average = 1.5; low-GI exercise session 2 average = 0.6; high-GI exercise session 2 average = 1.8; $P < 0.001$). Ratings of fullness were significantly higher during the low-GI trial *v.* the high-GI trial (low-GI exercise session 1 average = 2.4; high-GI exercise session 1 average = 1.6; low-GI exercise session 2 average = 2.5; high-GI exercise session 2 average = 1.44; $P < 0.001$). Adverse symptoms of bloating, nausea and abdominal cramps were not significantly different over time or between the treatments ($P = 0.182$, $P = 0.483$ and $P = 0.813$, respectively). Participants most often reported no symptoms (0 on a scale of 0 (no symptoms) to 4 (severe)). Participants consumed an average of 4000 (SD 400) ml of water during exercise on each trial day.

Discussion

Low-GI meals convey slightly better glycaemic control, lower blood lactate at the end of exercise, lower pre-exercise blood insulin and lower CHO oxidation early in exercise (Figs. 1, 2, 3 and 5). Performance outcomes, measured by distance

travelled in five 1-min repeated sprints at the end of each exercise session, were not different between treatments.

Blood glucose and insulin responses

The low-GI meal resulted in a decreased blood glucose response during the postprandial period in comparison with the high-GI meal, as would be expected based on previous results and the theoretical basis for GI⁽¹⁷⁾. Commonly, blood glucose during exercise is maintained and is not affected by varying treatments, although higher blood glucose levels at the end of exercise have been observed in one case employing a low-GI meal⁽²⁶⁾. The digestion rate of lentils contributes to sustained blood glucose levels throughout exercise⁽²⁷⁾. Thus, such results may be beneficial to offset the effects of reduced muscle glycogen at the end of exercise⁽²⁸⁾; however, the reduction in blood glucose at the end of exercise during the high-GI trial may be due to reductions in muscle glycogen, as exercising muscles increase uptake of blood glucose when endogenous stores are low^(26,29).

Serum insulin showed divergent profiles during each exercise trial. While insulin at the beginning of the high-GI trial was significantly higher than for the low-GI trial at the start of exercise, the low-GI meal elicited a delayed (non-significant) spike to a similar level at the first half-time break. This result may be expected due to continual absorption of blood glucose after the low-GI meal; resulting in slower increases in blood glucose to trigger insulin release⁽³⁾. After the start of exercise, differences in serum insulin were not present due to the pre-exercise meal; however, overall levels did decrease over the time course of the exercise sessions. No significant differences were evident for most NEFA levels and fat oxidation, between the trials, despite significantly higher insulin before exercise in the high-GI condition. The only exception was a higher NEFA in females during the high- *v.* low-GI treatment at the end of the second exercise session. This result is surprising based on previous studies identifying higher CHO oxidation and lower NEFA and fat oxidation during exercise following high-GI pre-exercise meals. These studies indicate that increases in insulin have long-lasting effects to decrease NEFA and fat oxidation after insulin levels have returned to baseline levels^(30,31).

Substrate utilisation

CHO oxidation rates were significantly higher at the beginning of the high-GI trial in comparison with the low-GI trial in the first exercise session (Fig. 5). Higher CHO oxidation in the first exercise session may have led to lower glucose observed in the second exercise session (Fig. 1)⁽²⁹⁾. Previously, high-GI, high-CHO diets have been reported to increase CHO oxidation^(1,3,5,32), and increase glycogen depletion throughout exercise, compared with low-GI meals, in most cases^(10,32). Although muscle glycogen was not measured in the present study, comparable reductions in blood glucose and CHO oxidation correspond to depletions of muscle glycogen observed in previous studies⁽³²⁾. Of CHO oxidised, 80% is provided from muscle glycogen and

the remaining 20% is provided from blood glucose and liver glycogen during exercise⁽³³⁾. Thus, the higher levels of blood glucose at the end of the second session during the low-GI trial may be explained as a byproduct of higher muscle glycogen available during the same time point in comparison with the high-GI trial. In our previous study of a single simulated soccer game, a low-GI trial resulted in a muscle glycogen level near the end of the game that was higher than control values (i.e. a 'fasted condition'), but not statistically different from a high-GI condition⁽⁹⁾.

In principle, increased mobilisation of NEFA during exercise will lead to an increased rate of fat oxidation during exercise⁽³⁴⁾. Previous investigations have found either higher serum NEFA during low-GI trials^(1,2,32) or no difference^(3,5,26,35). Similarly, fat oxidation rates have not varied between high- and low-GI pre-exercise meals in several studies^(1,2,5,26). Comparable RER data also demonstrate no greater reliance on fat oxidation during the low-GI trials. Similar RER between low- and high-GI trials have also been previously observed^(7,9,35). In the present study, the observed similarity in fat oxidation during exercise can be explained by the high intensity and duration of the intermittent soccer simulation protocol. Mobilisation of NEFA is suppressed during high-intensity exercise above 70–80% of $V_{O_{2max}}$ ⁽³⁶⁾. Similarly, sustained intermittent exercise results in a three-fold reduction in fat oxidation rates and elevations in CHO oxidation when compared with continuous submaximal exercise of the same workload⁽³⁷⁾. Females in the present study had increased NEFA after the sprints at the end of the second exercise session during the high-GI trials compared with the low-GI trials. A greater mobilisation of NEFA from adipose tissue in the high-GI condition at the end of the second sprints may be due to greater glycogen depletion in the high-GI condition.

Lactate production

Lactate production during the postprandial period of the low-GI trial was significantly higher than during the high-GI trial. Such an induction of postprandial lactate with low-GI meals has been reported previously⁽³⁸⁾. Postprandial lactate production is observed with meals high in fructose. The low-GI meal was comprised of lentils, which are low in fructose, but also integrated honey and Saskatoon berries. The fructose fraction of CHO in honey and Saskatoon berries is approximately 50%^(21,39). In comparison, potatoes contain only small amounts of fructose. The major metabolic pathway for fructose occurs hepatically, producing fructose-1-phosphate to be further metabolised to both glucose and lactate⁽⁴⁰⁾. A transient increase in elevated postprandial lactate during the low-GI trial is probably due to the relative increase in fructose content of the pre-exercise meal.

Lactate levels during the first high-intensity intermittent exercise session were similar between the two pre-exercise meals, but in the second exercise session rose significantly higher with the high-GI meal than with the low-GI meal condition. Accordingly, mean blood lactate levels during the first and second low-GI exercise sessions were 4.4 and 3.2 mmol/l, respectively, while during the high-GI exercise sessions levels

stayed at 4.3 mmol/l throughout both. Previous research on pre-exercise meal GI during steady-state cycling and running has shown similar reductions in blood lactate with low-GI trials^(1,3,32). Increased lactate accumulation may suggest higher muscle glycogen depletion during exercise⁽³²⁾.

Performance

Although pre-exercise low-GI meals have caused alterations in substrate oxidation and conferred performance benefits^(1,5,10,26), the present study found no differences in performance between the high-GI and low-GI pre-exercise meals. This result may have been expected, as twelve of twenty recently reviewed studies showed no direct differences between low-GI and high-GI pre-exercise meals⁽¹⁰⁾. Similarly, two previous studies in our laboratory, using the same high-intensity intermittent protocol to simulate a single soccer game, have demonstrated greater performance gains from low- and high-GI pre-exercise meals compared with a control trial (i.e. fasted state), with no differences between low- and high-GI meal conditions^(7,9). In both instances, fat oxidation was not significantly different between high-GI and low-GI conditions. A pre-exercise meal rich in CHO provides sufficient exogenous substrate to enhance performance and slow muscle glycogen depletion during exercise^(7,9). Although the two meals in the present study were significantly different in digestive and absorptive properties, the near-equal CHO content of the meals was enough to meet requirements to affect performance equally⁽¹⁶⁾. The present data provide further evidence that high-GI meals may not be necessary to achieve maximal performance.

Performance similarities between trials in the present study may be due to the high intensity and duration of the exercise protocol which differ when compared with previous studies and resulted in high levels of participant fatigue. The RPE reported by participants was high during both trials, approximately 17 on a scale of 6 to 20, or 'very hard'⁽²⁴⁾. Erith *et al.*⁽⁸⁾ reported no significant difference in performance between low- and high-GI recovery meals. In their study they suggest that high-GI recovery meals may increase muscle glycogen deposits to a greater extent after an initial bout of exercise, but high-GI meals may also stimulate greater muscle glycogen utilisation during a second bout of exercise, cancelling out any beneficial effect. Accumulation of metabolites (hydrogen ions, ADP, AMP, inorganic phosphate, etc.) was also purported as a contributor to the fatigue present in both low- and high-GI treatments⁽⁸⁾. Our exercise protocol instigated a decrease in CHO oxidation and increased fat oxidation over the course of both trials. While nutrition is an important factor to consider in preserving performance, this protocol may have induced muscular fatigue that could not be overcome by nutritional intervention.

As suggested by Erith *et al.*⁽⁸⁾, one advantage of consuming high-GI CHO after exercise is that it would theoretically enhance glycogen resynthesis compared with low-GI CHO. This was true in one study⁽⁴¹⁾; however, others have shown that the rate of glycogen resynthesis after exercise is similar when high-GI CHO consumption is compared with low-GI CHO consumption⁽⁴²⁾. If high-GI meals provided a benefit of

faster glycogen repletion, one would expect a performance benefit in subsequent (i.e. next-day) exercise performance; however, this is not the case. Two studies have evaluated next-day exercise performance after glycogen-depleting exercise (90 min of running) and either a high- or low-GI post-exercise diet (22 h), with one showing a benefit in next-day performance (running time to exhaustion at 70% V_{O2max}) for the low-GI diet compared with the high-GI diet⁽⁴⁾ and one showing no difference in next-day performance (75 min shuttle run followed by sprinting/jogging to fatigue) between diet conditions⁽⁸⁾.

Limitations and future research

Due to the nature of the experimental protocol (for example, extended high-intensity physical activity), the present investigation has some limitations. The high-intensity intermittent exercise sessions separated by a 3 h break induced high levels of fatigue. While most of the participants executed both exercise sessions at the same intensity, reducing the intensity of the second exercise session was necessary for some to ensure that they were able to maintain adequate running technique to avoid injury. Time–motion analysis of field hockey players shows reduced speed and greater time spent standing and running, compared with walking, jogging and sprinting, in subsequent games during international tournament play, so reducing the intensity of the second exercise session fell within externally valid criteria⁽⁴³⁾.

Female subjects were not required to report the stage of menses during the study although substrate metabolism is influenced by menstrual hormone cycles. Substrate metabolism is similar between males and females at moderate to high-intensity exercise when accounting for aerobic fitness between the sexes⁽⁴⁴⁾. Variation in substrate metabolism at different stages of the menstrual cycle are not greater than the differences observed between the sexes⁽⁴⁵⁾. With minimal significant differences noted between the sexes during statistical analysis, the higher exercise intensity and duration in the present protocol probably outweigh any metabolic differences between the sexes.

The test meals were not matched for macronutrient content, but CHO intake. While the low-GI meal delivered 71, 22 and 4% CHO, protein and fat, the high-GI meal delivered 71, 11 and 18%, respectively. This difference was unavoidable, as the study was designed to test whole foods and not individual macronutrient components. While the meals represent some limitations regarding the application to traditional North American breakfast consumption, many other populations, who participate in soccer, consume lentils and legumes (for example, dhal) for breakfast meals. Certainly, the increase in fat content of the high-GI meal could have resulted in increased fat oxidation during the trial⁽⁴⁶⁾, although differences between the two meals were not shown in the present study. Future studies need to replicate practices of elite soccer players by including provision of energy during and at half-time during the simulation. The most convenient would be to provide energy drinks and consumption of this type of high-GI beverage has been shown to negate the effects of pre-exercise meals

of different GI on metabolism during continuous endurance cycling⁽³⁵⁾. Alternatively, one could provide a small amount of high- or low-GI food at half-time, and we have previously shown that metabolism during exercise is affected by half-time feeding of foods of different GI⁽⁷⁾. Another limitation of the present study was that we did not assess muscle glycogen levels. Muscle glycogen synthesis during the low-GI trial may have been accelerated due to the increased protein content⁽⁴⁷⁾.

For the most part, our measures of blood metabolites (i.e. NEFA, lactate, glucose) showed little difference during the high-intensity intermittent exercise sessions between the different GI conditions. Changes in blood metabolites may be very subtle and our measurements may have lacked appropriate precision to detect differences.

The sprint protocol we chose for the assessment of performance (i.e. five 1-min sprints) has good reproducibility⁽⁷⁾ and was used to induce high rates of glycogenolysis; however, it does not match the type of performance of athletes such as soccer players who would perform sprints of much shorter duration. Better tests for assessing soccer player performance include performing the Drust protocol⁽²³⁾ on a non-motorised treadmill where power output could be measured during the sprints, the Longborough Intermittent Shuttle Run Test⁽⁸⁾, or other soccer-specific tests that include dribbling, heading, agility and shooting⁽⁴⁸⁾.

Conclusion

In summary, these data show that extended high-intensity intermittent exercise metabolism was altered to a small extent by changes to the GI of pre-exercise meals, although changes in exercise performance were not observed. Metabolic changes with low-GI meals included increased blood glucose and decreased lactate production late in exercise, and reduced insulin and CHO oxidation at the beginning of a simulated soccer tournament. The changes observed in the present study are similar to those seen in previous research utilising steady-state exercise protocols. During extended high-intensity intermittent exercise, low-GI meals may confer a small metabolic advantage in comparison with high-GI pre-exercise meals. Therefore, athletes can be comfortable in selecting high-quality, nutrient-rich CHO sources, such as lentils before exercise, to achieve optimal performance. Future research could include the testing of low-GI packaged foods (i.e. energy bars), provision of energy in the form of food or beverages during half-time of simulated soccer matches, and use of sport-specific performance testing to evaluate the effects of the GI.

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