Utilization of skeletal muscle triacylglycerol during postexercise recovery in humans

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Kiens, Bente, and Erik A. Richter. Utilization of skeletal muscle triacylglycerol during postexercise recovery in humans. Am. J. Physiol. 275 (Endocrinol. Metab. 38): E332–E337, 1998.—The utilization of muscle triacylglycerols was studied during exercise and in the postexercise recovery period. Subjects were fed a carbohydrate-rich diet (65–70% of energy from carbohydrates). Exercise decreased muscle glycogen concentrations by 53 ± 18% to 108 ± 10 mmol/kg dry wt, whereas muscle triacylglycerol concentrations were unaffected (49 ± 5 before vs. 49 ± 8 mmol/kg dry wt after exercise). During the first 12 h after exercise, muscle glycogen concentrations were restored to 409 ± 20 mmol/kg dry wt. In contrast, muscle triacylglycerol concentrations decreased (P < 0.05) to a nadir of 38 ± 5 mmol/kg dry wt, and muscle lipoprotein lipase activity increased by 72% compared with values before exercise. Pulmonary respiratory exchange ratio values of 0.80–0.82 indicated a relatively high fractional lipid combustion despite the high carbohydrate intake. From 18 to 42 h of recovery, muscle glycogen synthesis was slow and muscle triacylglycerol concentrations and lipoprotein lipase activity were restored to the preexercise values. It is concluded that muscle triacylglycerol concentrations are not diminished during exhaustive glycogen-depleting exercise. However, in the postexercise recovery period, muscle glycogen resynthesis has high metabolic priority, resulting in postexercise lipid combustion despite a high carbohydrate intake. It is suggested that muscle triacylglycerols, and probably very low density lipoprotein triacylglycerols, are important in providing fuel for muscle metabolism in the postexercise recovery period.

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**MATERIALS AND METHODS**

Eight well-trained male athletes (1 rower, 3 runners, 2 cyclists, and 2 swimmers) participated in the study. Five of these subjects participated in competition. Subjects were 20–30 yr of age, body weight averaged 68 kg (63–75 kg), and height averaged 182 cm (175–188 cm). Maximal oxygen uptake (Vo2max, measured rowing or a on Krogh bicycle ergometer or treadmill) averaged 4.5 l/min (range 3.9–5.4 l/min).

To establish daily energy intake and composition of the subject's habitual diet, 4-day diet records were carried out by all subjects (3 weekdays and 1 weekend day). All food intake and beverages were weighed and recorded, and energy intake and composition of the diets were calculated with a computer database (Dankost II, the Danish Catering Center, Copenhagen, Denmark). In addition, individual energy intakes were determined from the World Health Organization's equation for calculation of energy needs (32). All subjects were fully informed of the nature of the study and the possible risks associated with it before they volunteered to participate, and written consent was given. The study was approved by the Copenhagen Ethics Committee and conforms with the code of ethics of the World Medical Association (Declaration of Helsinki). Subjects were covered by state medical insurance and also by the insurance that covers hospitalized patients in case of complications.

Protocol. During the 2 days before the experiments, the subjects abstained from all sport activities and consumed a carbohydrate-rich diet [65–70% of energy (E%) from carbohydrates (CHO), 20 E% from fat, and 10–15 E% from protein] to ensure filled glycogen stores. On the experimental day (D0), the subjects reported to the laboratory either by bus or car in the morning after an overnight fast. After 30 min of rest in the supine position, resting oxygen uptake (VO2) and respiratory exchange ratio (RER) were measured. A needle biopsy was then taken from the vastus lateralis muscle under local
anesthesia with lidocaine. Then a light breakfast (800 kJ) was consumed, consisting mainly of CHO with a high glycemic index (GI). After 2 h of rest, exercise was initiated on a Krog bicycle ergometer. Exercise was performed at 75% of $V_{O_2max}$ for 20 min followed by alternating 2-min bouts of 90 and 50% of $V_{O_2max}$ as previously described (17), for ~90 min until exhaustion to ensure depleted muscle glycogen stores. At termination of exercise, another muscle biopsy was taken in the same leg as the morning biopsy through a new incision spaced 4–5 cm from the first. Blood was drawn from a catheter inserted in the antecubital vein. For the following 42 h subjects were asked to abstain from all sport activities.

In this period the subjects continued to follow the well-controlled diet. During the rest of $D_0$, forearm venous blood samples, muscle biopsies from the vastus lateralis muscle, and resting oxygen uptake were obtained frequently. The following day ($D_1$), samples were obtained before breakfast in the fasting state (morning $D_1$, hour 18 of recovery) and before dinner (evening $D_1$, hour 30 of recovery). On $D_1$ subjects were allowed to leave the laboratory between samplings, and they slept at home. On $D_2$ samples were obtained before breakfast only (morning $D_2$, hour 42 of recovery). Muscle biopsies were taken, with alternation of these between right and left thighs, through different incisions spaced 4–5 cm apart.

Diet. All food ingested by the subjects during the recovery period was prepared and weighed in a metabolic kitchen. It was prepared on an individual basis, to one gram of accuracy. The composition of the diet in the postexercise recovery period was aimed at providing 65–70 E% from CHO, 10–15 E% from protein, and 20 E% from fat. The first meal was begun 1 h after termination of exercise. The amount of CHO, as well as energy contained in this meal, was calculated to provide that utilized during the exercise bout. A light meal was consumed 3 h later, and dinner after another 3 h. On the following day ($D_1$) four meals were ingested, distributed over the day. Common food items were used in the diet, consisting of CHO-rich food items varying in GI and averaging a GI of 62 with glucose as reference. The subjects consumed 8–10 g CHO·kg body wt$^{-1}$·day$^{-1}$. Total energy intake during the experimental days was based on the energy intake calculated from the individual self-registrations.

Blood analyses. Blood glucose was analyzed by enzymatic fluorometric methods (19) after whole blood had been deproteinized in ice-chilled perchloric acid and neutralized by KOH. Plasma free fatty acids (FFA) were measured fluorometrically as described by Kiens et al. (12). Insulin in plasma was determined using a radioimmunoassay kit, kindly donated by Novo-Nordisk (Copenhagen, Denmark), and catecholamines in plasma were determined by a radioenzymatic procedure (2).

Muscle analyses. The biopsy samples were frozen in liquid nitrogen within 10–15 s and were stored at ~80°C until further analysis. Before biochemical analysis, muscle biopsy samples were freeze-dried and dissected free of connective tissue, visible fat, and blood with a stereomicroscope and were then powdered and mixed. TG$\text{m}$ concentration was determined from ~2 mg (dry wt) muscle sampled from the ~15 mg (dry wt) mixed powder. Glycol from the degraded TG was assayed fluorometrically as described by Kiens and Richter (15). Muscle glycogen concentration was determined as glucose residues after hydrolysis of the muscle sample in 1 M HCl at 100°C for 2 h (19). Lipoprotein lipase activity in muscle (LPL$\text{Am}$) was determined as described (13).

$V_{O_2}$ and heart rate. Pulmonary $V_{O_2}$ at rest and during exercise was determined by collection of expired air in Douglas bags. The volume of air was measured in a Collins bell-spirometer (according to the Tissot principle), and the fractions of oxygen and carbon dioxide were determined with paramagnetic (Servomex) and infrared (Beckmann LB-2) systems, respectively. Two gas samples with known compositions were used to calibrate both systems regularly. Heart rate was recorded with a PE 3000 Sports Tester (Polar Electro, Finland).

Statistical evaluation. Results are given as means ± SE, if not otherwise stated. For each variable measured, a one-way ANOVA with repeated measures for the time factor was performed to test for changes during recovery. Differences between time points were detected with an all pairwise multiple comparison procedure (Student-Newman-Keuls method). In all cases, an α of 0.05 was used as level of significance.

RESULTS

TG$\text{m}$ concentrations averaged 49 ± 5 mmol/kg dry wt at rest ($D_0$, Fig. 1) and remained unchanged at termination of the exercise bout. After 3 h of recovery, TG$\text{m}$ concentrations had decreased significantly and reached a nadir 18 h after the end of exercise (morning $D_1$), at which point TG$\text{m}$ concentrations were 20% lower than at rest (Fig. 1). TG$\text{m}$ remained lower than initial concentrations for 30 h after termination of exercise (evening $D_1$, Fig. 1). Muscle glycogen concentrations amounted to 533 ± 18 mmol/kg dry wt at rest and decreased to 268 ± 15 mmol/kg dry wt (P < 0.05). After 30 h of recovery, muscle glycogen concentrations had increased to 500 ± 25 mmol/kg dry wt, which was similar to initial values (Fig. 2). After exercise, LPL$\text{Am}$ was slightly but significantly higher than the value before exercise (Table 1). LPL$\text{Am}$ increased to a maximum value 18 h after termination of exercise and returned to basal levels by 42 h of recovery (Table 1).

Initially blood glucose concentrations averaged 4.42 ± 0.10 mmol/l (Table 2). After 2 h of recovery, blood glucose concentrations were significantly higher than baseline values and remained elevated for the following 2 h. Plasma insulin concentrations were higher (P < 0.05 vs. resting values).

Fig. 1. Concentrations of triacylglycerol in vastus lateralis muscle (TG$\text{m}$) at rest ($D_0$), immediately after exercise (Exer. stop), and during postexercise recovery. Morning (Morn.) $D_1$ = hour 18 of recovery, evening (Even.) $D_1$ = hour 30 of recovery, and Morn. $D_2$ = hour 42 of recovery. Values are means ± SE of 8 observations. dw, Dry wt. *P < 0.05 vs. resting values.
Total daily energy intake averaged 16.0 MJ, and the habitual diet of the subjects averaged 14.5 (13–18) MJ.

During the experimental period, resting V̇O₂ was significantly higher than baseline values. During the remaining period until the end of the experiment, plasma FFA concentrations were significantly higher than baseline values (Table 2). During the rest of D₀ and in the morning of D₁, RER averaged 0.81 (Table 2). Resting V̇O₂ measured in the morning 4 h before exercise start averaged 0.26 l/min (Table 2). Four and six hours after exercise stop, resting V̇O₂ was significantly higher than baseline values. During the remainder of the experimental period, resting V̇O₂ was similar to baseline values (Table 2).

On the basis of 4 days of self-registration records, the habitual diet of the subjects averaged 14.5 (13–18) MJ. Total daily energy intake averaged 16.0 ± 2.4 and 14.4 ± 0.6 MJ on D₀ (exercise day) and on D₁ (resting day), respectively. Calculated dietary CHO intake averaged 641 (560–761) g and 552 (538–567) g on D₀ and D₁, respectively. This amounts to an average of 8.9 (8.0–10.0) g/kg body wt on D₀ and 7.6 (7.1–8.9) g/kg body wt on D₁, which results in an average of 8.3 g·kg⁻¹·day⁻¹ during the postexercise recovery period.

On the basis of chemical analysis, the diet in the postexercise recovery period consisted of 70–73 E% of CHO, 15 E% of protein, and 12–15 E% of fat. The first meal (1 h after termination of exercise) contained 47 ± 7% of the total energy intake of D₀ and 49 ± 6% of total CHO intake for D₀.

DISCUSSION

The main finding in the present study is that skeletal muscle TG concentrations decrease in the postexercise recovery period despite a large intake of CHO (8.3 g CHO·kg body wt⁻¹·day⁻¹, amounting to ~570 g/day). In contrast, no TGₘ breakdown could be detected during exercise. The rapid and marked decrease in TGₘ concentrations during the postexercise recovery period was surprising because, in accordance with the literature, intake of diets rich in CHO for shorter or longer periods is associated with a high fractional CHO oxidation at rest and during exercise (1, 8). Thus it might be expected that during the present postexercise recovery period there would be no need for significant fat oxidation. Nevertheless, the RER values of an average of 0.81 in the postexercise recovery period indicate a substantial fractional fat oxidation during the first 18 h of recovery. It appears that muscle glycogen resynthesis has such high metabolic priority during recovery that utilization of lipids is necessary to cover energy expenditure in muscle and that TGₘ accounts for a substantial part of it.

The mechanisms involved in activating the TGₘ breakdown in postexercise recovery are elusive, because the regulation of the responsible lipase is not known. It has been proposed that a hormone-sensitive TG lipase (HSL) enzyme similar to the adipose tissue HSL could regulate TGₘ hydrolysis (26). After the production of an antibody raised against the purified rat adipose tissue HSL, immunological evidence has been presented to support this hypothesis. In rat skeletal muscle extracts, immunoblotting with this antibody revealed the presence of an antigenic protein with a molecular mass similar to that of the adipose tissue HSL (9). The use of a cDNA clone to perform Northern blotting showed that HSL mRNA in heart tissue HSL (9). The use of a cDNA clone to perform Northern blotting showed that HSL mRNA in heart tissue HSL (9). The use of a cDNA clone to perform Northern blotting showed that HSL mRNA in heart tissue HSL (9). The use of a cDNA clone to perform Northern blotting showed that HSL mRNA in heart tissue HSL (9). The use of a cDNA clone to perform Northern blotting showed that HSL mRNA in heart tissue HSL (9). The use of a cDNA clone to perform Northern blotting showed that HSL mRNA in heart tissue HSL (9). The use of a cDNA clone to perform Northern blotting showed that HSL mRNA in heart tissue HSL (9). The use of a cDNA clone to perform Northern blotting showed that HSL mRNA in heart tissue HSL (9). The use of a cDNA clone to perform Northern blotting showed that HSL mRNA in heart tissue HSL (9). The use of a cDNA clone to perform Northern blotting showed that HSL mRNA in heart tissue HSL (9).
Table 2. Blood glucose, plasma insulin, FFA, RER, and \( V_{\text{O2}} \) before and after exercise and during postexercise recovery

<table>
<thead>
<tr>
<th></th>
<th>Exercise</th>
<th>Recovery</th>
<th>Day 0</th>
<th>Day 1</th>
<th>Day 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Before</td>
<td>After</td>
<td>1 h</td>
<td>2 h</td>
<td>3 h</td>
</tr>
<tr>
<td>Glucose, mmol/l</td>
<td>4.42±0.10</td>
<td>4.56±0.28</td>
<td>3.94±0.24</td>
<td>6.03±0.15*</td>
<td>5.68±0.31*</td>
</tr>
<tr>
<td>Insulin, µU/ml</td>
<td>9.3±4.5</td>
<td>5.4±1.5*</td>
<td>4.5±2.0*</td>
<td>15.9±7.9*</td>
<td>36.1±7.8*</td>
</tr>
<tr>
<td>FFA, µmol/l</td>
<td>288±38</td>
<td>1,326±192*</td>
<td>2.038±198*</td>
<td>546±95*</td>
<td>285±28</td>
</tr>
<tr>
<td>RER</td>
<td>0.85±0.02</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
</tr>
<tr>
<td>Resting ( V_{\text{O2}} ), l/min</td>
<td>0.26±0.01</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
</tr>
</tbody>
</table>

Values are means ± SE of 8 observations. FFA, free fatty acids. Respiratory exchange ratios (RER) and resting oxygen uptake (\( V_{\text{O2}} \)) were obtained before exercise and during selected recovery times. ND, not determined. *P < 0.05 vs. before exercise.

Reflected in measurable increases in forearm venous plasma norepinephrine concentrations, from which our values stem, it is unlikely that sympathetic nervous activity was markedly increased to the muscles in postexercise recovery. Thus increased sympathetic activity may not play a major role for the observed breakdown of TGm, observed in the present postexercise recovery period.

Regarding insulin, it might seem surprising that the TGm content in the early recovery period decreased in the face of increased plasma insulin levels, because, if anything, one might expect the lipase to be inhibited by insulin as is the case in adipose tissue. This assumption is supported by recent findings using microdialysis, which show that the interstitial glycerol concentration in muscle is decreased during infusion of insulin (6). Thus, in the postexercise recovery period, the apparent inhibitory effect of insulin on muscle lipolysis is in effect overruled by some unknown stimulatory signal probably related to muscle glycogen depletion. There are other examples of activation or inhibition of enzymes by substrate. For instance, the activity of glycerol synthase in muscle is influenced by the glycogen concentration. Thus low glycogen concentrations are associated with a high glycerol synthase activity (22). The molecular mechanism linking low glycogen concentrations to glycerol synthase activation is not known, but it cannot be excluded that this mechanism might also cause activation of the TG lipase in skeletal muscle.

Another intriguing example of substrate-enzyme interaction is found after exercise: orally ingested CHO escapes the liver and is used for muscle glycogen repletion until the glycogen stores in muscle are refilled (20). Only then does the liver retain absorbed CHO to replenish its own glycogen stores (20). This example of how replenishment of muscle glycogen stores after exercise has priority over replenishment of other substrate stores is still biochemically unexplained but serves to support the notion that glycogen stores in muscle may also influence activity of the TG lipase in skeletal muscle.

It might be argued that the transient decrease in TGm content in the postexercise recovery period was due to the CHO-rich diet per se rather than the preceding exercise-induced muscle glycogen depletion. However, essentially the same CHO-rich diet was fed 2 days before the exercise bout as during the recovery period. It is very unlikely that a transient decrease in TGm content would suddenly occur after 2 days on the diet if no exercise had been performed. Furthermore, if the decrease in TGm were due to the CHO-rich diet by itself, then it would not be expected to be a transient effect, because the CHO-rich diet was consumed throughout the recovery period. Therefore, it is unlikely that the CHO-rich diet by itself led to the decrease in the TGm content in the postexercise recovery period.

In the present study we demonstrated an increase in LPLAm immediately after exercise (Table 1). This is in accordance with previous findings by Lithell et al. (18) after exhaustive prolonged exercise. The 4-h delayed increase in LPLAm after exercise previously reported by Kiens et al. (14) might be explained by a shorter exercise bout than in the present study and the study of Lithell et al. (18). In the present study, LPLAm was also increased in the postexercise recovery period, as observed previously (14), and the maximum activity was found at the same time that the TGm content was decreased the most. Because LPL is responsible for VLDL TG hydrolysis, our findings suggest that, in addition to TGm, providing lipid fuel in the postexercise recovery period, the breakdown of VLDL TG was probably also increased in muscle, providing supplementary long-chain fatty acids as fuel. Seip et al. (25) recently described increased muscle LPL mRNA and protein 4 and 8 h, respectively, after 72 min of exercise at 63% \( V_{\text{O2max}} \). These findings indicate that it is not only activity of the muscle LPL that is increased after exercise, but LPL gene transcription is also increased.

Several studies have previously addressed the question of whether TGm is utilized as a fuel during exercise. The answer has been equivocal, because some studies have demonstrated an exercise-induced decrease in TGm concentrations (3–5, 11, 23), whereas others have not (12, 27, 31). Part of the uncertainty regarding utilization of muscle TG stores during exercise probably stems from the difficulty in measuring TGm concentrations. It has recently been described that the aver-
age coefficient of variation for TG_m concentrations sampled three times from the same muscle in eight subjects was 24% (31). During exercise for 90 min at 65% VO2_max, it was reported that the average difference in TG_m concentrations from rest to after exercise was <24% (31). The authors concluded that differences in TG_m concentrations of <24% cannot be reliably measured with their biopsy technique. In our hands, the TG method allowed us to detect a difference of 10% between resting and 3-h postexercise concentrations (Fig. 1), possibly because we used a fraction (=2 mg dry wt) of a large powdered and mixed biopsy (=15 mg dry wt). Still, even though we can pick up relatively small differences after exercise, our data show no tendency toward a decrease in TG_m concentrations after exhausting glycolgen-depleting exercise. These data thus support evidence that, during such exercise, net utilization of intramuscular triglycerides even in well-trained subjects is negligible, in agreement with our earlier findings during 2 h of one-legged knee extensions in both trained and untrained muscle (12).

It is concluded that, in the recovery period after prolonged glycolgen-depleting exercise, oxidation of lipids covers >50% of oxidative metabolism despite a large intake of CHO. It appears that resynthesis of muscle glycogen in the postexercise recovery period has such high metabolic priority that TG_m, and possibly VLDL TG, are broken down at an increased rate to supply lipid fuel for oxidative muscle metabolism.

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