Effects of Moderate and High Glycemic Index Meals on Metabolism and Exercise Performance

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The purpose of this study was to determine whether pre-exercise ingestion of meals with moderate and high glycemic indexes (GI) affects glucose availability during exercise and exercise performance time. Six male volunteers (22 ± 1 years; 80.4 ± 3.7 kg; Vo_{2peak}, 54.3 ± 1.2 ml · kg^{-1} · min^{-1}) ingested 75 g of carbohydrate in the form of 2 different breakfast cereals, rolled oats (moderate GI, ~61; MOD-GI) or puffed rice (high GI, ~82; HI-GI), combined with 300 mL of water; or water alone (control). The trials were randomized ,and the meals were ingested 45 minutes before the subjects performed cycling exercise (60% Vo_{2peak}) to exhaustion. Venous blood samples were drawn to measure glucose, free fatty acids (FFAs), glycerol, insulin (INS), epinephrine (EPI) and norepinephrine (NE) concentrations. A muscle biopsy specimen was obtained from the vastus lateralis before the meal and immediately after exercise for glycogen determination. Before exercise, both test meals elicited significant ($P < .05$) hyperglycemia and hyperinsulinemia compared with control. The glycemic response was higher ($P < .05$) at the start of exercise after the HI-GI meal than after the control. During exercise, plasma glucose levels were higher ($P < .05$) at 60 (5.2 ± 0.1, 4.2 ± 0.2, and 4.6 ± 0.1 mmol · L^{-1}) and 90 (4.8 ± 0.1, 4.1 ± 0.1, and 4.3 ± 0.1 mmol · L^{-1}) minutes after the MOD-GI meal than after either the HI-GI or control. Total carbohydrate oxidation was greater ($P < .05$) during the MOD-GI trial than in control and was directly correlated with exercise performance time ($r = .95$, $P < .0001$). Pre-exercise plasma FFA levels were suppressed ($P < .05$) 30 and 45 minutes after ingestion of the HI-GI meal and 45 minutes after the MOD-GI meal compared with control. At 30, 60, and 120 minutes of exercise, FFAs remained suppressed ($P < .05$) for both test meals compared with control. At exhaustion, plasma glucose, INS, FFA, glycerol, EPI, and NE levels and muscle glycogen use were not different for all trials. Exercise time was prolonged ($P < .05$) after the MOD-GI meal compared with control, but the HI-GI trial was not different from control (MOD-GI, 165 ± 11; HI-GI, 141 ± 8; control, 134 ± 13 minutes). Thus, in contrast to the HI-GI meal or control, the MOD-GI breakfast cereal ingested 45 minutes before exercise enhanced performance time, maintained euglycemia for a longer period during exercise, and resulted in greater total carbohydrate oxidation during the exercise bout. We conclude that a MOD-GI meal provides a significant performance and metabolic advantage when consumed 45 minutes before exercise.

IN THE LATE 1930s, Christensen and Hansen[1] established a link between hypoglycemia and fatigue, which led researchers to search for ways to maintain euglycemia during exercise to optimize exercise and/or work output both on the sports field and in the workplace. As a result of this research, it is now widely accepted that carbohydrate ingestion before, during, and in recovery after exercise makes a very positive contribution to substrate availability and in most cases leads to enhanced exercise and work performance and promotes recovery from strenuous exercise.[2-4] However, the effect of pre-exercise carbohydrate ingestion has remained controversial based primarily on studies showing that ingestion of carbohydrate 30 to 60 minutes before exercise leads to hyperinsulinemia and hypoglycemia and that exercise performance may be impaired.[5,6] One way to counteract this problem is to ingest a carbohydrate-rich meal that produces an attenuated blood glucose response curve because of delayed digestion and absorption of the meal. Such meals have been found to have a reduced glycemic index (GI, defined as the incremental area under the glucose response curve compared with the glucose response curve of either a glucose solution or a white bread standard). Thomas et al[7] were the first to show that meals with a low GI response (typically < 40) were associated with enhanced exercise performance compared with high-GI (GI > 70; HI-GI) meals. The benefit of a low-GI meal over a HI-GI meal was recently corroborated by DiMarco et al.[8] We have previously reported that eating a moderate-GI (~63; MOD-GI) breakfast cereal with a high dietary fiber content 45 minutes before exercise resulted in a 41-minute (16%) increase in time to fatigue during prolonged submaximal exercise.[9] We have also observed that eating a MOD-GI breakfast cereal before exercise spared endogenous carbohydrate and facilitated increased hepatic glucose output during the final 30 minutes of exercise to fatigue.[10] However, the benefits of meals with a low to moderate GI on exercise performance is in question based on studies that have shown no beneficial effect of either high- or low-GI meals on time trial performance or on time to exhaustion during prolonged exercise.[11-13] The reason for this lack of agreement remains to be explained but may be attributable to small differences in study design, particularly timing of the meal, exercise intensity, meal composition, and the specific metabolic response to the meals.

The purpose of the present study was to determine the effects

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Submitted October 26, 2000; accepted December 19, 2000.

Supported by Quaker Oats, Inc, National Institutes of Health grants R29 AG12834 (to J.P.K.) and RO1 AG11811 (to W.J.E.), and General Clinical Research Center grant MO1 RR10732.

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0026-0495/01/5007-0002$35.00/0

doi:10.1053/meta.2001.24191

of a MOD-GI breakfast cereal on the metabolic response and exercise time during prolonged moderate-intensity exercise compared with a HI-GI breakfast cereal or water control. We postulated that meals with added fiber would produce a reduced glycemic response before exercise and alter substrate use during exercise, thus sparing endogenous carbohydrate stores and facilitating enhanced exercise performance. The study was designed to permit comparison of cereals with contrasting GI against each other and against a water control so that we could extend our previous observations on the effects of MOD-GI cereals on metabolism and exercise performance.

SUBJECTS AND METHODS

Subjects

Six young, healthy, active men volunteered to participate in the study (Table 1). The study was approved by the Institutional Review Board for Human Subjects at the University Park campus of the Pennsylvania State University. All participants provided signed informed consent in accordance with university guidelines for the protection of human subjects. Subjects were initially screened for exercise training and smoking status. Peak oxygen consumption ($V_{O_{2peak}}$) was determined on a semirecumbent cycle ergometer using an incremental protocol. All participants had normal responses to a 75-g oral glucose tolerance test. Body density was determined by hydrostatic weighing after an overnight fast according to the method of Akers and Buskirk.[14] Underwater weight was determined using electronic load cells. Residual lung volume was determined during immersion by open-circuit nitrogen washout, and percent body fat was estimated using the equation of Siri.[15] Height was measured to the nearest 1.0 cm without shoes. Body weight was measured to the nearest 0.1 kg with the subject wearing shorts.

Physical Activity and Dietary Control

To control diet and physical activity, the subjects lived in the General Clinical Research Center for 2 days and 3 nights before each exercise trial. During days 1 and 2, dietary intake included foods that provided 60% carbohydrate, 25% fat, and 15% protein and provided enough energy to meet the subject's needs based on the Harris-Benedict equation, using an activity factor of 2.0.[16] The diet consisted of normal foods and beverages. On day 3, after an overnight fast, each subject ate one of the test meals containing 75 g of available carbohydrate or consumed 300 mL of water (control). The breakfast cereals or control were consumed 45 minutes before the start of exercise. The MOD-GI meal (GI = 61) consisted of whole-grain rolled oats (75 g available carbohydrate, 7.1 g fat, 17.9 g protein, 11.9 g dietary fiber, 5.9 g soluble fiber). The contrasting HI-GI meal (GI = 82) was puffed rice (75 g available carbohydrate, 1.0 g fat, 5.5 g protein, 1.0 g dietary fiber, 0 g soluble fiber). Both meals were ingested with 300 mL of water. Trials were performed in a randomized crossover design with only one of the investigators aware of what was consumed during each trial. Trials were separated by 7 to 10 days during which the subjects ate their normal diets.

To control and standardize the amount of exercise each subject performed during the 48 hours before the exercise test, each subject trained for 2 days in the laboratory on the same semirecumbent cycle ergometer as was used for the performance ride. On each training day, the exercise duration was 45 minutes and the intensity was 50% of predetermined $V_{O_{2peak}}$.

Table 1. Characteristics of the Subjects

Age (yr)	22 ± 1
Body weight (kg)	80.4 ± 3.7
Body fat (%)	15.6 ± 1.2
BMI (kg/m^2)	26.4 ± 1.1
$V_{O_{2peak}}$ (mL · kg^{-1} · min^{-1})	54.3 ± 1.2
Muscle fibers (%)	
Type I	40.1 ± 3.9
Type II	59.9 ± 3.9

NOTE. Values are presented as mean ± SE (n = 6).

Exercise Performance

The exercise performance trial was performed as previously described.[9] The exercise tests were performed on a friction-braked high-precision semirecumbent cycle ergometer (Jaquet, Basel, Switzerland) at an intensity that corresponded to ~60% of $V_{O_{2peak}}$. Each subject exercised to exhaustion, defined as the time at which the pedaling rotations per minute decreased to less than 90% of the designated cadence. Subjects were given verbal encouragement by the same research assistant throughout the exercise trial and were given a monetary incentive based on performance time. Heart rate was monitored continuously by means of radiotelemetry (POLAR, Kempele, Finland).

Blood Analyses

A polyethylene catheter was placed in an antecubital vein for blood sampling. Blood samples for hormone and substrate determination were drawn before the test meal; 15, 30, and 45 minutes after the meal; and at 30-minute intervals during exercise until exhaustion. Plasma glucose concentration was measured immediately by the glucose oxidase method (Beckman Instruments, Fullerton, CA). Blood samples for hormone and substrate measurements were centrifuged at 4°C and stored at −70°C for subsequent analysis. Samples for insulin were assayed in duplicate by a double-antibody radioimmunoassay.[17] Blood samples for epinephrine and norepinephrine determination were collected in tubes containing reduced glutathione and ethylene glycol-bis(β-aminoethyl ether)-*N,N,N′-N′*-tetraacetic acid. The samples were analyzed by high-performance liquid chromatography (Waters Associates, Milford, MA) using electrochemical detection based on a modification of the method described by Hjemdahl et al.[18] Serum FFA levels were determined using an enzymatic colorimetric procedure (NEFA C kit; Wako Chemicals, Dallas, TX). Glycerol concentrations were measured using an enzymatic colorimetric procedure (triglyceride [GPO-Trinder], procedure 337; Sigma, St Louis, MO).

Muscle Analyses

A muscle biopsy specimen was obtained from the *m.* vastus lateralis of 1 leg before eating the test meal and from the other leg immediately after the subject stopped exercise. The samples were dissected free of connective tissue and fat, and 1 piece was immediately frozen in liquid nitrogen for subsequent analysis of muscle glycogen content.[19] A second piece was prepared for histochemical analysis of muscle fiber type. The muscle sample was mounted in tragacanth gum and quickly frozen in isopentane, cooled in liquid N_2. All muscle samples were stored at −70°C. Total muscle glycogen content was determined in duplicate on freeze-dried samples. Samples were weighed, acid hydrolyzed, and neutralized with NaOH, and the glucose concentration in each hydrolysate was measured by enzymatic fluorometry.[20] A total of 15 serial cross-sections (10 μm each) of each muscle sample were cut at −20°C in a cryostat microtome (Leica Cryocut 1800) and mounted on slides. The sections were dried at room temperature and stained for myosin adenosine triphosphatase (preincubation at pH 4.3 and 4.6). An average of 238 fibers per muscle sample were counted and identified as type I or II based on the adenosine triphosphatase stain.

Exercise Energy Expenditure

Exercise V_{O_2}, V_{CO_2}, and respiratory exchange ratio (RER) were determined by indirect calorimetry during the entire first 30 minutes of exercise and at 30-minute intervals during the remaining period of each exercise trial. Gas volumes were measured with a dry gas meter (Rayfield Equipment, Waitsfield, VT). Concentrations of O_2 and CO_2 were measured on an electrochemical O_2 analyzer (Applied Electrochemistry, S-3A, Sunnyvale, CA) and infrared CO_2 analyzer (Beckman LB-2, Fullerton, CA). Carbohydrate oxidation was calculated from V_{O_2} and RER data.

Statistics

All values are presented as means ± SE. Differences between dependent variables were examined by repeated-measures analysis of variance (ANOVA). Specific mean differences were identified with a Newman-Keuls post hoc test. The α level for statistical significance was set at .05.

RESULTS

Dietary Intervention

Plasma glucose and insulin levels increased after ingestion of both cereals compared with the control trial (Fig 1). After the HI-GI meal, the glucose response was higher at 15, 30, and 45 minutes than in control. Furthermore, 30 minutes after the meal, the glucose response was greater after the HI-GI meal than after the MOD-GI meal. The MOD-GI meal resulted in an elevated glucose response 15 and 30 minutes postmeal, but glucose values had returned to baseline by 45 minutes (start of exercise). The insulin response was significantly increased ($P < .05$) above control values 15, 30, and 45 minutes after ingestion of both meals, and both meals elicited similar insulinemic responses.

Exercise Performance

Exercise intensity expressed as a percent of $V_{O_{2peak}}$ was not different among all 3 trials (60% ± 3%, 58% ± 3%, and 60% ± 3% for the MOD-GI, HI-GI, and control trials, respectively). Oxygen consumption remained steady throughout each exercise bout, and no difference was noted between trials at the point of exhaustion. Heart rate remained relatively constant throughout the exercise bouts, and there were no differences between trials or between trials at the point of exhaustion (Table 2).

Exercise performance times were significantly longer ($P < .05$) after the MOD-GI meal than in control, whereas no difference was observed between the HI-GI meal and either the control or MOD-GI meal (165 ± 11, 141 ± 8, and 134 ± 13 minutes for MOD-GI, HI-GI, and control, respectively). The differences in these data represent ~23% and 5% improvements in performance after the MOD-GI and HI-GI meals compared with control.

Substrate and Hormone Measures During Exercise

At the start of exercise, plasma glucose levels had returned to premeal values with the MOD-GI meal and were not different from control (Fig 1). However, glucose levels were higher ($P < .05$) in the HI-GI trial than in the control trial. Glucose levels gradually decreased throughout exercise during all 3 trials, but the levels of glycemia were higher at 60 and 90 minutes of the

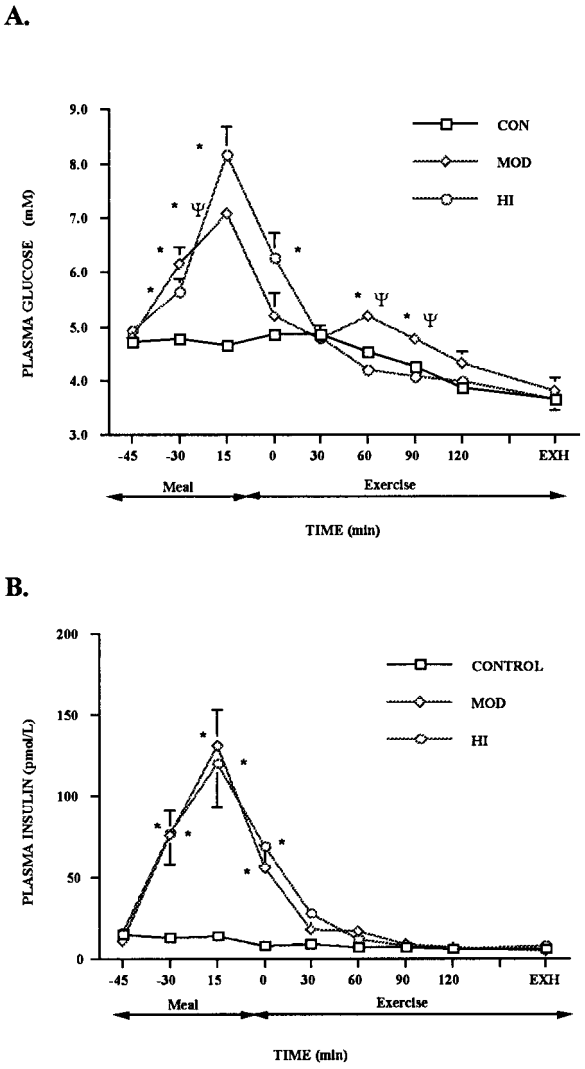

Fig 1. Substrate and hormone concentrations before (−45 to 0 minutes) and during exercise (0 minutes to exhaustion [EXH]) after MOD-GI, HI-GI, and control (CON) feedings. (A) Plasma glucose; (B) plasma insulin. Values represent means ± SE for 6 subjects. *MOD-GI and HI-GI trials significantly higher than control trial; $P < .05$. ΨMOD-GI trial significantly different from HI-GI trial; $P < .05$.

MOD-GI trial than in both the HI-GI and control trials. There were no differences in glycemia at exhaustion. Insulin levels were significantly elevated ($P < .05$) at the start of exercise during both the MOD-GI and HI-GI trials but had returned to premeal levels within the first 30 minutes of exercise, at which point they were not different from the levels observed throughout the control trial (Fig 1). Circulating FFA levels were suppressed ($P < .05$) before both exercise trials that were preceded by a test meal (Fig 2). Plasma FFA levels remained suppressed at 30, 60, and 120 minutes of exercise during both the MOD-GI and HI-GI trials compared with control (Fig 2). As expected, FFA levels increased during all 3 exercise trials and did not differ at exhaustion for all trials. At the start of exercise, plasma glycerol levels were not different for all 3 trials (Fig 2). Glycerol levels increased during each exercise

Table 2. Physiologic Parameters During Exercise to Exhaustion After Ingestion of MOD-GI or HIGH-GI Meals or Water Control

	Time (min)					
	5	30	60	90	120	Exhaustion
Vo_2 (mL · kg^{-1} · min^{-1})						
CON	32.4 ± 1.6	32.4 ± 1.8	32.4 ± 1.7	31.6 ± 2.0	34.7 ± 0.7	32.2 ± 2.1
MOD	31.7 ± 1.5	32.1 ± 1.4	32.3 ± 1.5	32.0 ± 2.1	33.9 ± 2.5	33.0 ± 2.3
HI	31.4 ± 1.6	31.3 ± 1.4	31.2 ± 1.5	30.9 ± 1.9	32.4 ± 2.2	32.3 ± 2.1
RER						
CON	0.88 ± 0.02	0.88 ± 0.01	0.87 ± 0.02	0.85 ± 0.01	0.86 ± 0.01	0.85 ± 0.01
MOD	0.91 ± 0.01	0.90 ± 0.01	0.87 ± 0.01	0.88 ± 0.01	0.86 ± 0.02	0.85 ± 0.01
HI	0.91 ± 0.02	0.90 ± 0.01	0.89 ± 0.01	0.89 ± 0.01	0.87 ± 0.01	0.87 ± 0.01
Heart rate (bpm)						
CON		142 ± 5	143 ± 6	143 ± 6	139 ± 4	147 ± 6
MOD		149 ± 6	147 ± 7	146 ± 8	147 ± 8	155 ± 6
HI		140 ± 6	142 ± 3	142 ± 4	147 ± 8	154 ± 6

NOTE. Values are means ± SE.

bout, but there were no differences between trials. Plasma epinephrine and norepinephrine levels were not different at baseline and were not significantly affected by the ingestion of either test meal. Both epinephrine and norepinephrine levels increased significantly during exercise, but there were no differences between trials (Table 3).

Muscle Glycogen and Carbohydrate Oxidation

Premeal muscle glycogen levels were not different among trials (346 ± 43, 360 ± 50, and 369 ± 50 mmol · kg^{-1} dry weight for the MOD-GI, HI-GI, and control trials, respectively). At the end of each exercise bout, there was a significant depletion of glycogen in the vastus lateralis (99 ± 30, 112 ± 20, and 100 ± 42 mmol · kg^{-1} dry weight for the MOD-GI, HI-GI, and control trials, respectively). Total muscle glycogen use was not different between trials (247 ± 33, 248 ± 55, and 269 ± 64 mmol · kg^{-1} dry weight for the MOD-GI, HI-GI, and control trials, respectively). RERs were not different for all 3 trials (Table 2). However, total carbohydrate oxidation was higher ($P < .05$) for the MOD-GI than the control meal (484 ± 40 and 409 ± 41 g, respectively). Furthermore, there was a significant association between total carbohydrate oxidation and exercise performance time ($r = .95$, $P < .0001$).

DISCUSSION

The effects of food sources of carbohydrate, containing simple sugars, complex carbohydrate, fiber, fat, and protein, on the glycemic response to ingestion, subsequent energy delivery during exercise, and ultimately exercise performance has not been characterized clearly. To address this issue, we used two whole-food breakfast cereals; one elicited a lower glucose response than the other, and the literature values indicate that one can be considered to have a moderate and the other a high GI.[21] The main finding from our study shows that eating a MOD-GI breakfast cereal 45 minutes before beginning exercise can improve performance time, whereas eating a HI-GI meal is no different from ingesting water. The results are consistent with our previously published data showing that women could exercise longer after they ate a moderate glycemic high-fiber breakfast cereal before the exercise bout.[9] However, the results from the present study extend our observations by contrasting the effects of MOD-GI and HI-GI meals.

The concept of the GI was first proposed by Jenkins et al[22] to evaluate the impact of different sources of carbohydrate on blood glucose using comparisons with a glucose solution or white bread standard. The index was developed because the blood glucose response to carbohydrate ingestion is not a simple function of the total amount of carbohydrate consumed, but is instead related to a complex interplay between a host of factors that affect digestion and absorption, and thus the rate at which glucose is delivered to the blood. Thus, even if the amount of carbohydrate is fixed, the blood glucose response may show considerable variation. Examples of factors with demonstrated effects on rates of digestion and absorption of carbohydrate are; the dietary source of the carbohydrate,[23] its physical form,[24] and other components in the food source or ingested with it such as soluble fiber, β-glucan,[25,26] protein, or fat.[22,27] The GI concept has raised questions about the appropriateness of generalizing results from studies of glucose solutions or purified carbohydrates to predict blood glucose responses to any carbohydrate, particularly those ingested in foods. Many of the early findings relating dietary carbohydrate to exercise performance did not always differentiate between types of carbohydrate and their food sources. Most of these studies used simple sugars, often in solution, which would elicit glycemic responses different from starch, especially if starch was consumed in solid form.[22,28] Furthermore, ingestion of simple sugar solutions has sometimes led to rebound hypoglycemia early in exercise and impaired performance.[5,6]

The GI of dietary carbohydrate was initially used as a clinical tool to regulate postprandial glucose responses among diabetic patients. Thomas et al[7] applied the findings to exercise and were the first to show that eating a meal with a low GI extended the time to exhaustion during cycling exercise by 20 minutes compared with a meal with a high GI. However, support for this observation has not been consistent and subsequent studies have shown no beneficial effect of either HI-GI or low-GI meals on time trial performance at the end of steady-state cycling or in time to exhaustion during treadmill running.[11-13] More recently, however, DeMarco et al[8] con-

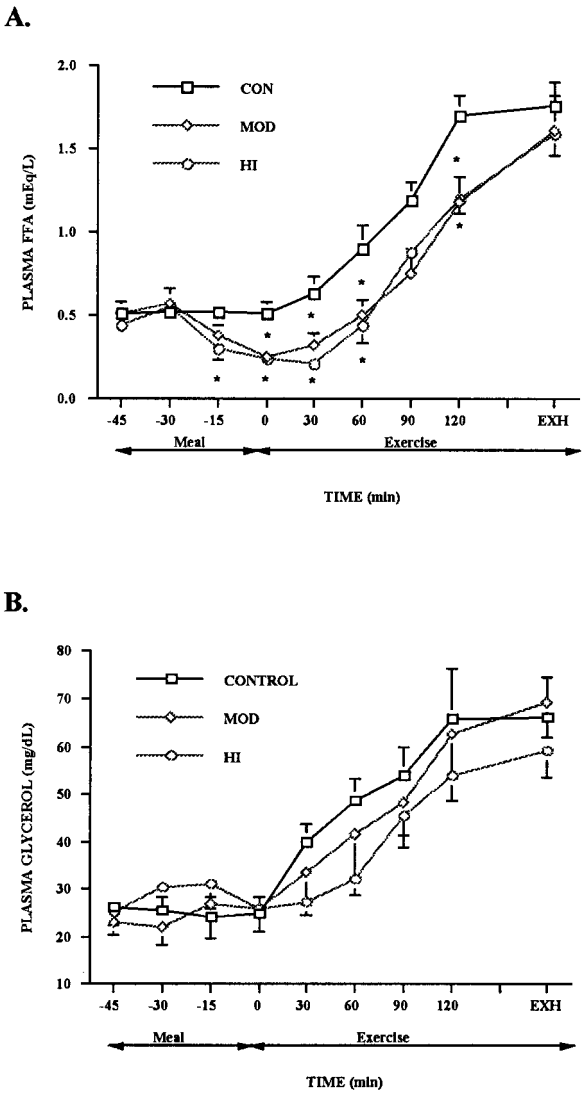

Fig 2. Lipid concentrations before (−45 to 0 minutes) and during exercise (0 minutes to exhaustion [EXH]) after MOD-GI, HI-GI, and control (CON) feedings. (A) Plasma FFA; (B) plasma glycerol. Values represent means ± SE for 6 subjects. *MOD-GI and HI-GI trials significantly lower than control trial; $P < .05$.

firmed the advantage of a low-GI meal over a high-GI meal when they found exercise time was 59% longer during a maximal effort after 2 hours of submaximal cycling. Although the evidence is still not overwhelming, together with the data from the present study, there are now at least 4 studies showing that meals with low or moderate GI meals can help athletes perform longer and/or better during prolonged exercise.

The cause for the disparity between the various studies is not readily apparent. It may be due to small but significant differences in study design, exercise intensity, meal composition, and the specific metabolic responses to the meals. Although timing of the meal is a potential reason, it does not seem to explain the differences adequately. Thomas et al[7] fed their subjects 1 hour before exercise, and DeMarco et al[8] provided the meal 30 minutes before exercise, but both saw a significant improvement in performance. We and others have waited 45 minutes,[9,11,12] and although we saw an improvement in performance, Febbraio and Stewart[11] and Sparks et al[12] report no benefits. Furthermore, Wee et al[13] waited 3 hours between the meal and exercise and found no advantage between HI-GI and low-GI meals. Alternatively, differences between studies may be explained by variations in the level of dietary and exercise control exerted before the experimental trials. The present study is the only one in which the subjects were kept in residence in a metabolic unit for the days preceding each trial. All meals were provided to the subjects, exercise was supervised in the laboratory, and the meals and exercise were replicated before each trial. In contrast, in the studies referenced above, the subjects were required to record and replicate diets and exercise training accurately before each experimental trial. If the subjects deviated from the diet and/or exercise training, it would have added variability to the experimental outcome and may have contributed to the different results.

In our previous studies, we suggested that when the meal caused a hyperinsulinemic state at the start of exercise there was a sustained suppression of FFA and a corresponding increased use of carbohydrate as fuel early in exercise.[9,10] We proposed that this metabolic milieu provided a potential explanation for the lack of improvement in exercise performance in some studies. However, in the studies that have shown enhanced exercise performance, it is apparent that glucose levels were significantly elevated over control levels[7,8]; in the studies that report no improvement, glucose levels are not different from control levels.[11-13] In the present study, we also found elevated glucose levels during the MOD-GI trial compared with control values. Thus, it appears that the improvement in exercise performance is dependent on whether the meal can maintain adequate euglycemia during exercise to sustain carbohydrate oxidation. However, this does not preclude the possibility that when lipolysis is severely inhibited, the relative contribution of carbohydrate oxidation to the total fuel supply early in exercise may place too great a burden on available supplies, blood glucose levels may decrease, and no exercise performance advantage ensues.

Ingestion of a meal before exercise may contribute additional carbohydrate for oxidation and spare limited muscle and liver glycogen stores.[10,29-32] On the other hand, a high-carbohydrate meal is known to stimulate carbohydrate oxidation in the initial period of exercise, which may stimulate greater rates of glycogenolysis and early depletion of stored glycogen. Glycogen depletion, leading to hypoglycemia, is believed to be the primary cause of fatigue during prolonged bouts of exercise and/or physically demanding work.[4,33,34] Thus, the titration of fuel use between endogenous and exogenous sources of carbohydrate after a carbohydrate-rich meal is critical for optimal exercise performance. In the present study, total carbohydrate oxidation was significantly correlated with exercise performance, which is consistent with the theory that carbohydrate availability is a primary determinant of endurance exercise duration. Total carbohydrate oxidation was also highest after the MOD-GI meal. Because muscle glycogen use did not differ between trials, it is most likely that the additional carbohydrate oxidized during the MOD-GI trial came from the ingested meal. In support of this observation, the estimated difference in

Table 3. Plasma Catecholamine Concentrations During Exercise to Exhaustion After Ingestion of MOD-GI and HI-GI Meals or Water Control

	Time (min)					
	0	30	60	90	120	Exhaustion
Epinephrine (pmol/L)						
CON	0.7 ± 0.2	1.8 ± 0.7	1.7 ± 0.4	2.4 ± 0.8	5.2 ± 2.3	6.9 ± 2.6
MOD	2.1 ± 1.0	1.4 ± 0.3	2.0 ± 0.4	2.2 ± 0.4	4.6 ± 1.3	7.3 ± 2.9
HI	1.6 ± 0.4	1.9 ± 0.5	3.0 ± 1.6	3.0 ± 0.4	7.4 ± 3.8	6.2 ± 3.9
Norepinephrine (pmol/L)						
CON	2.7 ± 0.3	6.8 ± 1.2	7.2 ± 1.1	7.8 ± 1.1	9.8 ± 1.6	11.0 ± 1.4
MOD	2.9 ± 0.7	5.9 ± 1.4	8.2 ± 1.2	7.8 ± 1.2	8.8 ± 1.5	10.9 ± 1.6
HI	4.2 ± 0.8	6.9 ± 0.8	6.2 ± 1.8	8.6 ± 2.0	9.2 ± 2.6	7.4 ± 2.4

NOTE. Values are means ± SE.

carbohydrate use between the MOD-GI meal and the water control was 75 g, which is exactly the amount of carbohydrate that was provided in the meal. We did not directly determine whether the carbohydrate in the meal was slowly being released from the gut or whether it was used early in the exercise period and thus spared hepatic and/or muscle glycogen. However, we have seen that ingestion of the breakfast cereal used in the MOD-GI trial is associated with greater hepatic glucose output late in the exercise bout than with a water control.[10] It has also been reported that pre-exercise glucose ingestion can decrease hepatic glucose output during 60 minutes of cycling exercise.[31] Thus, it seems reasonable to suggest that during the MOD-GI trial, the meal provided adequate glucose for oxidative metabolism and may also have reduced the dependence on hepatic glyogenolysis during the early period of exercise.

In conclusion, the data from the present study indicate that ingestion of a MOD-GI meal containing 75 g of carbohydrate 45 minutes before cycling exercise at ~60% of $V_{O_{2peak}}$ increased exercise duration compared with a control trial. In contrast, ingestion of a HI-GI meal did not improve performance. Before exercise, the MOD-GI meal elicited an attenuated glycemic response compared with the HI-GI meal. During exercise, the higher level of glycemia and greater total carbohydrate oxidation after the MOD-GI meal may have contributed to the enhanced performance. The results suggest that individuals who wish to perform exercise and/or physically demanding work for a prolonged period may benefit from eating a MOD-GI meal before the activity.

ACKNOWLEDGMENT

The authors acknowledge the excellent technical support provided by Marlin Druckenmiller, Rick Ball, and David Williamson. They also thank the Nursing and Dietary Staff of the GCRC and the Technical/Engineering Staff of the Noll Physiological Research Center for supporting the implementation of the study and assisting with data collection.

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