Oat, Wheat or Corn Cereal Ingestion before Exercise Alters Metabolism in Humans\textsuperscript{1,2,3}

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\textbf{ABSTRACT} This study was designed to determine metabolic and physical performance responses to ingestion of pre-exercise meals with different macronutrient and fiber profiles. Twelve physically active subjects (6 males and 6 females) were used to investigate the metabolic and physical performance consequences of consuming pre-exercise meals consisting of oat, corn, or wheat cereals. A fasting trial served as the control, and all subjects received each treatment in a Latin-square design. Blood samples were drawn before and 85 min after meal ingestion, during 90 min of cycling exercise (60% VO\textsubscript{2peak}), after a 6.4 km performance ride, and during 60 min of recovery. Expired air samples were collected to determine nutrient utilization. Resting carbohydrate oxidation rates and plasma insulin concentrations after oat ingestion were less than after wheat, and corn and wheat ingestion, respectively ($P < 0.05$). During exercise, the change in plasma glucose from pre-exercise was greater after consuming wheat and corn compared with oat ($P < 0.05$), and it was inversely related to pre-exercise plasma insulin concentration ($r = -0.55, P = 0.0001$). Plasma free fatty acid concentrations were inversely related to plasma lactate concentrations ($r = -0.58, P = 0.0001$). Free fatty acid concentrations and fat oxidation were greater in fasting trials than all others, but performance ride times did not differ among treatments. Plasma branched-chain amino acid concentrations resembled their respective meal profiles throughout exercise, the performance ride, and recovery. These results indicate that pre-exercise meal composition can influence glucose homeostasis during early exercise and plasma branched-chain amino acid concentrations over a substantial range of metabolic demands. J. Nutr. 126: 1372-1381, 1996.

\textbf{INDEXING KEY WORDS:}

- humans
- pre-exercise feeding
- performance
- metabolism
- amino acids

The impact of pre-exercise carbohydrate feedings on metabolism and physical performance has been the subject of several recent review articles [Coggan and Swanson 1992, Costill and Hargreaves 1992, Sherman 1991]. Metabolic perturbations consistently observed in early exercise following carbohydrate ingestion include elevated plasma insulin concentrations, decreased plasma glucose concentrations and increased carbohydrate oxidation rates [Costill et al. 1977, Hargreaves et al. 1987, Koivisto et al. 1985, Montain et al. 1991]. When exercise commences within 30–60 min after carbohydrate ingestion, the resulting hyperinsulinemia acts synergistically with contracting skeletal muscle to accentuate plasma glucose uptake [Coggan and Swanson 1992]. The subsequent drop in plasma glucose concentration below pre-exercise levels can return to normal [Devlin et al. 1986] or remain depressed throughout exercise [Costill et al. 1977, Sherman et al. 1991].

The most important factor governing exercise performance is carbohydrate oxidation [Coggan and Swanson 1992, Costill and Hargreaves 1992]. During the latter stages of exercise, plasma glucose becomes the major carbohydrate source for oxidation [Coggan and Swanson 1992]. Thus, pre-exercise carbohydrate feedings would most likely enhance exercise performance when euglycemia is restored before plasma glu-


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cose oxidation rates increase. The body’s ability to tolerate fluctuations in plasma glucose concentration during exercise may partially explain why physical performance test results after pre-exercise carbohydrate feedings have improved [Sherman et al. 1991], declined [Foster et al. 1979], or not changed [Hargreaves et al. 1987].

To minimize the effect of hyperinsulinemia on blood glucose homeostasis following carbohydrate ingestion, alternative pre-exercise feeding strategies have been investigated. Fructose has been proposed as one such alternative because it does not induce hyperinsulinemia or hypoglycemia. However, pre-exercise fructose ingestion does not improve exercise performance [Hargreaves et al. 1987], and fructose appears to produce gastrointestinal distress [Murray et al. 1989]. A more promising strategy to supply carbohydrate and maintain euglycemia during exercise is to alter the composition of the pre-exercise meal. Fat, protein, and soluble fiber diminish the postprandial rise in plasma glucose and insulin [Jenkins et al. 1981] as well as carbohydrate oxidation rates [Jarvis et al. 1992] following meal ingestion.

Grain cereals differ in macronutrient profile and fiber type and content. Corn and wheat cereals are typically fat free and contain predominantly insoluble fiber, whereas whole oats contain moderate amounts of protein, small amounts of fat, and soluble fiber [Englyst et al. 1989, Leveille et al. 1983]. We reasoned, therefore, that pre-exercise plasma insulin concentrations following oat cereal ingestion would be less than after ingestion of corn or wheat. Such a response would slow carbohydrate utilization and thereby improve physical performance by maintaining blood glucose concentrations and carbohydrate oxidation rates throughout exercise. Thus, the primary purpose of this study was to test the hypothesis that oat cereal ingestion will minimize perturbations in carbohydrate metabolism during exercise and thus enhance exercise performance compared with corn or wheat cereal ingestion. We also sought to determine whether pre-exercise meal composition influences metabolic responses during the early recovery period.

**SUBJECTS AND METHODS**

**Subjects.** Twelve healthy adult subjects (six men and six women) of above average aerobic power served as subjects. Subject characteristics are provided in Table 1. Exclusion criteria for subject participation included the following: history of metabolic disorders including diabetes, hyperlipidemia, or thyroid dysfunction; history of psychiatric illness including any eating disorders; history of serious premenstrual distress; pregnancy; current prescription and/or nonprescription drug use; <90% or >120% ideal body weight; average consumption of more than 200 mg/d caffeine; history of lactose intolerance; peak oxygen uptake <45 mL (kg · min) or >65 mL (kg · min); and history of skipping breakfast. The experimental protocol was reviewed and approved by the Institutional Review Board of the University of Illinois at Urbana-Champaign, and all subjects provided informed consent.

**Preliminary testing.** Beginning 2 wk before the first experimental session, peak oxygen uptake was determined during a progressive exercise test using standard road bikes affixed to Velodyne Trainers (Schwinn Bicycle Company, Chicago, IL). Subjects began exercising at 100 W. Workloads were increased 25 and 50 W every 2 min for females and males, respectively, until subjects voluntarily terminated the exercise test. Peak VO$_2$ was defined as the highest value obtained after the respiratory quotient (RQ)$^5$ exceeded 1.0. Respiratory samples of expired air were collected continuously during the test using an automated gas analysis system. Sample volume was measured using a pneumoscan S-300 (K L Engineering, Northridge, CA) and an air flow transducer (Model K-520; K L Engineering), and sample temperature was measured using a YSI Model 46 Telethermometer (Yellow Springs Instruments, Yellow Springs, OH). An air flow meter (AMETEK, Pittsburgh, PA) was used to draw a 200-mL aliquot of expired air sample from a mixing chamber into an oxygen (Oxygen Analyzer S-3A1, AMETEK) and carbon dioxide analyzer (Carbon Dioxide Analyzer, CD-3A, AMETEK). The gas analyzers were calibrated prior to each test with gases of known concentration. Sample volume, temperature, and percentage of O$_2$ and CO$_2$ were downloaded to a personal computer, and VO$_2$ was calculated at 30-s intervals throughout the test according to the standard equation for open-circuit spirometry [Lamb 1984].

Subjects completed a second test ride to ensure that workloads were correct. Subjects peddled for 15 min at

<table>
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<tr>
<th>TABLE 1</th>
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<tr>
<td><strong>Subject characteristics$^1$</strong></td>
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</tr>
<tr>
<td>Age, y</td>
</tr>
<tr>
<td>Body weight, kg</td>
</tr>
<tr>
<td>Height, cm</td>
</tr>
<tr>
<td>Body surface area, m$^2$</td>
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<tr>
<td>VO$_2$peak, L/min</td>
</tr>
<tr>
<td>VO$_2$peak, mL/(kg·min)</td>
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$^1$ Values are means ± SD.

* Significantly different from males at $P < 0.05$ using an unpaired Student’s t test.

5 Abbreviations used: BCAA, branched-chain amino acids; FFA, free fatty acids; RPE, ratings of perceived exertion; RQ, respiratory quotient.
a workload calculated to elicit 60% \( \dot{VO}_{2\text{peak}} \). Gas samples were collected as described above every 2 min throughout the test. Another 15-min measurement period followed for subjects to obtain a new steady state if workload adjustments were necessary. After cycling for 30 min, subjects completed a 6.4-km timed ride to orient themselves to the performance ride demands.

**Experimental procedure.** The experimental protocol is outlined in Figure 1. The protocol is divided into four distinct time periods: a 90-min pre-exercise period, 90 min of steady-state exercise at 60% \( \dot{VO}_{2\text{peak}} \), a 6.4-km timed performance ride, and a 60-min recovery period.

At 1900 h on the evening preceding each experiment, subjects consumed a standardized meal from commercially available food that contained 56 ± 3.1% carbohydrate, 27 ± 2.1% fat, and 17 ± 1.7% protein [mean energy% ± SD]. Meal energy represented 33% of the subjects’ daily energy requirement which was calculated by multiplying the resting energy expenditure by 1.1 and 2 to account for the thermic effects of food and exercise, respectively (Roza and Shizgal 1984). Subjects finished the meal by 1930 h, then fasted until the experimental meal. During the 36 h before testing, subjects avoided alcohol, caffeine and exercise.

At 0700 h, subjects reported to the testing center and completed an initial questionnaire to chronicle their physical activity, sleep, and dietary habits, including alcohol consumption, for the preceding 36 h. Afterwards, with subjects in a seated position, a 22-gauge flexible catheter was inserted into a forearm vein. Catheters were kept patent by periodically flushing with 1 mL of 10,000 U.S.P. units/L heparin in 9 g/L saline.

Subjects then received one of 3 experimental meals (Table 2) comprised of either wheat or corn ready-to-eat cereals or oatmeal (oat), skim milk [125 mL for males, 95 mL for females], 4 g of sucrose and water [equivalent to amount required to cook the oat cereal]. Energy from the cereal component of the experimental meal was based on body surface area, and represented 645 and 582 kJ/m² for males and females, respectively. Mean ± SD total energy intake was 1540 ± 71 and 1176 ± 63 kJ for males and females, respectively. In addition, a fasting trial served as the control. Treatments were administered at 1-wk intervals in a single-blind, Latin-square design, and subjects served as their own controls. A sham trial using an oat-based ready-to-eat cereal was unknowingly completed by each subject as their first trial to minimize learning effects and to allow for final adjustments of meal energy and exercise workloads.

A 90-min pre-exercise period followed the experimental meal. Subjects were permitted to move freely about the test center for the initial 45 min, but remained seated thereafter. After calibrating the Velodyne Trainers according to the manufacturer’s specifications [3–5 min], subjects cycled for 90 min at a workload determined to elicit 60% \( \dot{VO}_{2\text{peak}} \). To minimize heat stress and dehydration effects on exercise performance, all trials were conducted at ambient temperature (23°C), and subjects consumed 3.5 mL/kg water after 24, 45, and 66 min and 1.75 mL/kg water after 87 min of exercise. Immediately upon finishing this ride, subjects completed a 6.4-km performance ride. During the performance ride, subjects were aware only of the distance traveled. Subjects were free to change gears at will, and power output varied with cycling speed. To encourage maximal performance, monetary rewards were tied to the time required to complete the performance ride. Subjects were unaware of all results until all trials were completed.

A 60-min recovery period followed the performance ride. Subjects remained seated throughout recovery, and water [3.5 mL/kg] was provided after 15 and 35 min.

**Data collection and analyses.** Blood samples [10 mL] were collected upon catheter insertion, 85 min following breakfast, after 21, 42, 63, and 84 min of exercise, immediately upon completion of the 6.4-km performance ride, and 30 and 60 min after exercise (Fig. 1). Hematocrit changes were used to calculate the percentage of plasma volume change (Van Beaumont 1972).

### TABLE 2

<table>
<thead>
<tr>
<th>Carbohydrate, fat, and protein content of the corn, oat, and wheat cereals and skim milk consumed by the subjects 90 min before exercising at 60% ( \dot{VO}_{2\text{peak}} )(^1,2 )</th>
<th>Corn</th>
<th>Oat</th>
<th>Wheat</th>
<th>Skim milk</th>
</tr>
</thead>
<tbody>
<tr>
<td>per 419 kJ of cereal</td>
<td>95 mL</td>
<td>125 mL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbohydrate, g</td>
<td>22.9</td>
<td>17.4</td>
<td>22.6</td>
<td>4.8</td>
</tr>
<tr>
<td>Dietary fiber, g</td>
<td>0.3</td>
<td>2.4</td>
<td>3.0</td>
<td>0</td>
</tr>
<tr>
<td>Insoluble, g</td>
<td>0.2</td>
<td>1.0</td>
<td>2.4</td>
<td>0</td>
</tr>
<tr>
<td>Soluble, g</td>
<td>0.1</td>
<td>1.4</td>
<td>0.6</td>
<td>0</td>
</tr>
<tr>
<td>Fat, g</td>
<td>0</td>
<td>1.6</td>
<td>0.6</td>
<td>0.2</td>
</tr>
<tr>
<td>Protein, g</td>
<td>1.9</td>
<td>4.2</td>
<td>3.0</td>
<td>3.4</td>
</tr>
<tr>
<td>Isoleucine, mg</td>
<td>77</td>
<td>171</td>
<td>135</td>
<td>203</td>
</tr>
<tr>
<td>Leucine, mg</td>
<td>298</td>
<td>316</td>
<td>207</td>
<td>329</td>
</tr>
<tr>
<td>Valine, mg</td>
<td>102</td>
<td>231</td>
<td>175</td>
<td>225</td>
</tr>
</tbody>
</table>

\(^1\) The pre-exercise meal also included 4 g of sucrose.

\(^2\) Macronutrients and amino acids for corn and wheat from Levine et al. (1983); macronutrients and amino acids for oat from USDA Agriculture Handbook 8–20 (1989); milk data obtained from Nutritionist III; all fiber data obtained from Englyst et al. (1989).
during exercise and recovery. Plasma glucose and lactate [YSI Model 2300 analyzer, Yellow Springs Instruments] were measured after a whole-blood sample was microfuged for 5 min in tubes containing sodium fluoride and heparin. Aliquots of plasma, collected from tubes containing EDTA and centrifuged at 1800 × g for 15 min (4°C), were frozen at −70°C for subsequent analysis of free fatty acids [FFA; NEFA C kit, Wako Pure Chemical, Richmond, VA] and insulin (Coat-ACount® radioimmunoassay, Diagnostic Products, Los Angeles, CA). For amino acid analysis, a 100 µL aliquot of plasma was mixed 1:1 with a 0.1 mol/L HCl solution containing 5 g/L sodium dodecyl sulfate and 0.4 mmol/L norleucine (internal standard). After 15 min, plasma proteins were precipitated by adding 300 µL of 50 g/L trichloroacetic acid. This mixture was microfuged for 5 min, and 50 µL of the resulting supernatant was derivatized with phenylisothiocyanate and analyzed for amino acids using HPLC [Waters, Marlborough, MA; Sarwar and Botting 1988]. This measurement technique produced mean ± SD intra- and interassay coefficients of variation of 1.1 ± 1.2% and 2.3 ± 2.6%, respectively. Thus, intraindividual variations in plasma amino acid concentrations likely produced the differences observed in the pre-meal plasma amino acid concentrations.

Heart rates [Exersentry Heart Rate Monitor, Computer Instruments, Hempstead, NY] and Ratings of Perceived Exertion [RPE; 20-point Borg Scale; Borg and Linderholm 1967] were recorded at the end of the pre-exercise period, every 10 min during steady-state exercise, and after 1.6 and 4.8 km of the performance ride. Subjects recorded their own body weight before and after exercise.

Expired gas samples were collected 60 min following meal ingestion and after 30, 54, and 78 min of exercise by open-circuit spirometry as described in the section on preliminary testing. Respiratory quotients [RQ] and VO₂ measurements were used to estimate carbohydrate and fat oxidation and energy expenditure [kJ] as previously described [Bemben et al. 1992].

Statistical analyses. Main effects were determined by 2-way repeated measures ANOVA with treatment and time as independent variables (SAS Version 6.0, SAS Institute, Cary, NC). When a significant treatment or treatment × time effect was observed (P < 0.05), a least significant difference test was used to distinguish mean differences [P < 0.05; Steel and Torrie 1980]. Relationships among dependent variables were assessed using Pearson’s Product Moment Correlation [Steel and Torrie 1980], and gender differences for the descriptive data were determined using an unpaired Student’s t test. All data are presented as mean ± SEM unless noted.

RESULTS

Respiratory and cardiovascular responses. Sixty minutes after meal ingestion, RQ values associated with the wheat meal were greater than all others (Fig. 2), and carbohydrate oxidation was significantly less when subjects fasted or consumed oat compared with wheat (Table 3). After 30 min of exercise, RQ values from fasting trials were lower compared with all others. No treatment differences existed for oxygen consumption [59.3 ± 3.9% VO₂peak] or total energy expenditure during the 90-min exercise period (Table 4); however, fat oxidation was greater and carbohydrate oxidation was less in fasting trials compared with fed trials (Table 4). No treatment differences occurred for heart rate (data not shown) or plasma volume changes during exercise (Fig. 3).

Plasma glucose and insulin concentrations. Plasma glucose concentrations were lower at the start of exercise when subjects consumed the oat cereal compared with when subjects fasted (Fig. 4). Twenty minutes into exercise, plasma glucose concentrations decreased from pre-exercise levels during the corn and wheat trials, but not during the oat or fasting trials. Performance ride plasma glucose concentrations increased in all trials with concentrations for wheat and corn being higher than for the fast.

Plasma insulin concentrations were elevated 85 min after meal consumption (Fig. 4), but concentrations associated with corn and wheat ingestion were greater than concentrations for oat. An inverse relationship was observed between early exercise plasma glucose responses and pre-exercise insulin concentrations [r = −0.55, P = 0.0001]. No treatment effects were observed.
TABLE 3

Total energy expenditure and total fat and carbohydrate oxidation after an overnight fast or 60 min after ingesting a corn, oat, or wheat cereal-based meal\(^1,2,3\)

<table>
<thead>
<tr>
<th></th>
<th>Fast</th>
<th>Corn</th>
<th>Oat</th>
<th>Wheat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total energy expenditure (kJ/min)</td>
<td>5.24 ± 0.34</td>
<td>5.82 ± 0.29</td>
<td>5.82 ± 0.29</td>
<td>5.82 ± 0.42</td>
</tr>
<tr>
<td>(kJ/(g BW \cdot min))</td>
<td>78.4 ± 4.6</td>
<td>88.0 ± 4.6</td>
<td>87.2 ± 4.6</td>
<td>87.2 ± 5.9</td>
</tr>
<tr>
<td>Total fat oxidation (mg/min)</td>
<td>85.1 ± 10.3</td>
<td>91.5 ± 8.9</td>
<td>98.7 ± 12.9</td>
<td>75.7 ± 12.0</td>
</tr>
<tr>
<td>(mg/(kg BW \cdot min))</td>
<td>1.28 ± 0.16</td>
<td>1.37 ± 0.14</td>
<td>1.45 ± 0.19</td>
<td>1.12 ± 0.16</td>
</tr>
<tr>
<td>Total carbohydrate oxidation (mg/min)</td>
<td>120.0 ± 19.7*</td>
<td>142.4 ± 22.9</td>
<td>124.7 ± 19.9*</td>
<td>178.0 ± 21.4</td>
</tr>
<tr>
<td>(mg/(kg BW \cdot min))</td>
<td>1.79 ± 0.27*</td>
<td>2.16 ± 0.37</td>
<td>1.91 ± 0.35*</td>
<td>2.68 ± 0.35</td>
</tr>
</tbody>
</table>

\(^1\) Calculations are described in Bemben et al. (1992).
\(^2\) Values are expressed as mean ± SEM, \(n = 12\).
\(^3\) BW = body weight.

* Significantly different than the wheat value only at \(P < 0.05\) using ANOVA and least significant difference post-hoc test.

for insulin during steady-state exercise or recovery, but insulin concentrations for the wheat and oat treatments increased during the performance ride. 

Plasma lactate and free fatty acid concentrations.

Plasma lactate concentrations did not differ among groups (Fig. 5). All values increased significantly during the performance ride, then decreased during recovery. FFA concentrations were depressed at the start of exercise when subjects were in the fed state (Fig. 5). Regardless of treatment, plasma FFA concentrations increased during exercise (fasting > fed), decreased in response to the performance ride (fasting and fed values were nearly identical), and increased during recovery (fasting > fed). FFA concentration changes during the performance ride and recovery period were inversely related to plasma lactate concentrations \((r = -0.58; P = 0.0001)\).

Plasma amino acid concentrations.

Alanine. Meal feeding and meal composition strongly influenced plasma alanine concentrations at the start of exercise (Fig. 6). No treatment differences were observed thereafter, except after 40 min of exercise when fasting alanine concentrations were less than after consumption of oat or wheat. For all trials, alanine responses were biphasic during steady-state exercise, initially increasing, then decreasing. Alanine concentrations increased sharply during the performance ride, then declined to pre-meal levels during recovery.

Glutamine. At the start of exercise, plasma glutamine concentrations were highest when subjects ingested the wheat cereal (Fig. 6). Glutamine responses varied during steady-state exercise (fasting increased, corn and wheat decreased, and oat did not change), increased during the performance ride (fasting > all others), then declined to pre-meal levels during recovery.

Branched-chain amino acids. Meal consumption was associated with greater plasma leucine concentrations (Fig. 7). Corn cereal ingestion exacerbated this increase during the first half of exercise, but thereafter, plasma leucine concentrations declined to pre-meal...
levels. Plasma isoleucine and valine concentrations were greater when oat or wheat was ingested compared with corn and the fasting trial. Plasma branched-chain amino acids (BCAA) differences were directionally related to their respective meal concentrations (Table 2), and these differences were maintained throughout exercise and recovery. During the latter period, all BCAA concentrations dropped below pre-meal levels.

**Exercise performance, ratings of perceived exertion (RPE), and body weight.** No treatment differences were observed for exercise performance times (637.7 ± 14.3, 631.7 ± 12.7, 632.2 ± 14.2, and 642.6 ± 15.7 s for fasting, corn, oat, and wheat trials, respectively), RPE, or body weight changes during exercise (data not shown).

**DISCUSSION**

The purpose of this investigation was to compare the effects of ingesting isocaloric meals composed of cereal grains with various macronutrient and fiber profiles on endurance performance and nutrient metabolism during exercise and recovery. The pre-exercise meals were isocaloric, but differed in macronutrient and fiber compositions. Compared with corn and wheat, the oat cereal contained less carbohydrate and more protein, fat, and soluble fiber (Table 2). These factors attenuate the insulinemic response to meal ingestion by slowing glucose absorption or by providing less glucose for disposal [Jenkins et al. 1981]. The lower plasma glucose concentration and carbohydrate oxidation rate observed after oat ingestion compared with corn and wheat (Table 3) are consistent with the slowed absorption and utilization of carbohydrate observed by others when soluble fiber, fat, and protein are added to a meal [Jarvis et al. 1992].

The divergent insulinemic responses to meal ingestion were not without metabolic consequences. During the initial 20 min of exercise, plasma glucose concentrations were lower in fed subjects than in fasted subjects. Glucose decreased from pre-exercise concentrations only when wheat or corn was ingested. However, no treatment produced hypoglycemia (<3.5 mmol/L) or differences in RPE. An inverse relationship was ob-

**FIGURE 3** Percentage change in plasma volume during 90 min of cycling exercise at 60% VO2peak, during a timed performance ride, and during 60 min of recovery. The arrow denotes the start of the performance ride. Exercise began 90 min after subjects ingested either a corn, wheat, or oat cereal meal. Plasma volume changes were calculated from changes in hematocrit according to Van Beaumont (1972), and each value represents the mean ± SEM of 12 subjects.

**FIGURE 4** Plasma insulin and glucose concentrations before subjects ingested either a corn, wheat, or oat cereal meal [M] and during exercise and 60 min of recovery. The exercise period consisted of 90 min of cycling at 60% VO2peak followed immediately by a 6.4-km timed performance ride. The arrow denotes the start of the performance ride. Each value represents the mean ± SEM of 12 subjects. The drop in plasma glucose concentration from the start of exercise to the first exercise data point was significant for wheat and corn [P < 0.05]. Group means with different letters at the same time are significantly different at P < 0.05 as determined by repeated measures ANOVA and least significant difference test.
served between early exercise plasma glucose responses and pre-exercise insulin concentrations \( r = -0.55, P = 0.0001 \). This corroborates earlier findings (Ahlborg and Felig 1977, Koivisto et al. 1985), and indicates that the blood glucose concentrations observed after 20 min of exercise partially resulted from the hyperinsulinemic response to meal ingestion.

After 40 min of exercise, plasma glucose concentrations in fed subjects (corn, oat, and wheat groups) rebounded from their 20-min values, indicating that plasma glucose appearance exceeded tissue glucose uptake. Endogenous glucose production via gluconeogenesis could contribute to glucose appearance. However, glucose ingestion before exercise decreases hepatic oxygen consumption and uptake of gluconeogenic precursors (Ahlborg and Felig 1977). The increase in plasma alanine concentration during the first 40 min of steady-state exercise (Fig. 6) is thought to reflect increased alanine release from muscle accompanied by a low alanine flux through gluconeogenesis (Felig 1977). Assuming that alanine production by muscle was constant during the last 45 min of the steady-state exercise period, the decline observed in plasma alanine concentra-

**FIGURE 5** Plasma lactate and free fatty acid concentrations before subjects ingested either a corn, wheat, or oat cereal meal (M) and during exercise and 60 min of recovery. The exercise period consisted of 90 min of cycling at 60% \( \dot{V}O_{\text{peak}} \) followed immediately by a 6.4-km timed performance ride. The arrow denotes the start of the performance ride. Each value represents the mean \( \pm \text{SEM} \) of 12 subjects. FFA values from the start of exercise up to the performance ride are significantly higher in the fasting trial compared with all others \( P < 0.05 \). Group means with different letters at the first recovery point are significantly different at \( P < 0.05 \) as determined by repeated measures ANOVA and least significant difference test.

**FIGURE 6** Plasma alanine and glutamine concentrations before subjects ingested either a corn, wheat, or oat cereal meal (M) and during exercise and 60 min of recovery. The exercise period consisted of 90 min of cycling at 60% \( \dot{V}O_{\text{peak}} \) followed immediately by a 6.4-km timed performance ride. The arrow denotes the start of the performance ride. Each value represents the mean \( \pm \text{SEM} \) of 12 subjects. Mean alanine values for all treatments increased during the first half of exercise \( P < 0.05 \), decreased during the second half of exercise \( P < 0.05 \), increased during the performance ride \( P < 0.05 \), and decreased throughout recovery \( P < 0.05 \). Mean glutamine values during exercise increased and decreased in the fasting trial and corn and wheat trials, respectively, \( P < 0.05 \). Mean glutamine values for all treatments increased during the performance ride \( P < 0.05 \) and decreased during the first 30 min of recovery \( P < 0.05 \). Group means with different letters at the same time are significantly different at \( P < 0.05 \) as determined by repeated measures ANOVA and least significant difference test.
In agreement with earlier findings [Montain et al. 1991, Thomas et al. 1991], fasting plasma FFA concentrations were always higher than those determined when subjects were fed. The decrease in plasma FFA concentrations from the end of steady-state exercise to the end of the performance ride and the subsequent increase during the recovery period were inversely related to plasma lactate concentrations \((r = -0.58, P = 0.0001)\). Lactate decreases plasma FFA concentrations by inhibiting lipolysis [Boyd et al. 1974], enhancing reesterification [Issekutz et al. 1975], or possibly both. Upon lactate removal, FFA concentrations rapidly increase [Boyd et al. 1974]. Thus, it is likely that lactate accumulation during the high intensity performance ride inhibited plasma FFA appearance. Because lactate was rapidly cleared during recovery, this inhibition was removed, and plasma FFA concentrations increased.

Although substrate utilization during exercise differed between fed and fasted trials [Table 3], performance times were remarkably similar. Lavoie et al. [1987] calculated that liver glycogenolysis can supply enough glucose to increase plasma concentrations 1.6 mmol/L during short-term, high intensity exercise when subjects consume a carbohydrate-free diet the day before exercise and then fast overnight. Because plasma glucose for all groups increased 1.2–1.5 mmol/L from the end of steady-state exercise to the end of the performance ride, the standardized meal consumed on the eve of each test day may have supplied enough carbohydrate so that liver glycogen stores were sufficient to meet the performance ride fuel demands even when subjects fasted.

The lack of a performance effect agrees with earlier findings [Devlin et al. 1986, Hargreaves et al. 1987], but contradicts results obtained in similar studies when foods with various insulinemic responses were consumed before exercise [Anderson et al. 1994, Thomas et al. 1991]. In these studies, performance ride times to exhaustion were 15–20% longer when subjects ingested a low insulinemic response meal 60 min before exercise compared with a high insulinemic response meal. Moreover, Thomas and others [1991] report lower carbohydrate oxidation rates and higher plasma FFA concentrations during exercise in the low insulinemic response trial.

Several differences between the present study and that of Thomas et al. [1991] make direct comparisons difficult [physiological responses during the exhaustive ride in Anderson et al. [1994] were not reported]. First, our time trial performance task was highly anaerobic (plasma lactate concentrations ranged from 10 to 12 mmol/L), whereas the ride to exhaustion in Thomas et al. [1991] was conducted below the anaerobic threshold (final lactate concentrations ranged from 2 to 3 mmol/L). Thus, the two tasks measured different physical capacities. Whether similar results would have occurred if subjects in the present study rode to exhaustion is unknown. Additionally, we did not observe dif-

**FIGURE 7** Plasma leucine, isoleucine, and valine concentrations before subjects ingested either a corn, wheat, or oat cereal meal (M) and during exercise and 60 min of recovery. The exercise period consisted of 90 min of cycling at 60% \(\dot{V}O_{2\text{peak}}\) followed immediately by a 6.4-km timed performance ride. The arrow denotes the start of the performance ride. Each value represents the mean ± SEM of 12 subjects. Mean values for leucine, isoleucine, and valine decreased during the recovery period \((P < 0.05)\) such that the final recovery values were different from the pre-meal values \((P < 0.05)\). Group means with different letters at the same time are significantly different at \(P < 0.05\) as determined by repeated measures ANOVA and least significant difference test.

tions from 40 to 85 min indicates that gluconeogenesis may have helped maintain plasma glucose concentrations for all groups later in exercise. Thus, the plasma glucose rebound observed between 20 and 40 min of exercise in the fed state was likely due to increased liver glycogenolysis, continued intestinal glucose absorption, or both, while gluconeogenesis appeared to help maintain plasma glucose concentrations as exercise duration progressed.
ferences among the fed trials in carbohydrate oxidation rates or plasma FFA concentrations during exercise. Although insulinemic responses to oat ingestion were less than those in the corn or wheat trials, the difference was apparently insufficient to affect exercise fuel utilization or endurance performance.

In agreement with earlier data (Stegink et al. 1991), plasma BCAA changes after meal ingestion reflected their respective meal profiles (Table 2 and Fig. 6, 7). However, to our knowledge, these are the first data to demonstrate that plasma amino acid differences observed during the absorptive period are maintained over a wide range of metabolic challenges (i.e., moderate and high intensity exercise and recovery).

The ability to regulate plasma amino acid concentrations during exercise may be important for future investigations into the relationship between plasma amino acid concentrations and human performance. The BCAA compete with tryptophan for brain uptake at the blood-brain barrier (Bender 1986), and brain tryptophan uptake is the rate-limiting step in serotonin synthesis (Bender 1986). An elevation in brain serotonin is thought to heighten the sensitivity to fatigue and negatively affect physical performance (Newsholme et al. 1987). Our results indicate that it may be possible to increase plasma BCAA concentrations during exercise by increasing the BCAA content of a pre-exercise meal. In turn, this would decrease brain tryptophan uptake and subsequent synthesis of serotonin, thereby improving exercise performance.

Considering that plasma volume and plasma alanine and glutamine concentrations returned to pre-exercise or pre-meal levels, the decline in plasma BCAA concentrations during recovery indicates a net loss of BCAA from the plasma pool. Such a loss could have resulted from an increased flux into tissue intracellular free pools or increased oxidation. Tissues accumulate leucine following contractile activity (Pain and Manchester 1970), but leucine oxidation rates are not increased (Rennie et al. 1981). However, synthesis rates of acute phase liver proteins (Carraro et al. 1990) and muscle proteins (unpublished data) increase rapidly during the early hours after exercise. Hence, a decrease in plasma BCAA concentrations during recovery may indicate increased tissue uptake to supply substrates for protein synthesis.

In summary, meal consumption before exercise elevated plasma insulin and reduced plasma FFA concentrations. Plasma glucose concentrations 20 min after exercise were inversely related to plasma insulin concentrations at the start of exercise. Accordingly, the reduced insulinemic response to oat ingestion attenuated the fall in blood glucose concentration early in exercise compared with corn or wheat ingestion. The lower plasma FFA concentrations observed after meal ingestion persisted throughout exercise and were associated with an increased carbohydrate oxidation rate. However, performance times for a 6.4-km ride did not differ among groups. Plasma BCAA concentrations during recovery were significantly less than before exercise indicating a net plasma loss. Plasma BCAA profiles throughout exercise and recovery reflected the ingested meal BCAA profile which may be important for future investigations into the relationship between plasma amino acid concentrations and human performance.

LITERATURE CITED


PRE-EXERCISE CEREAL INGESTION ALTERS METABOLISM


