Moderate Exercise, Postprandial Lipemia, and Skeletal Muscle Lipoprotein Lipase Activity

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One mechanism by which prior exercise decreases the plasma triacylglycerol (TG) response to dietary fat may involve enhanced clearance of TG-rich lipoproteins. The purpose of the present study was to examine the influence of moderate intensity exercise on postprandial lipemia and muscle lipoprotein lipase (LPL) activity. Eight physically active, normolipidemic men aged 27.0 years (SD 4.2), body mass index 24.5 kg · m^{-2} (SD 1.3), participated in 2 oral fat-tolerance tests with different preceding conditions. The afternoon before one test (~ 16 hours), subjects cycled for 90 minutes at 62.3% (SD 1.7%) of maximal oxygen uptake. Before the other test, subjects refrained from exercise. Samples of muscle, venous blood, and expired air were obtained in the fasted state. Subjects then consumed a high-fat meal (1.4 g fat, 1.2 g carbohydrate, 0.2 g protein, 73 kJ energy per kg body mass) before further blood and expired air samples were collected until 6 hours. The 6-hour areas under the TG concentration *v* time curves for plasma and for the chylomicron-rich fraction were lower ($P < .05$) after exercise (plasma, 7.91 [SE 1.09] *v* 5.72 [SE 0.47] mmol · L^{-1} · h; chylomicron-rich fraction, 1.98 [SE 0.51] *v* 0.92 [SE 0.16] mmol · L^{-1} · h). Muscle LPL activity was not significantly influenced by prior exercise, but the 4 subjects who had higher muscle LPL activity after exercise also had the most noticeable decreases in postprandial lipemia. The difference in lipemia between trials was inversely related to the difference in LPL activity (rho = −.79, $P < .05$). In the fasted state and postprandially, carbohydrate oxidation was lower after exercise ($P < .05$). Thus moderate exercise attenuates postprandial lipemia, possibly by altering muscle LPL activity.

IMPAIRED METABOLISM of triacylglycerol (TG)-rich lipoproteins constitutes an atherogenic stimulus, particularly during the postprandial period.[1] When these particles reside in the circulation for a long time, the opportunity for exchange of TG for cholesterol from the cholesterol-rich lipoproteins is enhanced. Thus the effect of repeated episodes of exaggerated postprandial lipemia is to deplete high-density lipoproteins (HDL) of cholesterol, impair reverse cholesterol transport, and promote the formation of small, dense low-density lipoproteins.[2] The clinical significance of these events is supported by case-control studies that have found that high postprandial plasma TG concentrations are strong predictors of the presence of coronary heart disease.[3] Interventions that attenuate postprandial lipemia are therefore the subject of considerable research interest.

Moderate-intensity exercise performed 18 to 20 hours before a meal attenuates the postprandial increase in plasma TG,[4,5] but the mechanisms involved have not been explored. One possibility is increased activity of lipoprotein lipase (LPL) in the previously exercised skeletal muscle. Recent studies have found increased activity of this enzyme in skeletal muscle after prolonged vigorous exercise.[6] This could enhance the removal of TG-rich lipoproteins and oppose the increase in plasma TG concentration after a meal. The fact that the increase after exercise in muscle LPL messenger RNA and the decrease in plasma TG concentrations follow similar time courses[7] suggests that these changes in muscle are probably functionally important.

However, 2 factors argue against an important role for enhanced muscle LPL in the attenuation of postprandial lipemia by moderate exercise undertaken 18 to 20 hours earlier. First, the increase in muscle LPL activity induced by vigorous exercise seems likely to be dissipated by 24 hours,[8] and this effect seems likely to be even more short-lived after less intense exercise. Second, the metabolic milieu in the postprandial state facilitates the storage of TG in adipose tissue rather than muscle. Insulin stimulates adipose tissue LPL, while downregulating muscle LPL,[9] and there is evidence that muscle plays only a minor role in the disposition of lipoprotein TG after a mixed meal.[10,11]

The purpose of the present study was to examine the influence of prior exercise (~16 hours earlier) of moderate intensity on muscle LPL activity before an oral fat-tolerance test alongside the effects of this exercise on postprandial lipemia. Cycling was the mode of exercise so that the muscle from which the biopy specimen was taken (vastus lateralis) would be expected to be heavily engaged in the exercise.[12]

MATERIALS AND METHODS

Subjects

Eight men aged 27.0 (SD 4.2) years and with body mass index 24.5 (SD 1.3) kg · m^{-2} participated. They were normolipidemic, with plasma concentrations of total cholesterol, HDL cholesterol, and TG measured in the fasted state of 3.62 (SD 0.60) mmol · L^{-1}, 1.21 (SD 0.15) mmol · L^{-1}, and 0.76 (SD 0.19) mmol · L^{-1}, respectively. The study was approved by Loughborough University's Ethical Advisory Committee, and subjects gave written consent after being informed of the risks. They were all physically active at a recreational level, and none was taking any medication that would affect lipid or carbohydrate

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metabolism. Six subjects had the most common apolipoprotein E phenotype (E3/3), 1 the E3/2 phenotype, and 1 had the E3/4 phenotype.

Protocol

Each subject undertook 2 oral fat-tolerance tests with different preceding conditions, in a balanced cross-over design and with an interval of 1 week. The day before 1 test (control), subjects performed only activities of daily living. During the afternoon before the other test (prior exercise), starting at about 3 PM, subjects exercised for 90 minutes on a cycle ergometer at a work rate selected to elicit 60% of maximal oxygen uptake ($\dot{V}O_{2max}$).

Diet and exercise were standardized during the days leading up to each fat-tolerance test. Other than the session described above, subjects refrained from exercise for 3 days before each test. Food intake was weighed and recorded during the 2 days before the first fat-tolerance test and repeated exactly (food items, quantity, and time of eating) during the 2 days before the second test. Subjects consumed a low-fat meal the evening before fat-tolerance testing (15.7 g [SD 3.7g] fat, 14.8% [SD 4.9%] of energy) because the plasma TG response to a meal consumed after an overnight fast may be influenced by the carryover of fat ingested the previous evening.[13]

Exercise Tests

Preliminary exercise tests on a cycle ergometer (Monark 814E; Monark Exercise AB, Varberg, Sweden) were undertaken to determine $\dot{V}O_{2max}$ and the steady-state relationship between $\dot{V}O_2$ and work rate. The work rate needed to elicit 60 % of $\dot{V}O_{2max}$ was then interpolated. Heart rate was measured using short-range telemetry (PE 3000 Sport-Tester; Polar Electro, Kempele, Finland), and ratings of perceived exertion[14] were recorded. Capillary blood samples were taken during 90-minute exercise sessions for blood lactate determination.

Oral Fat-Tolerance Tests

Subjects arrived at the laboratory after a 12-hour fast, and a cannula was introduced into a forearm or antecubital vein. After an interval of 15 minutes, during which subjects remained in a supine position, a baseline blood sample was drawn and a 5-minute sample of expired air was collected. A muscle sample was then obtained from the vastus lateralis after local anesthesia of superficial tissues using lidocaine hydrochloride (5% wt/vol). The sample was blotted on filter paper to remove excess blood and frozen in liquid nitrogen within ~10 seconds. Biopsies were performed on the same leg in each trial, using incisions 2.5 cm apart. Biopsies were performed on the left leg of 4 subjects and on the right leg of 4 subjects. The time from the end of exercise to muscle sampling was 15.8 (SD 0.2) hours. After the biopsy, subjects consumed the high-fat meal within 15 minutes. The meal consisted of whipping cream, fruit, cereal, nuts, and chocolate and was given according to body mass (1.4 g fat, 1.2 g carbohydrate, 0.2 g protein, and 73 kJ per kilogram of body mass). For these subjects, this meant 95.4 (SD 5.9) g of fat, 87.5 (SD 4.8) g of carbohydrate, 15.1 (SD 0.9) g of protein, and 5.2 (SD 0.9) MJ of energy. The time from the end of exercise to the start of the postprandial observation period was 16.3 (SD 0.2) hours. Further blood samples were drawn one-half hour after completion of the meal and then hourly until 6 hours. Five-minute samples of expired air were collected hourly using Douglas bag techniques. Subjects rested in a supine position for at least 10 minutes before expired air and blood sampling. At all other times they sat quietly, reading, or watching television. Water was available ad libitum, but no other food or drink was consumed.

Analysis

Expired air was sampled in Douglas bags, and oxygen uptake and carbon dioxide production were measured using a paramagnetic oxygen analyzer (model 570A; Taylor-Servomex, Crowborough, England), an infrared carbon dioxide analyzer (Lira, model 3250; Mines Safety Appliances Ltd, Pittsburgh, PA), and a dry gas meter (Harvard Instruments, Edenbridge, England).

Muscle samples were stored at −70°C and later analyzed for LPL activity[15] and intramuscular triacylglycerol (IMTG) concentration.[16] Briefly, LPL was released from the vascular bed during incubation with heparin, and a [^{3}H]triolein emulsion before activity was measured by the release of [^{3}H]oleic acid. IMTG was assayed in a freeze-dried sample of muscle from 6 subjects after dissection of connective tissue, visible fat, and blood.

Plasma or serum was separated within 15 minutes of collection. Portions of plasma were stored at 4°C for determination of TG in the chylomicron-rich fraction[17] (within 48 hours) and HDL cholesterol (within 5 days). To prepare the chylomicron-rich fraction, plasma was gently pipetted under sodium chloride (density, 1.006 $g \cdot mL^{-1}$) and centrifuged at 17,602*g* for 99 minutes. Chylomicrons were harvested by aspiration. The concentrations of TG and cholesterol in this fraction were determined spectrophotometrically by enzymatic methods (Boehringer Mannheim UK Ltd, Lewes, England). Remaining plasma was stored at −70°C for determination of plasma concentrations of TG, total cholesterol, nonesterified fatty acids (NEFA), glycerol, and glucose by spectrophotometric, enzymatic methods (Boehringer Mannheim UK Ltd and Wako Chemicals GmbH, Neuss, Germany) and apolipoprotein B by an immunoturbidimetric assay (Roche Diagnostic Systems, Herts, England). Serum samples were separated and stored at −70°C for determination of insulin by radioimmunoassay (EURO/DPC Ltd., Caernarfon, England). Except when analysis was performed on fresh samples, all samples from 1 subject were assayed together. Intra-assay coefficients of variation for plasma TG, chylomicron-rich fraction TG, total cholesterol, HDL cholesterol, NEFA, glycerol, glucose, lactate, apolipoprotein B, and insulin were 1.47%, 2.42%, 0.67%, 0.80%, 0.59%, 2.37%, 0.83%, 2.77%, 1.27%, and 3.74%, respectively. Hemoglobin concentration and hematocrit were measured in baseline and 6-hour blood samples for estimation of differences between trials in plasma volume.[18] Apolipoprotein E phenotypes were determined by isoelectric focusing using Western blotting techniques.

Data Analysis

The concentration of TG in the non–chylomicron-rich fraction of plasma was determined as the difference between that in plasma (corrected for free glycerol) and that in the chylomicron-rich fraction. Summary measures[19] of postprandial responses were the total and incremental (above the fasting concentration) areas under the serum or plasma concentration-time curves or, if a quantity changed little over the observation period, the mean value. Suppression of NEFA was the difference between the baseline concentration and that at the nadir of the postprandial response.

Substrate oxidation was estimated by indirect calorimetry and used to calculate energy expenditure.[20] Whole-body substrate storage during the postprandial period was the difference between fat or carbohydrate ingested and the oxidation of that substrate during the 6-hour observation period, assuming that the amount of dietary fat and carbohydrate that had left the intestine within this period was not different between trials.

Data are reported as mean (SD) for descriptive indices and as mean (SE) for comparisons between trials.[21] Comparisons were made using the Wilcoxon matched-pairs signed rank test, and Spearman rank correlation coefficients were calculated to examine the relationships between variables, adopting a 5% level of significance.

RESULTS

Responses During Cycling

Oxygen uptake during cycling was 2.46 (SD 0.29) L · min^{-1} or 62.3% (SD 1.7%) of $\dot{V}O_{2max}$, and gross energy expenditure was 4.5 (SD 0.5) MJ. Average heart rate was 145 (SD 13) beats · min^{-1}, and the average rating of perceived exertion (on a scale from 9 at rest to 21 at exhaustion) was 11.8 (SD 1.4). Blood lactate concentration increased from 3.17 (SD 1.36) mmol · L^{-1} at 30 minutes to 4.85 (SD 3.14) mmol · L^{-1} at 90 minutes.

Oral Fat-Tolerance Tests

IMTG concentration (Fig 1) was decreased ~16 hours after exercise in 3 subjects and essentially unchanged in 3 subjects, compared with control values ($P = .09$). Muscle LPL activity 16 hours after exercise (Fig 1) was higher in 4 subjects and lower in 4 subjects than control values; mean values were not significantly different between trials ($P > .05$).

Plasma concentrations of total cholesterol, apolipoprotein B, and glucose measured in the fasted state were significantly lower and those of NEFA significantly higher 16 hours after exercise compared with control (Table 1).

The plasma TG response and the chylomicron-rich fraction TG response (6-hour areas under the plasma concentration-time curves) were significantly lower after exercise than in the control trial (Figs 1 and 2, Table 2). The difference between trials in the plasma TG response was inversely related to the difference in muscle LPL activity (rho = −.79, $P < .05$). This relationship was weaker for the response of TG in the chylomicron-rich fraction (rho = −.69; $P = .07$). The area under the TG concentration-time curve for the non–chylomicron-rich fraction was somewhat lower after exercise ($P = .07$; Table 2). The incremental area under the TG concentration-time curve differed between trials only for plasma TG (Table 2).

Postprandially, plasma concentrations of cholesterol, HDL cholesterol, and apolipoprotein B changed little during either trial, so mean values over 6 hours were adopted as summary measures. Mean total cholesterol concentration was lower during the trial conducted after exercise (3.42 [SE 0.22] mmol · L^{-1} *v* 3.76 [SE 0.21] mmol · L^{-1}; $P < .05$), but mean HDL cholesterol concentration did not differ (1.18 [SE 0.08] mmol · L^{-1} *v* 1.20 [SE 0.05] mmol · L^{-1} for exercise and control, respectively). Mean apolipoprotein B concentration was lower in the prior exercise trial (0.78 [SE 0.04] g · L^{-1} *v* 0.86 [SE 0.05] g · L^{-1}; $P < .05$).

Postprandial responses of serum insulin, plasma glucose, and NEFA and the respiratory exchange ratio are shown in Fig 3. NEFA concentration at the nadir was higher after exercise than in the control trial (0.23 [SE 0.02] mmol · L^{-1} *v* 0.16 [SE 0.02] mmol · L^{-1}; $P < .05$), and NEFA suppression was greater (0.38 [SE 0.04] mmol · L^{-1} *v* 0.22 [SE 0.05] mmol · L^{-1}; $P < .05$). However, the areas under the concentration-time curves for NEFA, glucose, and insulin were not influenced by prior exercise (Table 2).

The respiratory exchange ratio was significantly lower after prior exercise, both in the fasted state and postprandially (area under the respiratory exchange ratio–time curve; Fig 3). Table 3 shows estimates of substrate oxidation and storage over the 6-hour postprandial period. Prior exercise reduced carbohydrate oxidation by 24% ($P < .05$) and increased fat oxidation by >30% ($P = .09$).

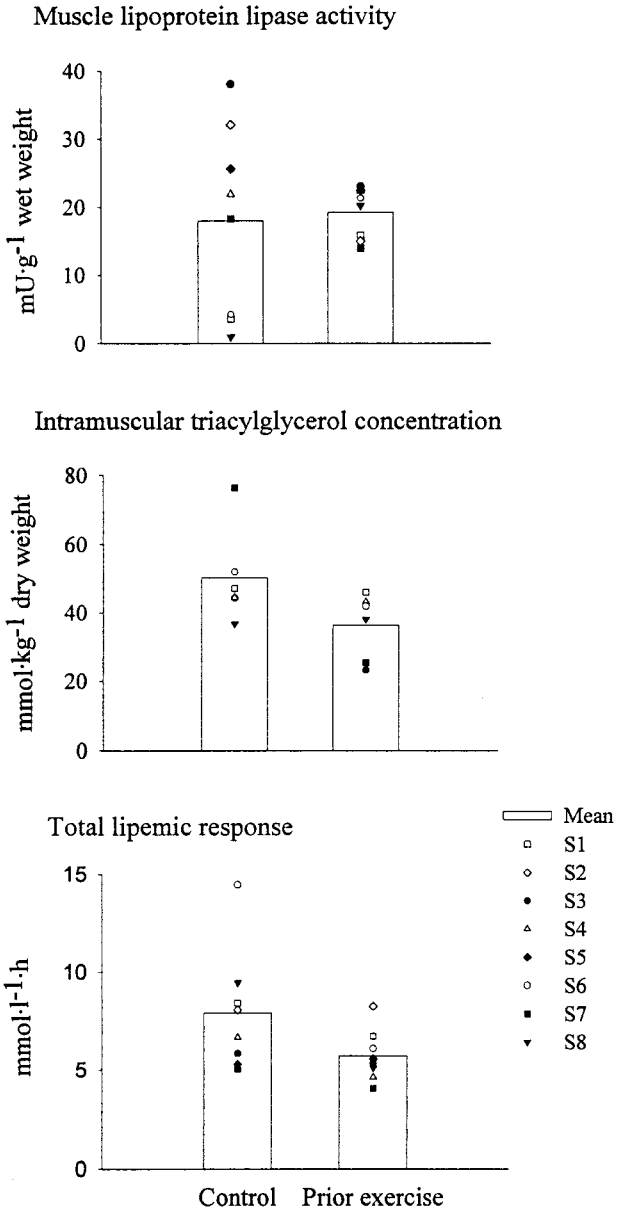

Fig 1. Individual values for LPL activity and intramuscular TG concentration measured in biopsy samples of skeletal muscle obtained before oral fat tolerance tests and the total lipemic response (area under the plasma TG concentration-time curve). Control, morning after a day with minimal physical activity; prior exercise, morning after 90 minutes of exercise on a cycle ergometer at 60 % $\dot{V}O_{2max}$ (~16 hours after the end of exercise). Bars show mean values for 8 men. Total lipemic response is significantly different between control and prior exercise ($P < .05$).

DISCUSSION

A single session of moderate intensity exercise completed ~16 hours previously decreases the plasma TG response to

Table 1. Concentrations Measured in the Fasted State of Plasma TG, Total and HDL Cholesterol, Apolipoprotein B, and NEFA, Serum Insulin and Plasma Glucose

	Control	Prior Exercise
Total plasma TG (mmol · L^{-1})	0.76 (0.07)	0.63 (0.04)
Total cholesterol (mmol · L^{-1})	3.62 (0.21)	3.35 (0.23)*
HDL cholesterol (mmol · L^{-1})	1.21 (0.05)	1.18 (0.07)
Apolipoprotein B (g · L^{-1})	0.83 (0.04)	0.76 (0.05)*
NEFA (mmol · L^{-1})	0.39 (0.06)	0.60 (0.04)*
Insulin (μIU · mL^{-1})	7.7 (0.5)	7.3 (0.4)
Glucose (mmol · L^{-1})	4.68 (0.07)	4.52 (0.05)*

NOTE. Control, morning after a day with minimal physical activity; prior exercise, morning after 90 minutes of exercise on a cycle ergometer at 60% $\dot{V}O_{2max}$. Data are mean (SE) values for 8 men.

* Significantly different from control, $P < .05$.

a standard high-fat meal,[4,22] suggesting that regular frequent exercise at this level may diminish the atherogenic stimulus apparent during the postprandial period. In the present study, we examined the proposition that the induction of LPL in skeletal muscle may be one mechanism involved. Previous studies have demonstrated that vigorous exercise acutely induces muscle LPLA,[6,23,24] but ours are the first data to evaluate the potential of prior (~16 hours earlier) moderate exercise in this regard. Although we found no statistically significant difference in muscle LPL between the exercise and control trials, 2 aspects of the results suggest that muscle LPLA might contribute to the attenuation of postprandial lipemia by prior exercise of this intensity.

First, the 4 subjects who showed clear increases in muscle LPL activity after exercise also had the most noticeable decreases in postprandial lipemia (Fig 1). The average decrease in lipemia in these 4 individuals was 4.11 (range, 1.69 to 8.36) mmol · L^{-1} · h, compared with a decrease of only 0.27 (range, −0.26 to 1.00) mmol · L^{-1} · h in the remaining subjects. The 4 subjects in whom lipemia was decreased had the highest levels of postprandial lipemia in the control trial, (9.76 [range, 6.68 to 14.46] mmol · L^{-1} · h *v* 6.07 [range, 5.05 to 8.08] mmol · L^{-1} · h). Furthermore, the difference between trials in LPL activity was inversely related to the difference in the postprandial TG response (rho = −.79, $P < .05$, n = 8). Thus those subjects with the highest levels of postprandial lipemia showed the greatest decrease after exercise, alongside increases to skeletal muscle LPL activity.

Second, more than half of the decrease in postprandial lipemia after exercise was accounted for by the reduction in TG in the chylomicron-rich fraction of plasma, although the absolute concentration of TG was much lower in this fraction. This observation is consistent with an LPL-mediated mechanism because LPL appears to hydrolyze chylomicron-TG in preference to very low-density lipoprotein TG.[10]

Whole-body fat oxidation was higher after exercise, in the fasted state, and during the postprandial period. Sources that might have provided additional fatty acids for oxidation are IMTG, TG-rich lipoproteins, and plasma NEFA. IMTG concentrations have been reported to remain low for up to 30 hours after exercise, presumably reflecting enhanced hydrolysis of IMTG to provide fatty acids to cover energy expenditure in muscle during the period of glycogen replenishment.[6] However, IMTG was not significantly lower 18 hours after exercise in the present study, possibly because muscle glycogen replenishment was achieved earlier than in the study of Kiens and Richter,[6] whose subjects performed prolonged exhaustive exercise. The higher fat oxidation after prior exercise is more likely to reflect enhanced use of fatty acids derived from TG-rich lipoproteins, facilitated by the higher muscle LPL activity. This would be in line with the observation that skeletal muscle LPL activity was significantly inversely related to 24-hour respiratory quotient.[25] The elevated plasma NEFA concentrations could also have contributed to higher fat oxidation by inhibiting glycolysis in skeletal muscle.[26]

The influence of prior exercise on plasma TG concentrations was particularly marked in the postprandial state. This might not be expected when insulin inhibits muscle LPL[27] and could argue against the view that induction of muscle LPL mediated the decrease in postprandial lipemia. However, there is evidence from measurements of arteriovenous differences to show that skeletal muscle does take up chylomicron-TG postprandially.[10] Speculatively, this could be enhanced by prior exercise, perhaps particularly when type I fibers (reported in animal studies to have higher LPL activity[28]) have been heavily recruited. However, an effect of

Table 2. Postprandial Responses for TG in Total Plasma, Chylomicron-Rich Fraction, and Non–Chylomicron-Rich Fraction and Responses for Plasma NEFA, Serum Insulin, and Plasma Glucose

	Total Area Under Concentration-Time Curve		Incremental Area Under Concentration-Time Curve*	
	Control	Prior Exercise	Control	Prior Exercise
Total plasma TG (mmol · L^{-1} · h)	7.91 (1.09)	5.72 (0.47)†	3.35 (0.80)	1.95 (0.45)†
Chylomicron-rich TG (mmol · L^{-1} · h)	1.98 (0.51)	0.92 (0.16)†	N/A	N/A
Non–chylomicron-rich TG (mmol · L^{-1} · h)	5.69 (0.45)	4.76 (0.45)	1.13 (0.33)	0.99 (0.31)
Plasma NEFA (mmol · L^{-1} · h)	2.50 (0.10)	2.81 (0.10)	0.17 (0.36)	−0.80 (0.27)
Serum insulin (μIU · mL^{-1} · h)	112.3 (6.0)	108.7 (6.3)	65.9 (6.9)	64.9 (7.1)
Plasma glucose (mmol · L^{-1} · h)	27.34 (0.64)	27.99 (0.39)	−0.75 (0.71)	0.88 (0.54)

NOTE. Control, morning after a day with minimal physical activity; prior exercise, morning after 90 minutes of exercise on a cycle ergometer at 60% $\dot{V}O_{2max}$. Data are mean (SE) values for 8 men.

* Area under the concentration-time curve minus fasting value extrapolated over 6 hours.

† Significantly different from control, $P < .05$.

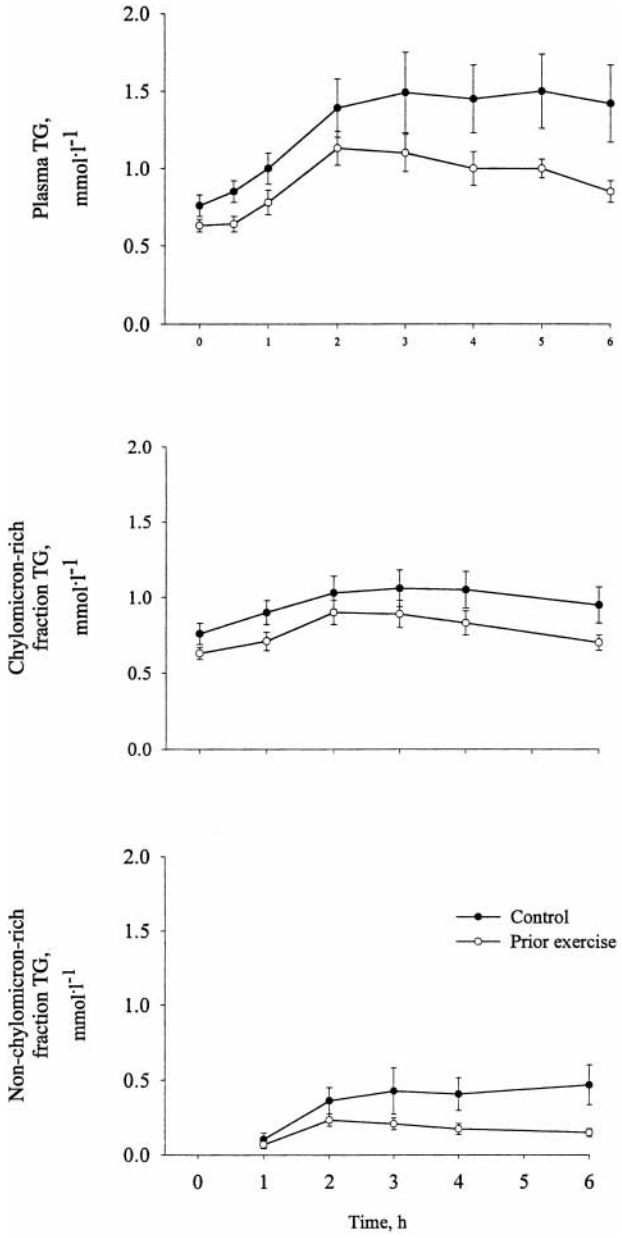

Fig 2. TG concentrations in plasma, the chylomicron-rich fraction, and the non–chylomicron-rich fraction in the fasted state and after consumption of a high-fat mixed meal. Control, morning after a day with minimal physical activity; prior exercise, morning after 90 minutes of exercise on a cycle ergometer at 60% $\dot{V}O_{2max}$ (~16 hours after end of exercise). Values are means and SEs for 8 men. Summary statistics comparing responses are shown in Table 2.

exercise on TG clearance may have been masked to some degree by insulin as the difference in TG concentration between trials was more marked when serum insulin returned towards the fasting level (Figs 2 and 3).

Furthermore, the effect of prior exercise in decreasing fasting TG concentration (nonchylomicron TG) reduces the postprandial excursion of plasma TG through reducing competition by incoming chylomicrons for clearance by the "common saturable removal mechanism."[29] Therefore, the decrease in fasting TG concentrations after exercise may explain much of the decrease seen after consumption of the meal.

The effect of prior exercise on plasma TG concentration could reflect a decrease in the number of TG-rich particles circulating and/or a decrease in the average TG content per particle. The mass concentration of apolipoprotein B was 8% lower after exercise and, because each apolipoprotein B containing particle contains just 1 molecule of this protein, suggests that the number of such particles circulating was lower after exercise.

Theoretically, apolipoprotein E phenotype may influence the effect of exercise on lipemia because both the E2 allele[30] and the E4 allele[31] have been associated with less effective TG removal. One of our subjects (subject 3) was heterozygous for E2, and 1 (subject 4) was heterozygous for E4, but for each of our 3 main outcome measures their responses to exercise were within the variation evident for the 6 men who were homozygous for E3.

The background diet influences the plasma TG responses to a standard meal[32]; therefore, the effect of prior exercise that we observed may reflect to some degree our subjects' habitual dietary practices. Furthermore, because food intake was standardized before fat-tolerance testing, the exercise session meant that our subjects were in negative energy balance compared with the control situation. This would be expected to promote a greater postprandial increase in adipose tissue LPL activity[33] and hence lower plasma TG concentrations. However, the TG-reducing effect of prior exercise is greater by an order of magnitude than that of the associated energy deficit,[22] so this could not account for our findings.

In summary, although muscle LPL activity was not significantly higher ~16 hours after a session of moderate exercise, aspects of the data suggest that this mechanism may be at least partly responsible for the lower lipemic response to a high-fat meal. Our data were characterized by considerable variation, both in absolute values and in changes after exercise. This

Table 3. Estimated Energy Production From Fat and Carbohydrate and Whole-Body Net Substrate Oxidation and Storage Over the 6-Hour Postprandial Period

	Energy Production (MJ)		Substrate Oxidation (g)		Substrate Storage (g)	
	Fat	Carbohydrate	Fat	Carbohydrate	Fat	Carbohydrate
Control	0.59 (0.13)	0.98 (0.22)	15.1 (3.2)	57.8 (13.5)	80.4 (6.1)	29.7 (13.1)
Prior exercise	0.77 (0.10)	0.74 (0.16)*	19.6 (2.7)	43.9 (9.5)*	75.8 (6.6)	43.6 (9.5)*

NOTE. Control, morning after a day with minimal physical activity; prior exercise, morning after 90 minutes of exercise on a cycle ergometer at 60% $\dot{V}O_{2max}$. Data are mean (SE) values for 8 men.

* Significantly different from control, $P < .05$.

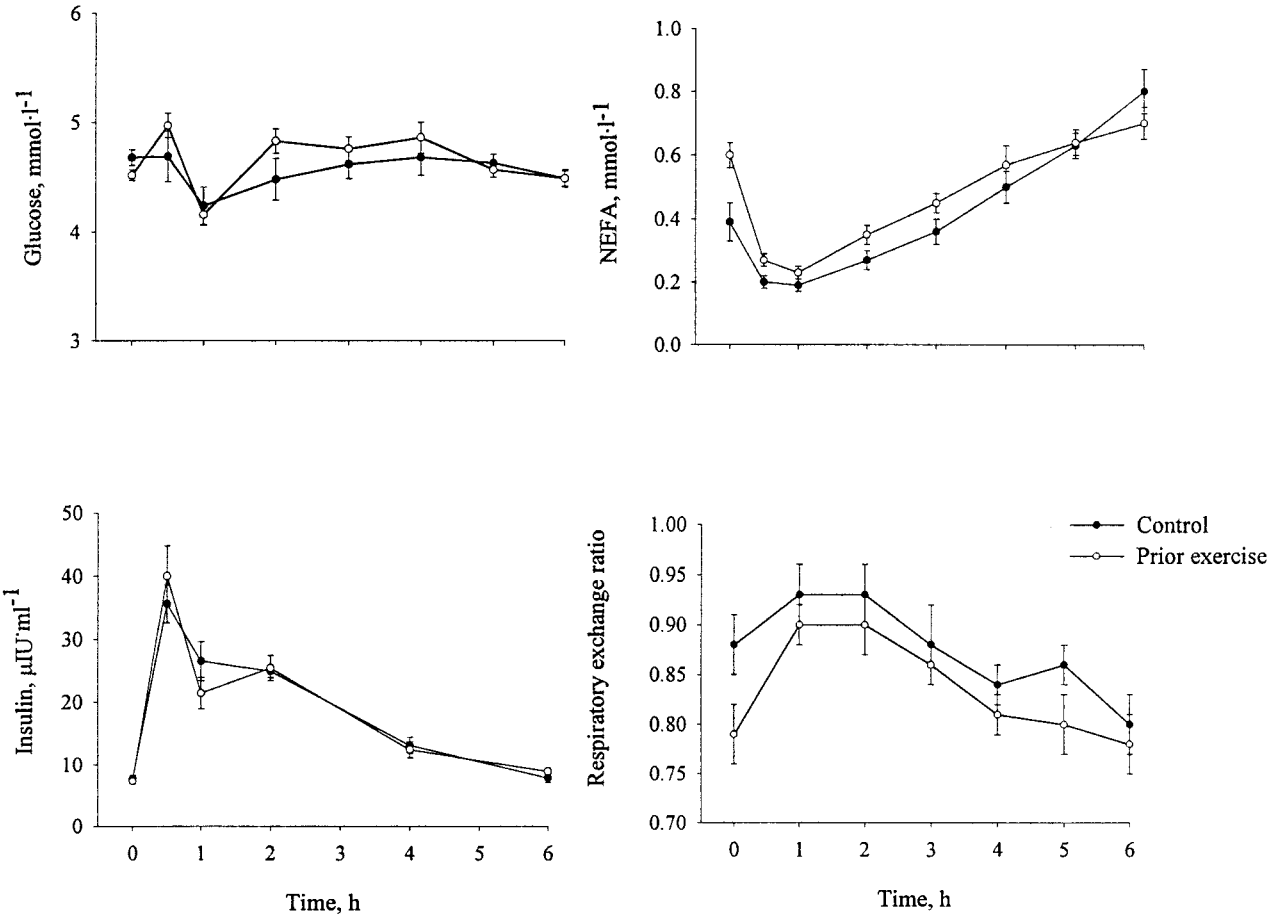

Fig 3. Concentrations of serum insulin, plasma NEFA, and plasma glucose and respiratory exchange ratio in the fasted state and after consumption of a high-fat mixed meal. Control, morning after a day with minimal physical activity; prior exercise, morning after 90 minutes of exercise on a cycle ergometer at 60% $\dot{V}O_{2max}$ (~16 hours after end of exercise). Values are means and SEs for 8 men. No significant differences in responses (area under concentration- or ratio- time curves) between control and prior exercise. Plasma NEFA concentrations at the nadir of the postprandial response significantly higher than control with prior exercise and NEFA suppression (difference between baseline concentration and that at the nadir) significantly greater with prior exercise (both $P < .05$).

underlines the difficulty of extrapolating from in vitro measurements of muscle LPL activity and IMTG concentrations and suggests that measurements of TG flux and fractional extraction across muscle may better elucidate the physiologic role of LPL in the attenuation of postprandial lipemia by moderate exercise.

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REFERENCES

1. Miesenböck G, Patsch JR: Postprandial hyperlipidemia: the search for the atherogenic lipoprotein. Curr Opin Lipidol 3:196-201, 1992

2. Karpe F, Hamsten A: Postprandial lipoprotein metabolism and atherosclerosis. Curr Opin Lipidol 6:123-129, 1995

3. Patsch JR, Miesenböck G, Hopferwieser T, et al: Relation of triglyceride metabolism and coronary artery disease. Studies in the postprandial state. Arteriosclerosis 12:1336-1345, 1992

4. Tsetsonis NV, Hardman AE, Mastana SS: Acute effects of exercise on postprandial lipemia: A comparative study in trained and untrained middle-aged women. Am J Clin Nutr 65:525-533, 1997

5. Zhang JQ, Thomas TR, Ball SD: Effect of exercise timing on postprandial lipemia and HDL cholesterol subfractions. J Appl Physiol 85:1516-1522, 1998

6. Kiens B, Richter EA: Utilization of skeletal muscle triacylglycerol during postexercise recovery in humans. Am J Physiol 275:E332-E337, 1998

7. Seip RL, Mair D, Cole TG, et al: Induction of human skeletal muscle lipoprotein lipase gene expression by short-term exercise is transient. Am J Physiol 272:E255-E261, 1997

8. Seip RL, Semenkovich CF: Skeletal muscle lipoprotein lipase: molecular regulation and physiological effects in relation to exercise. Exerc Sports Sci Rev 26:191-218, 1998

9. Kiens B, Lithell H, Mikines KJ, Richter E: Effects of insulin and

exercise on muscle lipoprotein lipase activity in man and its relation to insulin action. J Clin Invest 84:1124-1129, 1989

10. Potts JL, Fisher RM, Humphreys SM, et al: Peripheral triacylglycerol extraction in the fasting and post-prandial states. Clin Sci 81:621-626, 1991

11. Nguyen TT, Hernández M, Johnson CM, et al: Postprandial leg and splanchnic fatty acid metabolism in nonobese men and women. Am J Physiol 271:E965-E972, 1996

12. Hamill J, Knutzen KM: Biomechanical Basis of Human Movement. Baltimore, MD, Williams & Wilkins, 1995

13. Fielding BA, Callow J, Owen RM, et al: Postprandial lipemia: The origin of an early peak studied by specific dietary fatty acid intake during sequential meals. Am J Clin Nutr 63:36-41, 1996

14. Borg GAV: Psychophysical bases of perceived exertion. Med Sci Sports Exerc 14:377-387, 1982

15. Kiens B, Lithell H: Lipoprotein metabolism influenced by training-induced changes in human skeletal muscle. J Clin Invest 83:558-564, 1989

16. Kiens B, Richter EA: Types of carbohydrate in an ordinary diet affect insulin action and muscle substrates in humans. Am J Clin Nutr 63:47-53, 1996

17. Griffiths AJ, Humphreys SM, Clark ML, et al: Immediate metabolic availability of dietary fat in combination with carbohydrate. Am J Clin Nutr 59:53-59, 1994

18. Dill DB, Costill DL: Calculation of percentage changes in volumes of blood, plasma, and red cells in dehydration. J Appl Physiol 37:247-248, 1974

19. Matthews JNS, Altman DG, Campbell MJ, et al: Analysis of serial measurements in medical research. Br Med J 300:230-235, 1990

20. Frayn KN, Macdonald IA: Assessment of substrate and energy metabolism in vivo, in Dranzin B, Rizza R (eds): Clinical Research in Diabetes and Obesity. Part I: Methods, Assessment, and Metabolic Regulation. Totowa, NJ, Humana, 1997, pp 101-124

21. Gardner MJ, Altman DG: Statistics With Confidence—Confidence Intervals and Statistical Guidelines. London, UK, BMJ, 1989, p 16

22. Gill JMR, Hardman AE: Postprandial lipemia; effects of exercise and energy intake restriction compared. Am J Clin Nutr 71: 465-471, 2000

23. Lithell H, Örlander J, Schéle R, et al: Changes in lipoprotein-lipase activity and lipid stores in human skeletal muscle with prolonged heavy exercise. Acta Phys Scand 107:257-261, 1979

24. Lithell H, Schéle R, Vessby B, et al: Lipoproteins, lipoprotein lipase, and glycogen after prolonged physical activity. J Appl Physiol 57:698-702, 1984

25. Ferraro RT, Eckel RH, Larson DE, et al: Relationship between skeletal muscle lipoprotein lipase activity and 24-hour macronutrient oxidation. J Clin Invest 92:441-445, 1993

26. Randle PJ, Garland PB, Hales CN, et al: The glucose fatty-acid cycle: its role in insulin sensitivity and the metabolic disturbances of diabetes mellitus. Lancet 1:785-789, 1963

27. Farese RV, Yost TJ, Eckel RH: Tissue-specific regulation of lipoprotein lipase activity by insulin/glucose in normal-weight humans. Metabolism 40:214-216, 1991

28. Borensztajn J (ed): Lipoprotein Lipase. Chicago, IL, Evener, 1987

29. Brunzell JD, Hazzard WR, Porte D, et al: Evidence for a common, saturable, triglyceride removal mechanism for chylomicrons and very low density lipoproteins in man. J Clin Invest 52:1578-1585, 1973

30. Weintraub MS, Eisenberg S, Breslow JL: Dietary fat clearance in normal subjects is regulated by genetic variation in apolipoprotein E. J Clin Invest 80:1571-1577, 1987

31. Bergeron N, Havel RJ: Prolonged postprandial responses of lipids and apolipoproteins in triglyceride-rich lipoproteins of individuals expressing an aoplipoprotein E4 allele. J Clin Invest 97:65-72, 1996

32. Blades B, Garg A: Mechanisms of increase in plasma triacylglycerol concentrations as a result of high carbohydrate intakes in patients with non-insulin-dependent diabetes mellitus. Am J Clin Nutr 62:996-1002, 1995

33. Taskinen M-R, Nikkilä EA: Basal and postprandial lipoprotein lipase activity in adipose tissue during caloric restriction and refeeding. Metabolism 36:525-533, 1987