Effect of dietary fat on metabolic adjustments to maximal VO₂ and endurance in runners

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ABSTRACT
MUOIO, D. M., J. J. LEDDY, P. J. HORVATH, A. B. AWAD, and D. R. PENDERGAST. Effect of dietary fat on metabolic adjustments to maximal VO₂ and endurance in runners. Med. Sci. Sports Exerc. Vol. 26, No. 1, pp. 81–88, 1994. The present study examined the effects of dietary manipulations on six trained runners. The percent energy contributions from carbohydrate, fat, and protein were 61/24/14, 50/38/12, and 73/15/12 for the normal (N), fat (F), and carbohydrate (C) diets, respectively. Expiratory gases and blood responses to a maximum measures did not differ significantly among diets. These data suggest indicated that they were consuming approximately 700 kcal-d<sup>−1</sup> less than estimated daily expenditures. Running time to exhaustion was greatest after the F diet (91.2 ± 9.5 min, P < 0.05) as compared with the C (75.8 ± 7.6 min, P < 0.05) and N (69.3 ± 7.2 min, P < 0.05) diets. VO<sub>2max</sub> was also higher on the F diet (66.4 ± 2.7 ml·kg<sup>−1</sup>·min<sup>−1</sup>, P < 0.05) as compared with the C (59.6 ± 2.8 ml·kg<sup>−1</sup>·min<sup>−1</sup>, P < 0.05) and N (63.7 ± 2.6 ml·kg<sup>−1</sup>·min<sup>−1</sup>, P < 0.05) diets. Plasma FFA levels were higher (P < 0.05) and glycerol levels were lower (P < 0.05) during the F diet than during the C and N diets. Other biochemical measures did not differ significantly among diets. These data suggest that increased availability of FFA, consequent to the F diet, may provide for enhanced oxidative potential as evidenced by an increase in VO<sub>2max</sub> and running time. This implies that restriction of dietary fat may be detrimental to endurance performance.

DIET, FAT METABOLISM, PERFORMANCE

Endurance capacity is influenced by the availability of metabolic fuels. The majority of attention in this area has been focused on the observation that fatigue is well correlated with glycogen depletion (1,6,16), which provides the basis for the common practice of “carbohydrate loading.” Historically, researchers have agreed that endurance during moderate- to high-intensity exercise can be enhanced by a high-carbohydrate diet (1,16,24). However, many of the studies that support this proposal have been conducted using moderately trained or untrained subjects. Since endurance training significantly affects fuel metabolism during exercise (9,23), these results may not apply to highly trained athletes. In addition, investigations that have evaluated the effects of a fat-rich diet have imposed strenuous pretest exercise bouts before introducing the diet. The high-fat diets were also severely carbohydrate restricted. Such extreme exercise and diet conditions yielded glycogen levels that were essentially exhausted at the onset of the endurance test. Furthermore, most investigations examined short-term diets (2–3 d) and thus had not allowed sufficient time for full adaptation to a high-fat diet. For these reasons, the apparent advantages of a high-carbohydrate diet over a high-fat diet may have been biased by the experimental design.

There is also accumulating evidence that argues against the contention that preexercise glycogen concentration is the primary factor that limits endurance performance (27,32,34). Although fatigue appears to correlate well with glycogen depletion (1,16), some investigators have failed to produce improved endurance following muscle glycogen supercompensation (6,27). In addition both animal (29) and human (32) studies have reported preserved or increased endurance capacity in response to a high-fat diet. Since endurance training adapts the muscle to utilize lipid fuel during exercise (9,23), dietary manipulations that enhance fatty acid metabolism may be beneficial to the trained muscle. Fatty acids are supplied by both exogenous (adipose tissue) and endogenous (in intramuscular) lipid reserves. A number of researchers have demonstrated that intramuscular triglycerides (TG) were significantly depleted after strenuous exercise and suggested that intramuscular TG were crucial for supplying free fatty acids (FFA) to working muscle (8,22,37). Thi
was further corroborated by data which indicated that endurance training resulted in greater storage and utilization of intramuscular fat reserves (17). The literature also provides considerable evidence that enzymatic adaptations to a high-fat diet resulted in an increased capacity for lipid oxidation during exercise (19,21,25,29,32,34). On the contrary, consumption of a high-carbohydrate diet has been associated with reduced increased capacity for lipid oxidation during exercise (19,25,26). These data suggest that a severe fat restriction may neutralize some of the metabolic advantages conferred by endurance training. Earlier reports which concluded that fat-rich diets were detrimental to endurance have utilized untrained subjects and high-fat diets that were severely carbohydrate deficient. The purpose of the present study was to examine physiological, metabolic, and performance effects in highly trained runners, performing high intensity exercise, in response to a high-carbohydrate, fat-restricted diet compared with a moderate-carbohydrate, fat-rich diet.

METHODS

Subjects. Six male collegiate distance runners participated in this study. Minimum criteria for oxygen uptake (VO$_{2\text{max}}$ $\geq$ 55 ml·kg$^{-1}$·min$^{-1}$) and weekly training distance (≥ 50 miles·wk$^{-1}$ for the past year) were used to screen the subjects. Participants were medically cleared and fully informed of the risks and stresses associated with the project before giving their written consent. Pre-tests were conducted to determine VO$_{2\text{max}}$ and to familiarize subjects with laboratory procedures and treadmill running. Body composition was determined by hydrostatic densiometry using residual lung volumes predicted from standard tables (39). The runners were 21 ± 0.7 yr old, 65.8 ± 2.5 kg in weight, and 177.5 ± 2.2 cm in height. They had 9.2 ± 2.8% fat, a maximum heart rate of 189 ± 2 beats·min$^{-1}$, and a VO$_{2\text{max}}$ of 63.7 ± 2.6 ml·kg$^{-1}$·min$^{-1}$.

Design. The novelty of this study depended upon the recruitment of subjects from a specific population of highly trained runners. Therefore, both the diet and exercise protocols were adjusted to accommodate the members of the university track team. At the onset of the investigation, subjects were involved in their maintenance phase of training. Approximately 3 wk remained before the start of the indoor season, at which time their training regimen would be altered. Accordingly, the study was designed to be completed within a 3-wk time frame. The data collection component was adapted to fit within the constraints of the subjects' class schedule.

Subjects performed two treadmill tests after three different dietary conditions: their normal (N) diet, a 7-d high-fat (F) diet, and a 7-d high-carbohydrate (C) diet. According to self-reported training schedules, subjects adhered to a consistent training regimen throughout the duration of the study. Subjects were first tested on their N diet. Exercise tests were then performed in response to the F and C diets, respectively. The rationale for this sequence was twofold. First, the team coach requested that the experimental (F) diet did not precede their first indoor competition. Second, this schedule would minimize any order advantage that would have been gained during the F diet. By having subjects follow the F diet before the C diet, performance measured during F could not be attributed to a training effect or a carryover effect from the glycogen loading (C) diet.

Dietary protocol. Prior to the onset of this investigation, the subjects were given detailed instructions regarding food record keeping. Food records were maintained for four consecutive days, including at least one weekend day, and were subsequently reviewed with each subject. Diets were analyzed using Nutritionist III (ver. 7.0, N$^{2}$ Computing, Salem, OR). In addition, the subjects completed a food preference questionnaire that was used when constructing the diet menus.

Subjects were tested on their N diet and then spent 7 d on each of the two experimental diets. The protein and energy contents of these two diets were kept constant. Energy requirements were based on an analysis of daily energy expenditure using the FIT III energy requirement program with Nutritionist III. Daily menus for the F and C diets were created using Auto-Nutritionist III and were modified according to individual preferences. Subjects were required to check off daily menu items as they were consumed. They were also required to record any deviations from the provided menus. Diets and records were subsequently reviewed with each subject. To encourage dietary compliance, subjects were informed that they would receive financial compensation upon successful completion of the entire program.

Exercise protocol. On the day of the exercise testing, the subjects reported to the laboratory following an overnight fast. Body weight and a resting blood sample were taken prior to exercise. The exercise testing protocol was repeated for each dietary trial. The subject first performed a progressive maximum treadmill test at a comfortable running speed (9.7 km·h$^{-1}$ to 11.3 km·h$^{-1}$). During this test, the grade was progressively increased every 3 min until the subject could no longer continue. Cardiorespiratory measurements were recorded during the last minute at each grade and during the final 60–90 s of the maximum test. Blood samples were drawn from the antecubital vein immediately following the maximum test. The subject then rested for 30 min before beginning a prolonged (endurance) treadmill test. During the first 30 min of the endurance test, the grade was elevated to a level consistent with approximately 85% of VO$_{2\text{max}}$ to facilitate glycogen depletion. After 30 min, the grade was reduced to a workload of 75–80% of VO$_{2\text{max}}$ for the remainder of the exercise. Cardiorespiratory measures were recorded at 5 min and 15 min, and every 15 min.
thereafter. The treadmill was stopped momentarily at 30 min and 60 min, so that blood samples could be drawn. Blood samples were also taken immediately after the subject stopped running (voluntary exhaustion).

Cardiorespiratory parameters. Throughout the exercise tests, an ECG was recorded to determine heart rate (HR). Expiratory gas volumes were collected by an Ohio Spirometer (Ohio Medical Products, Madison, WI) and analyzed using mass spectrometry (Perkin-Elmer Medical Instrument Co., Pomona, CA). Data for VO₂, ventilation (V₇), and the respiratory exchange ratio (R = VCO₂/VO₂) were calculated by computer from Soltec (San Fernando, CA) recorder tracings. End tidal O₂ (P₉O₂) and CO₂ (P₁₀O₂) were also measured and recorded. R was corrected for changes in ET CO₂ to better estimate the respiratory quotient (RQ) at the muscle (35).

Biochemical parameters. At the times described above, a 3-ml blood sample was drawn from the antecubital vein and then transferred to two test tubes pretreated with dried heparin. One sample was immediately deproteinized with 2 ml of 0.6 M perchloric acid and centrifuged (3,000 g, 4°C until measurement of lactate. The second sample was similarly centrifuged and plasma was separated and stored at 4°C until analysis of TG, glycerol, and glucose. A 0.2-ml aliquot of plasma was immediately transferred into 4 ml of chloroform:methanol (2:1) and was kept refrigerated at 4°C for analysis of FFA. FFA were determined using the colorimetric method of Itaya (18). Enzymatic analysis of blood lactate was measured by the Rapid Lactate Test obtained from Behring Diagnostics (Somerville, NJ) (7). Enzymatic determination of glucose, glycerol and TG were performed using materials obtained from Sigma Diagnostics (St. Louis, MO) (2,4).

Statistics. Descriptive statistics are given as means and standard error of the means (SEM). Using Number Cruncher Statistical System (ver. 5.0, Kaysville, UT), a one-way or two-way ANOVA (diet or diet and time, when applicable) was conducted. Statistical analyses were performed by employing a repeated measures design using a pooled SEM to minimize variation due to subject differences (13). When the ANOVA results were significant, differences between means were tested (P < 0.05) by the Newman-Keuls post-hoc test.

RESULTS

Diet composition. Table 1 shows the composition of the N, F, and C diets. The macronutrient composition of the N diet was in between that of the two experimental diets. The total energy intake reported during the N diet averaged 711 kcal-d⁻¹ less than the energy intake during the F and C diets. Based on our estimation of energy expenditures, consumption during the N diet did not provide for their predicted energy needs. Subjects’ body weight was unaffected by dietary changes.

Maximum test. Standard criteria for defining VO₂max were met, including an increase in VO₂ to greater than 150 ml, blood lactate concentration greater than 8.0 mmol, and an R value greater than 1.0. One subject became ill during the last week of the study. As a result, only five subjects were tested on the C diet. VO₂max (Table 2) during the progressive maximum tests was significantly greater (P < 0.05) during the F diet by 4.2% and 11.4% as compared with the N and C diets, respectively. There was no significant difference in VO₂max between the N and C diets. The total time of the maximum test averaged 12.5 ± 0.7 min, 13.1 ± 0.9 min and 12.9 ± 1.0 min for the N, F, and C diets, respectively. These differences were not statistically significant.

Values obtained during the maximum tests were analyzed as a function of increasing grade. VO₂ (Fig. 1), HR, and R (Fig. 2) were not significantly different at any grade interval when comparing values for the three dietary conditions. The average maximum HRs (189 ± 2 beats-min⁻¹) during the maximum tests were not significantly different among the three diets. A statistical analysis of resting blood values revealed that there were no dietary effects on resting blood chemistries. Lactate levels were significantly (P < 0.05) increased during the maximum tests (0.8 ± 0.4 mmol at rest to 11.2 ± 1.3 mmol, 10.3 ± 0.7 mmol, and 8.3 ± 0.7 mmol for the N, F, and C diets, respectively). However, there were no significant differences among the diets.

Changes in plasma FFA during the maximum tests are illustrated in Figure 3. Compared with resting levels, FFA following maximal exercise decreased (P < 0.05) by 25% and 47% for the N and C diets, respectively. In contrast, FFA increased (P < 0.05) by 49% during the maximum test for the F diet. Plasma glycerol was 42.7 ± 7.9 mg·dl⁻¹ after the maximum test for the C diet. The glycerol levels were significantly lower (P < 0.05) for the N and F diets (20.1 ± 4.3 mg·dl⁻¹ and 17.5 ± 2.8 mg·dl⁻¹,

### Table 1. Diet composition of the fat (F), carbohydrate (C), and normal (N) diets.

<table>
<thead>
<tr>
<th>Diet</th>
<th>kcal·d⁻¹</th>
<th>CHO%</th>
<th>Fat%</th>
<th>Protein%</th>
</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>3,500</td>
<td>50</td>
<td>38</td>
<td>12</td>
</tr>
<tr>
<td>C</td>
<td>3,500</td>
<td>73</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>2,789</td>
<td>61.2</td>
<td>24.3</td>
<td>13.7</td>
</tr>
</tbody>
</table>

### Table 2. Mean ± SEM for VO₂max and time to exhaustion measured after feeding the fat (F), normal (N), and carbohydrate (C) diets.

<table>
<thead>
<tr>
<th></th>
<th>F</th>
<th>C</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fat (% kcal)</td>
<td>38</td>
<td>24</td>
<td>15</td>
</tr>
<tr>
<td>VO₂max (N = 6)</td>
<td>66.4*</td>
<td>63.7*</td>
<td>59.6*</td>
</tr>
<tr>
<td>(mg·kg⁻¹·min⁻¹)</td>
<td>(SEM)</td>
<td>2.7</td>
<td>2.6</td>
</tr>
<tr>
<td>Endurance time (N = 5)</td>
<td>91.2*</td>
<td>68.3*</td>
<td>75.8*</td>
</tr>
<tr>
<td>(min)</td>
<td>(SEM)</td>
<td>9.5</td>
<td>7.2</td>
</tr>
</tbody>
</table>

* Values having different superscripts are significantly different (P < 0.05).
respectively) (Fig. 4). Blood glucose levels averaged 5.0 ± 0.2 mmol at rest. Glucose measured after the maximum tests were significantly higher (P < 0.05) during the N and F diets as compared with the C diet (8.6 ± 0.6 mmol, 8.1 ± 0.5 mmol, and 4.6 ± 0.1 mmol, respectively). Serum TG levels averaged 67.0 ± 6.6 mg/dl and were not significantly affected by diet or exercise. 

**Endurance test.** During the endurance test for the F diet, one runner stopped because of pain in his knees. Therefore, his running time on the F diet was not included in the data analysis. The running times to exhaustion, during the endurance tests, for the three dietary conditions are shown in Table 2. Subjects ran 32% longer (P < 0.05) during the F diet as compared with the N diet. The average running time for the F diet was 20% greater (P < 0.05) than that for the C diet. 

Measurements taken at the end of each endurance test are illustrated at different times, according to the time of voluntary exhaustion (Figs. 5–8). Cardiorespiratory parameters, including VO_{2max} (Fig. 5), HR (175 ± 1 beats-min^{-1}), and R (Fig. 6), were similar regardless of diet. However, during all dietary trials, VO_{2max} and R were significantly lower (P < 0.05) after 30 min of exercise. This observation is consistent with the change in workload which occurred at that time.

During the endurance tests, plasma FFA levels (Fig. 7) were higher (P < 0.05) for the F diet as compared with the C diet at both 30 min and 60 min. Statistical analysis revealed that the combined average FFA level for all
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The primary objective of the present study was to examine running performance in response to a high-carbohydrate, fat-restricted diet compared with a moderate-carbohydrate diet that included the addition of dietary fat. In contrast to previous work, the subjects selected were all highly trained (Division I NCAA college) middle-distance runners and the high-fat diet regimen was not carbohydrate deficient. Performance was measured during both a maximum (VO$_2$max) and submaximal endurance (time to exhaustion) test. The most significant result was that subjects performed best in response to the F diet.

Figure 5—Oxygen consumption (VO$_2$, ml·kg$^{-1}$·min$^{-1}$) plotted as a function of time during the endurance tests after feeding the normal (NORM), fat (FAT), and carbohydrate (CHO) diets.

Figure 6—Respiratory exchange ratio (R) plotted as a function of time during the endurance tests after feeding the normal (NORM), fat (FAT), and carbohydrate (CHO) diets.

Figure 7—Plasma free fatty acids (FFA, mmol) levels during the endurance tests after feeding the normal (NORM), fat (FAT), and carbohydrate (CHO) diets. * denotes significant differences ($P < 0.05$) between blood values obtained on different diets (*F vs C).

Figure 8—Plasma glycerol levels (mg·dl$^{-1}$) during the endurance tests after feeding the normal (NORM), fat (FAT), and carbohydrate (CHO) diets. b* denote significant differences ($P < 0.05$) between blood values obtained on different diets (bN vs C and *F vs C).

DISCUSSION

The overall mean for serum TG was 76.4 ± 2.7 mg·dl$^{-1}$. Serum TG were not affected by the duration or intensity of exercise.

Diet did not affect lactate levels at any of the measured time intervals during the endurance tests. Mean blood glucose concentrations were 5.9 ± 0.9 mmol during the first 30 min and fell to 5.3 ± 0.3 mmol for the remainder of the endurance test. Lactate and glucose levels fell in accordance with the reduction in workload at 30 min. However, lactate and glucose levels remained constant for the balance of the exercise. A decline in blood glucose or lactate levels were not observed at the time of exhaustion.
In addition, dietary assessment revealed a possible negative imbalance between energy intake and estimated daily expenditures when subjects were making their own dietary choices.

**Diet composition.** Energy intake was an intervening covariable during the N diet and, therefore, must be considered. Energy consumption reported during the N diet was approximately 700 kcal d⁻¹ less than the energy provided on the F and C diets and was likewise lower than subjects' estimated energy requirements. This finding appears to contradict the observation that subjects' body weights remained stable throughout the duration of the study. There are several possible explanations for this discrepancy.

First, consumption during the N diet may have been underestimated. We consider this an unlikely account, since food records were validated and many others have recorded daily energy consumptions (2,959 kcal d⁻¹ and 3,034 kcal d⁻¹) that were very similar to our assessments (3,10). Brownwell et al. (3) reported that energy consumption in runners is often below expected values because these athletes believe that a low body weight is necessary for optimal performance. Second, intakes may have been accurately recorded but may not be representative of the subjects' true average consumption. This scenario is contraindicated by the fact that all subjects reported that the amount of food provided on the F and C diets was greater than what they normally consume. Alternatively, the FIT III software is not without limitation, thus energy expenditures may have been underestimated. Finally, subjects' normal consumption may have imposed an energy deficit that resulted in a compensatory reduction in basal metabolic rate. A number of investigators have reported that energy consumptions below predicted expenditures failed to result in corresponding weight losses (3,28). Some have proposed that endurance athletes maintain body weight in the presence of a caloric deficit due to an adaptive mechanism that defends against excessive energy depletion (3,28).

**Performance.** Previous studies have reported that a hypocaloric diet is associated with low muscle glycogen levels and reduced performance (15,28). These findings may account for our observation that endurance (running time to exhaustion) was lowest on the N diet. Even in the event that a hypocaloric diet did elicit metabolic alterations that favored energy conservation, it is probable that muscle energy stores were still suboptimal, thereby contributing to reduced performance. Since the subjects had been training regularly prior to the onset of this investigation, it is unlikely that the reported differences in performance were consequent to a training elicited effect. The observation that HR and R values were reflective of fuel metabolism, the data imply that the relative contributions of fat (30%) and carbohydrate (70%) to the total energy cost of exercise was independent of dietary factors. Others have challenged the contention that fuel selection is determined by the magnitude of muscle and blood substrate concentrations (5,27). Some have suggested that the control of metabolic factors play an important role in limiting maximal VO₂ (11). In the present study, the finding that VO₂max increased in response to the F diet was unexpected. Since total work output during the maximum test was not significantly different, in spite of the apparent increases in VO₂ max, and the oxygen consumption may be due to a higher oxygen cost of producing ATP from fat. Of the contrary, although not statistically significant, the subjects did perform longer at the highest workload during the maximum test on the F diet. Sim et al. (34) reported similar observations in rats and theorized that a possible mechanism could be an enhancement of beta-oxidizing capacity consequent to enzymatic changes. Other researchers have documented similar enzymatic adaptations to a high-fat diet in both animals and humans (29,32). These findings offer evidence that animals and humans adapt to a fat diet by increasing skeletal muscle oxidative capacity in a manner similar to that observed in response to endurance training. Thus, one could postulate that dietary manipulations which facilitate lipid utilization may allow for an increased power output from fat oxidation.

In contrast to current views, our data indicate that endurance performance may be optimized by a fat-rich diet. Most of the classic studies that have documented performance benefits following a high-carbohydrate diet were conducted with untrained or moderately trained subjects (1,16,24). Highly trained subjects have higher glycogen levels (33) and a higher potential for lipid utilization (23) than untrained individuals. Consequently, glycogen loading diets may not always be advantageous for endurance trained athletes (27). The extent to which initial glycogen levels influence performance is dependent on the intensity of the exercise and the specificity of the event. In the present investigation, subjects performed a high-intensity running exercise. Although muscle biopsies were not obtained, our results appear consistent with the study of Madisen et al. (27); muscle biopsies did indicate that glycogen concentration was not a limiting factor in trained runners during a middle-distance exercise (75-85% VO₂max).

**Metabolism.** Our finding that R was unaffected by dietary manipulations disagrees with previous studies (1,20,21,31). This discrepancy may be due to the fact the present dietary conditions were not as extreme as those used previously. In addition, R may not provide an adequately sensitive measure to detect differences in substrate selection during heavy exercises. In the event that R values were reflective of fuel metabolism, the data imply that the relative contributions of fat (30%) and carbohydrate (70%) to the total energy cost of exercise was independent of dietary factors. Others have challenged the contention that fuel selection is determined by the magnitude of muscle and blood substrate concentrations (5,27). Some have suggested that the control of
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substrate selection may be dependent on the intensity of the exercise (38). During heavy exercise, when energy metabolic pathways are working at or near their maximum capacity, there may be less latitude to select substrates on the basis of availability. This proposal is speculative and greatly oversimplified, but deserves further experimental attention.

Blood glucose levels were maintained throughout the endurance exercise. Thus, hypoglycemia was not faulted for exhaustion. Although arterial pH was not obtained, low venous lactate concentrations suggest that acidosis was also an unlikely factor in fatigue. Blood glucose levels were lower after the maximum exercise test when subjects were on the C diet. This finding was puzzling, since we would expect glucose levels to be higher following the C diet. However, others have reported similar findings (27). Alterations in the maximal capacity of glucose transport mechanisms or enhancement of carbohydrate utilization may provide a possible explanation. These too require further investigation.

Plasma FFA were lower and glycerol levels were higher during exercise in response to the C diet compared with the F diet. Since glycerol provides a rough indicator of adipose tissue lipolysis, the observation that glycerol levels were higher during the C diet favors the interpretation of an increase in the rate of FFA uptake (17,20), rather than a decrease in FFA mobilization. It has been reported that during heavy exercise, increased uptake of plasma FFA cannot be balanced by a compensatory increase in mobilization (14,22). The appearance of FFA in the blood represents the net result of FFA release from the adipose and FFA uptake at the muscle. Our findings imply that the release, as well as the uptake, of FFA was greater during the C diet. This suggests that the FFA pool immediately available to the muscle may have been lower at the onset of exercise after the C diet. Reduced availability of intramuscular lipids would create an increased dependency on the supply of fat from exogenous (blood) sources. Assuming this to be true, our data agree with others who have shown that a low-fat diet results in reduced availability of intramuscular FFA (19,25,26). Furthermore, our observation that performance was improved during the F diet compared with the C diet is consistent with Soza and Karpati (36). They demonstrated that skeletal muscle endurance was diminished when the availability of endogenous TG was reduced.

The availability of muscle glycogen has long been considered the primary limitation during endurance exercise. However, there is accumulating evidence that argues against the premise that endurance, especially in trained individuals, is directly and exclusively related to glycogen levels (6,27,32). Recently, researchers have proposed that the capacity to oxidize FFA during prolonged exercise plays a more important role than was previously thought (12). Intramuscular TG appears to be the major source for maintaining the muscle FFA pool during exercise. Numerous studies have provided evidence that muscle TGs are significantly depleted during relatively high-intensity, submaximal exercise (17,22,37). During such exercise, the contribution of fat may be critical to the overall energy supply, but mobilization of adipose tissue TGs may be limited (14,22). Therefore, just as depleted glycogen levels can result in reduced performance, low muscle TG stores may also produce the same consequence.

A high-carbohydrate, low-fat diet has been shown to inhibit the optimal refilling of the muscle TG pool (19,25,26). These findings may be of particular significance in highly trained endurance runners (37). Low concentrations of muscle TG at the onset of heavy exercise would lead to a reduced availability of FFA substrate for oxidative metabolism. This would require an increased uptake of plasma FFA to maintain the intramuscular FFA pool. Hodgetts et al. (14) proposed that the rate of exogenous FFA delivery to working muscle may be limited by the rate of release by the adipose tissue or by the transport capacity of the plasma. This may, in part, explain our observation that plasma concentrations of FFA were reduced during exercise on the C diet. Therefore, our data are in agreement with others and suggests that dietary manipulations to increase intramuscular TG levels may provide an advantage to endurance athletes.

SUMMARY

Our data are consistent with a number of investigations that have shown muscular adaptations to a high-fat diet which result in preserved submaximal exercise endurance. Furthermore, our findings present evidence that severe restriction of dietary fat may be detrimental to endurance performance. This investigation was designed as a prototype study that would be extended, if warranted. We recognize that there are limitations to our design that consequently restrict the certainty of the conclusions which can be delivered. However, our results do indicate a need for further research to reevaluate the limitations of fat as an energy substrate during heavy exercise. Future investigations will need to incorporate a more precise protocol and include more mechanistic metabolic measures. Although it would not be prudent to advise fat intake in excess of 30% of total daily calories athletes who limit fat consumption to well below this level, especially without adequately compensating with other energy sources, may adversely affect performance.

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REFERENCES


