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REVIEWS: CURRENT TOPICS

Exercise and postprandial lipid metabolism: an update on potential mechanisms and interactions with high-carbohydrate diets (Review)

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Abstract

Endurance trained people exhibit low levels of postprandial lipemia. However, this favorable situation is rapidly reversed with de-training and it is likely that the triglyceride (TG) lowering effects of exercise are mainly the result of acute metabolic responses to recent exercise rather than long-term training adaptations. A large body of evidence suggests that postprandial lipemia can be attenuated following an individual exercise session, with the energy expended during exercise being an important determinant of the extent of TG lowering. Increased lipoprotein lipase-mediated TG clearance and reduced hepatic TG secretion are both likely to contribute to the exercise-induced TG reductions. These changes may occur in response to post-exercise substrate deficits in skeletal muscle and/or the liver. In addition, regular exercise can oppose the hypertriglyceridaemia sometimes seen with low-fat, high-carbohydrate diets. Levels of physical activity should therefore be taken into account when considering nutritional strategies for reducing the risk of cardiovascular disease.

Keywords: Physical activity; Postprandial lipemia; Triglyceride; Lipoprotein; Energy expenditure; Fat

1. Introduction: the importance of the postprandial state

An increased plasma concentration of high-density lipoprotein (HDL) cholesterol is the most consistent alteration to the lipid profile evident following a program of regular aerobic exercise [1,2]. The concentration of this lipoprotein is an important predictor of cardiovascular risk [3] and the extent of its change provides a useful marker of the efficacy of an exercise intervention. However, the study of fasting lipid and lipoprotein concentrations reveals little information about the mechanisms by which exercise influences the lipoprotein profile.

The efficiency of metabolism of TG-rich lipoproteins (TRL) is a major determinant of the HDL cholesterol concentration and one which is particularly evident during the postprandial period [4,5]. After ingestion of a meal, intestinally derived chylomicrons compete with hepatically-derived very-low-density lipoproteins (VLDL) for clearance by the same lipolytic pathway—i.e. hydrolysis of lipoprotein-TG by lipoprotein lipase (LPL) residing on the capillary endothelium of extra-hepatic tissues, particularly adipose tissue and skeletal muscle [6,7]. This leads to an accumulation of circulating TG contained in TRL (chylomicrons and VLDL) and accelerated transfer of esterified cholesterol from HDL and low-density lipoprotein (LDL) to TRL, with TG transferring in the opposite direction (a process mediated by cholesteryl ester transfer protein (CETP)). This reduces the HDL cholesterol concentration and leads to TG-enriched, cholesteryl ester-depleted HDL and LDL particles. The TG content of these particles is then hydrolyzed by hepatic lipase, resulting in small HDL particles which are removed from the circulation at an enhanced rate [8] and atherogenic small-dense LDL particles [9]. Thus, exaggerated postprandial lipemia is an important feature of the 'atherogenic lipoprotein phenotype' (low HDL cholesterol and small-dense LDL) and the HDL cholesterol concentration can viewed as an integrative marker of TG metabolism.

However, postprandial metabolism is important for reasons other its role in remodelling HDL and LDL. Over 20 years ago Donald Zilversmit proposed that atherogenesis

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was a postprandial phenomenon with the remnants of postprandial lipoproteins directly infiltrating the arterial wall leading to the accumulation of atheromatous plaques [10]. A large body of *in vitro* and *in vivo* studies support the direct atherogenicity of TRL and their remnants [5,11] and it has recently become recognized that 'endothelial dysfunction'—an early feature of the atherosclerotic disease process—is evident during the hours following fat ingestion [12,13]. Additionally, changes to lipid metabolism occurring during the hours after a meal can result in an increase in blood coagulability, with elevations in plasma factor VII coagulant activity [14,15]. As factor VII initiates the thrombotic response following the rupture of an atheromatous plaque, postprandial rises in activity may play a role in the acute phase of the atherosclerotic disease process. While many of these postprandial changes are transient in nature, this must be viewed in the context of daily living. People typically consume multiple meals during the day, with additional food ingested long before the metabolic disturbances associated with previous meals have subsided. Thus, the dynamic postprandial state prevails for perhaps two-thirds of the day and these repeated metabolic challenges represent the 'normal' physiological state of free-living humans.

Evidence from cross-sectional and case-control studies suggests that impaired metabolism of postprandial lipoproteins is implicated in the development of clinically relevant atherosclerosis [11] and thus, interventions which reduce postprandial lipemia may play a role in delaying the atherosclerotic disease process.

2. Effects of exercise on postprandial metabolism

2.1. Effects of exercise training—chronic adaptation or acute response?

There is clear evidence from a number of cross-sectional studies comparing endurance-trained men with untrained control subjects that regular exercisers exhibit low levels of postprandial lipemia [16–19] and enhanced rates of TG clearance [16,20–22]. However, while these studies accurately describe the usual state of TG metabolism in well-trained people, interpretation of these findings is difficult as exercise could theoretically have both chronic (i.e. long-term training adaptations) and acute (i.e. short-term effects of recent exercise) influences on TG metabolism. In the above studies, subjects were requested to maintain their normal training regimen in the days prior to assessment of fat tolerance [16], to refrain from vigorous exercise for the 12-36 h prior to testing [17,19–21] or no information was provided on this issue [18,22]. Athletes will invariably exercise unless specifically requested not to do, thus in all the above studies the subjects would only have refrained from exercise for, at most, the day prior to testing. Consequentially, acute changes due to recent exercise are likely to have contributed to the findings of these studies and it not possible to ascertain whether long-term training adaptations *per se* contributed to the enhanced TG metabolism observed in these endurance athletes. In studies specifically designed to exclude the influence of recent exercise by studying subjects $>$60 hr after their last exercise session, no differences in postprandial lipemia were observed between endurance trained, sprint/strength trained and untrained young adults [23] or endurance trained and untrained middle-aged women [24].

Intervention studies have reported that a period of endurance training can reduce postprandial concentrations of TG and TG-rich lipoproteins [25,26] and in some instances increase TG clearance [27,28]. However, in the majority of these studies [25,27,28] post-training assessments of fat tolerance were undertaken within 36 hr of exercise, making it difficult to assess the relative importance of acute and chronic exercise effects. In studies where post-training assessments of fat tolerance were made more than 48 hr post-exercise, no significant effects of training on postprandial lipemia [29] or TG clearance [30] were observed, despite clear improvements in endurance fitness. Although one study [26] found that postprandial lipemia, assessed after four days without exercise, was significantly reduced following an exercise training program, subjects lost over 4 kg in body mass during the intervention period and this rather than exercise training *per se* may have contributed to the TG attenuation.

De-training studies provide compelling evidence that exercise training may not markedly influence TG metabolism in the absence of recent exercise. Cessation of exercise for 14–22 days has been reported to induce increases of approximately 40% in postprandial chylomicron and chylomicron remnant concentrations (assessed by Vitamin A fat loading) in male distance runners [31]. Other studies, evaluating the early phase of de-training, suggest that training-induced changes to TG metabolism may be very short-lived. In one, where endurance-trained subjects refrained from exercise for six and a half days, postprandial lipemia was increased by 35% (compared with values 15 hr post-exercise) after just 60 hr without exercise, with little further increase after nearly a week of de-training [32]. Similarly, in another report where untrained men and women were trained for 13 weeks, then de-trained for 9 days, postprandial lipemia increased rapidly (by 37% within 60 hr and 46% within 9 days) when the training stimulus was interrupted [33].

Thus, the weight of evidence suggests that, while endurance-trained people have efficient TG metabolism, evidenced by low levels of postprandial lipemia and rapid TG clearance, this favorable condition is rapidly reversed in the absence of recent exercise.

2.2. Effects of individual exercise sessions

There is a large body of evidence showing that postprandial lipemia can be attenuated by a prior session of exercise

[24,34–44]. The effects of exercise performed after meal ingestion on postprandial TG concentrations are less clear with some studies reporting an exercise-induced reduction [45–50] and others reporting no effect [44,51]. Studies of both the fasted [52,53] and the postprandial state [44] suggest that maximal exercise-induced TG attenuation occurs after a delay of some hours, rather than during or immediately post-exercise. This implies that the exercise-induced changes to TG metabolism are not simply a consequence of altered blood flow and substrate delivery occurring during exercise as these changes would be maximal during exercise and early in recovery. Thus, it probable that more subtle exercise-induced changes to metabolism are responsible for the exercise-induced TG diminution.

The TG-lowering effect of exercise appears to be related to the energy expended during the exercise session. Exercise for 90 min at 60% of maximal oxygen uptake ($\dot{V}O_2$max) induced twice the reduction in subsequent postprandial lipemia seen after exercise at 30% $\dot{V}O_2$max for the same duration [42]. However, three hours of exercise at 30% $\dot{V}O_2$max induced a similar reduction as 90 min at 60% $\dot{V}O_2$max [43], demonstrating that energy expenditure, independent of exercise intensity, is an important determinant of the magnitude of the exercise-induced reduction in postprandial lipemia. A recent report of 81 subjects showed that the energy expended during exercise was a significant predictor of the exercise-induced reduction in postprandial lipemia [54]. The magnitude of the exercise-induced reduction in postprandial TG concentrations also appears to be independent of the type of substrate utilized during exercise. In one study, this was manipulated by administration of acipimox (which suppresses fatty acid release from adipose tissue) one hour before a 90-min session of moderate exercise. Acipimox increased carbohydrate oxidation and reduced fat oxidation during exercise (compared with the same exercise session without prior acipimox ingestion) but the reduction to subsequent postprandial TG concentrations was the same for both exercise sessions [40].

It is also evident that the same exercise energy expenditure will attenuate postprandial lipemia to the same degree whether exercise is performed in single or multiple sessions. Three 30-min moderate exercise sessions attenuated postprandial TG concentrations on the following day to the same degree as one 90-min session [36] and in another study where the metabolic responses to sequential meals (breakfast, lunch, dinner) was assessed, three 10-min brisk walks spread throughout the day attenuated day-long TG concentrations to the same degree as 30 min of walking before breakfast [55].

Although exercise training (in the absence of acute exercise) does not appreciably influence postprandial lipemia, in the long-term it could enhance the acute changes to TG metabolism elicited by individual exercise sessions. In one report, endurance-trained and untrained middle-aged women each undertook two oral fat tolerance tests; one was ~16 hr after 90 min of walking at 60% $\dot{V}O_2$max, the other after 3 days without exercise [24]. Exercise attenuated postprandial lipemia by 16% in the untrained women but by 30% in their trained counterparts, which might reflect a synergistic interaction between exercise training and acute exercise. However, due to their higher functional capacities, the trained women expended 41% more energy during the exercise session than the untrained subjects and this may have contributed to the greater TG reduction. Thus, in practical terms, exercise training *per se* is likely to be beneficial to TG metabolism, even if this is only because trained individuals are able to expend more energy during an exercise session than their untrained peers.

3. Potential mechanisms responsible for the exercise-induced TG attenuation

The lower postprandial TG concentrations observed following exercise could theoretically be due to an increased rate of clearance from the circulation of TRL-TG and/or to a reduced rate of appearance of TRL (either chylomicrons and/or VLDL) into the circulation. Well-trained individuals display enhanced TG clearance compared with untrained controls [16,20–22] and TG clearance can be increased by a period of endurance exercise training or a prolonged (≥3 hr) session of exercise [56–58]. This increase in TG clearance is likely to be mediated by an upregulation of LPL activity. Post-heparin plasma LPL activity is higher in endurance-trained people compared with untrained control subjects [21,59] and decreases with a period of de-training [31]; the functional significance of this is illustrated by positive relationships between TG clearance and plasma LPL activity in runners [20,21]. Increases in plasma LPL activity of 46-74% have also been observed 18 hr following prolonged exercise lasting several hours [58,60], but changes reported after more modest exercise (yet sufficient to decrease lipemia) have been much smaller [59,61].

It is likely that these changes in whole-body LPL activity largely reflect differences in LPL activity in skeletal muscle. One report demonstrated that 5–13 consecutive days of exercise increased LPL mRNA and mass in skeletal muscle, with no changes evident in adipose tissue LPL mRNA or mass [62]. Another showed that in runners, a two-week period of detraining in runners decreased in LPL activity in skeletal muscle but increased LPL activity in adipose tissue [63]. Increases in skeletal muscle LPL activity of 200-240% have been reported following a session of prolonged intense exercise lasting many hours [64–66], whereas acute exercise-induced changes to adipose tissue LPL activity appear to be of a much smaller magnitude [67].

Data from Seip and colleagues suggest that the effects of acute exercise on skeletal muscle LPL are delayed and transient, with maximal increases in skeletal muscle LPL mRNA occurring perhaps four hours post-exercise and returning to baseline levels within 24 hr [68,69]. Post-exercise changes to LPL protein mass, and presumably LPL activity,

were evident after a further delay, with the maximal response occurring ≥8 hr post-exercise [68,69]. This delayed activation of skeletal muscle LPL following exercise has also been reported by other workers [70] and is consistent with the delayed maximal attenuation in TG concentrations following exercise.

Thus, it is likely that increased LPL-mediated clearance of TRL-TG is an important contributor to the low levels of postprandial lipemia experienced by endurance-trained people and to the attenuation in plasma TG seen following prolonged exercise. However, there is now a body of evidence suggesting that increased TG clearance cannot entirely account for exercise-induced TG reductions, at least when exercise is of moderate intensity and duration. As most population health guidelines now recommend regular participation in moderate intensity exercise [71], understanding how this quality of exercise influences TG metabolism has widespread relevance.

A recent report has demonstrated that while 90 min of brisk walking significantly reduced postprandial lipemia in a group of middle-aged men, the same amount exercise did not increase clearance of an intravenous lipid emulsion [35]. This is in line with an earlier study of normally active young men which showed that while TG clearance was significantly increased following three hours of moderate-intensity exercise (50% of maximal work load), this was not altered by 90 min of exercise at the same intensity [56]. Another study of young men revealed that 90 min of moderate exercise did not increase mean skeletal muscle LPL activity 18 hr following exercise despite significantly reducing postprandial lipemia at this time, although the individual subjects who experienced increases in LPL activity after exercise also experienced the largest exercise-induced TG reductions [39]. Furthermore, a report using arterio-venous difference methods demonstrated that two hours of moderate exercise did not significantly increase absolute TG-uptake across the leg (which is mainly skeletal muscle) 18 hr post-exercise, despite again significantly attenuating postprandial TG concentrations [41]. Taken collectively, these studies suggest that mechanisms other than increased TG uptake into skeletal muscle are likely to contribute to the TG reduction seen after moderate intensity exercise.

It seems unlikely that a reduced rate of chylomicron appearance into the circulation would be an important mechanism, at least when fat tolerance is measured some hours after exercise. Prior exercise does not delay the time to peak postprandial chylomicron-TG concentration (which would be evident if the rate of chylomicron appearance was reduced) [38,41] and studies administering paracetamol during an oral fat tolerance test as a marker of gastric emptying suggest that this is not slowed on the day following exercise [35,38].

If increased lipoprotein-TG clearance and reduced chylomicron-TG appearance cannot entirely account for reduction in postprandial TG concentrations evident following (moderate-intensity) exercise, it is plausible that reduced hepatic VLDL secretion could contribute. While there is currently no direct evidence to support this concept in humans, animal studies and indirect evidence in humans are consistent with this view. Studies in rats have shown that hepatic VLDL secretion rates are reduced by exercise training [72–74] with one report showing that the exercise training-induced reduction in hepatic-TG secretion occurred alongside an increase in hepatic ketone body production—the two being inversely related [74]. The authors concluded that exercise altered the partitioning of fatty acids in the liver between oxidation and esterification pathways and this was one of the causative factors for the TG-lowering effect. Increased circulating concentrations of 3-hydroxybutyrate (suggesting increased hepatic fatty oxidation), alongside reduced postprandial TG concentrations have also been reported in humans following exercise [38,41]. This is consistent with the mechanism of TG reduction proposed by Fukada and co-workers [74], and in the latter studies postprandial concentration of VLDL-TG were also markedly reduced by exercise [38,41] . While these data do not permit firm conclusions about the underlying cause of the VLDL-TG reduction to be made, the findings are consistent with reduced hepatic VLDL secretion playing a role. This possibility warrants investigation.

It therefore seems likely that exercise reduces postprandial TG concentrations by two complementary mechanisms. Increased TG clearance is evident in well-trained subjects, but only in the presence of a recent exercise session. Prolonged, intense exercise has also been shown to increase TG clearance. However, exercise below a certain threshold energy expenditure does not appear to increase TG clearance, while still reducing postprandial TG concentrations. This suggests that another mechanism, such as reduced VLDL secretion, also contributes to the exercise-induced TG-lowering effect. The relative importance of these two mechanisms on TG lowering is likely to depend on a number of factors including the characteristics of the individual (for example, training status, degree of body fatness, age, gender), the energy expended during exercise and perhaps even dietary intake. Further study is needed to increase understanding about the mechanisms by which exercise reduces TG concentrations in different circumstances.

4. Role of energy deficit and fuel depletion

Both the time-scale of the exercise-induced reductions to postprandial TG concentrations (i.e. the effects of exercise are lost within days) and the fact that exercise energy expenditure seems to be the primary determinant of the degree of TG reduction, suggest that exercise-induced depletion of energy stores, and their subsequent replenishment, plays a key role in the TG-lowering process. However, an exercise-induced energy deficit induces a much greater reduction to postprandial lipemia than a dietary-induced energy deficit of the same magnitude [37], imply-

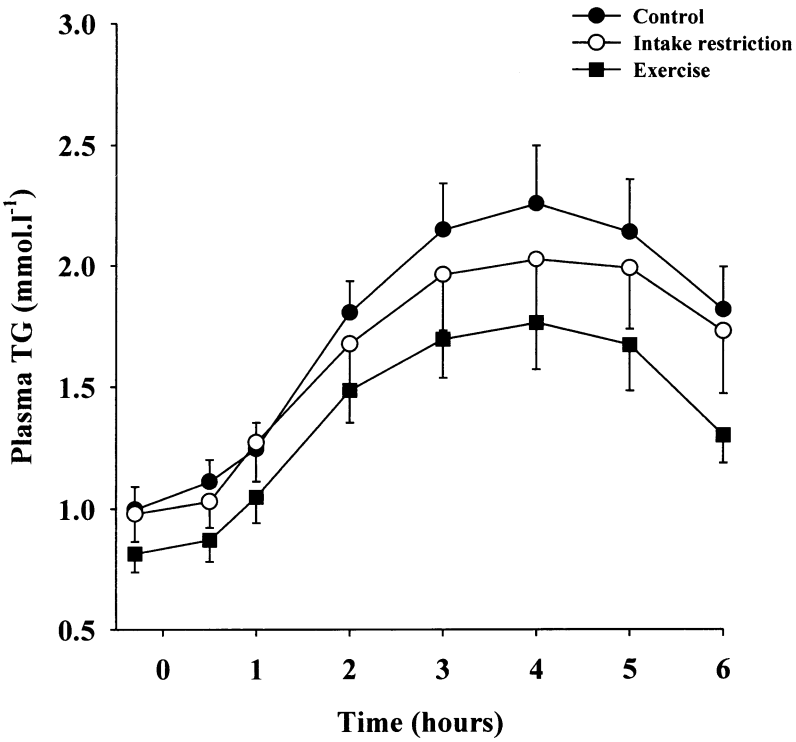

Fig. 1. Plasma TG responses to high fat test meals administered after three days of no exercise (Control, ●), on the day following a 90-min treadmill walk at 60% maximal oxygen uptake (Exercise, ■), and after a day when no exercise was undertaken but energy intake was restricted to induce the same energy deficit as that incurred due to the 90-min walk (Intake restriction, ○). Subjects were post-menopausal women. Areas under the TG *vs* time curve were 20% ($p < 0.05$) and 7% ($p = 0.17$) lower than control after exercise and energy intake restriction, respectively. Values are mean ± SEM, n = 11. Reproduced from reference [37] with permission by the *American Journal of Clinical Nutrition.* © Am J Clin Nutr. American Society for Clinical Nutrition.

ing that exercise-induced changes to TG metabolism cannot replicated by simply reducing energy intake (Fig. 1). This has practical implications—i.e. controlling body weight by restricting energy intake does not induce the same metabolic benefits as controlling body weight through increased physical activity—but also suggests that it is substrate levels in particular body tissues which are specifically influenced by exercise, rather than global 'whole-body' changes, that play a role for the exercise-induced TG-lowering effect.

Indirect evidence for tissue substrate deficits playing a role in post-exercise hypotriglyceridemia comes from data showing that whole-body postprandial fat oxidation is increased on the day following an exercise session [38,43,55,75]. This increase is due to both increased oxidation of meal-derived exogenous fat and of endogenous lipid stores [38]. Furthermore, Kiens and co-workers reported that intra-muscular TG concentrations decreased, and the whole-body fat oxidation rate was high during the hours following exhaustive exercise, despite a high carbohydrate intake [76]. Intra-muscular TG concentrations reached their minimum value 18 hr after exercise and the authors speculated that the exercised muscle preferentially oxidized fat during recovery to allow the immediate replenishment of muscle glycogen—a metabolic priority. By contrast, repletion of intra-muscular TG stores, probably mediated by an upregulation of LPL in this tissue (as well as increased uptake of non-esterified fatty acids (NEFA) released from adipose tissue), occurred more slowly, with concentrations remaining significantly lower than pre-exercise values 30 hr after exercise [76]. Reliance on circulating lipoproteins to replete intramuscular TG stores may be a determinant of the exercise-induced TG-reduction and the timescale of these changes is in line with the time-scale for exercise-induced changes in TG concentrations.

Fasting and postprandial blood or serum 3-hydroxybutyrate concentrations (a marker of hepatic fat oxidation) are also increased on the day following exercise [38,41], suggesting that increased hepatic fat oxidation contributes to the increases in whole-body fat oxidation observed at this time. Indeed, fat-carbohydrate interactions similar to those occurring in skeletal muscle following exercise may also occur in the liver. Prolonged exercise depletes hepatic glycogen stores and these are replaced during the hours following exercise, a process facilitated by carbohydrate ingestion [77]. During this post-exercise period, circulating concentrations of ketone bodies can increase markedly, reaching peak levels at least five to seven hours following exercise [78,79], consistent with the time-course of plasma TG changes. It has been hypothesed that this post-exercise ketosis is a consequence of hepatic carbohydrate deficiency [80]. Certainly, post-exercise carbohydrate ingestion reduces postexercise ketosis [78] and, in rats, post-exercise

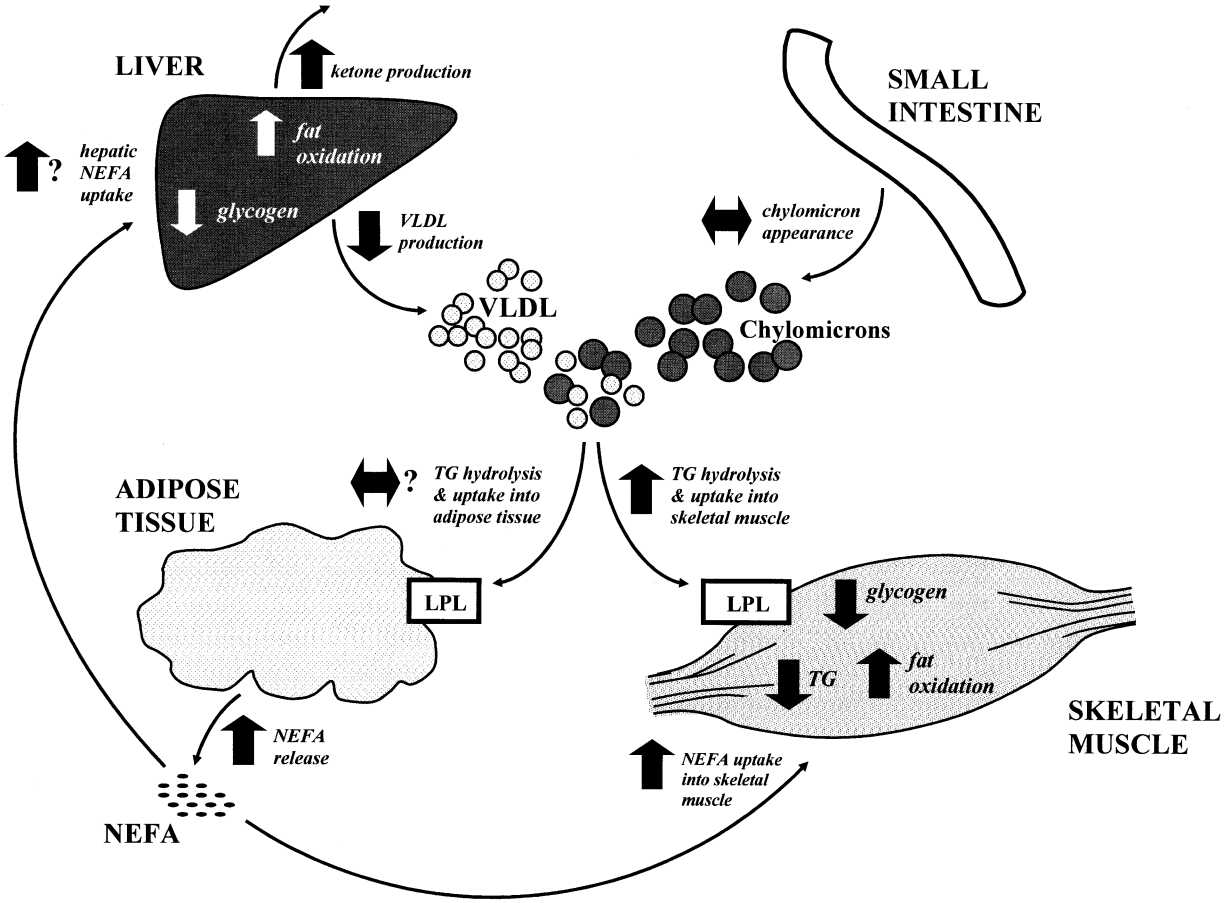

Fig. 2. Postulated effects of exercise on postprandial TG metabolism. Bold arrows represent changes (relative to the unexercised state) occurring during the hours following an exercise session. (An 'up-arrow' indicates an exercise-induced increase, a 'down-arrow' indicates a decrease, a 'sideways-arrow' indicates no change and a question mark indicates that the effect is uncertain). The relative magnitude of these exercise-induced changes is likely depend on a number of factors including the energy expended during the exercise session and the training status of the individual.

blood 3-hydroxybutyrate concentrations have been shown to be negatively related to hepatic glycogen concentrations [81,82]. Thus, increased post-exercise hepatic ketone body production, which might reflect a shift in the hepatic partitioning of fatty acids towards oxidation thereby reducing VLDL production [74], may well be a consequence of exercise-induced hepatic glycogen depletion.

An overview of the potential changes to postprandial TG metabolism which occur during the hours following an exercise session is presented in Fig. 2.

5. High-carbohydrate diets, exercise and postprandial lipemia

Low-fat, high-carbohydrate diets have traditionally been viewed as a attractive alternative to atherogenic high-saturated fat diets as they reduce LDL cholesterol concentrations [83] and help in the maintenance of a healthy body weight [83–85], but recently the desirability of such diets has been a matter of debate as they can increase postprandial TG concentrations [86,87] and reduce HDL cholesterol concentrations [88]. This has led some investigators to advocate diets high in monounsaturated fatty acids as an alternative nutritional strategy [89,90]. However, these potentially adverse consequences of high-carbohydrate diets have generally been observed in sedentary Western populations and may not occur in those with high levels of physical activity. Indeed, physically active populations consuming low-fat, high carbohydrate diets, such as those living in rural China, have favorable lipid profiles [91,92] and endurance athletes who typically consume diets with a very high carbohydrate content [93] have high HDL cholesterol and low plasma TG concentrations [1]. These observations raise the possibility that regular exercise might offset the potential adverse consequences of high levels of carbohydrate ingestion.

There is a large body of evidence suggesting that carbohydrate-induced hypertriglyceridaemia (at least in the fasted state) is due to increased hepatic production of VLDL-TG, with both the number of VLDL particles secreted and the amount of TG per particle being increased [94]. This is

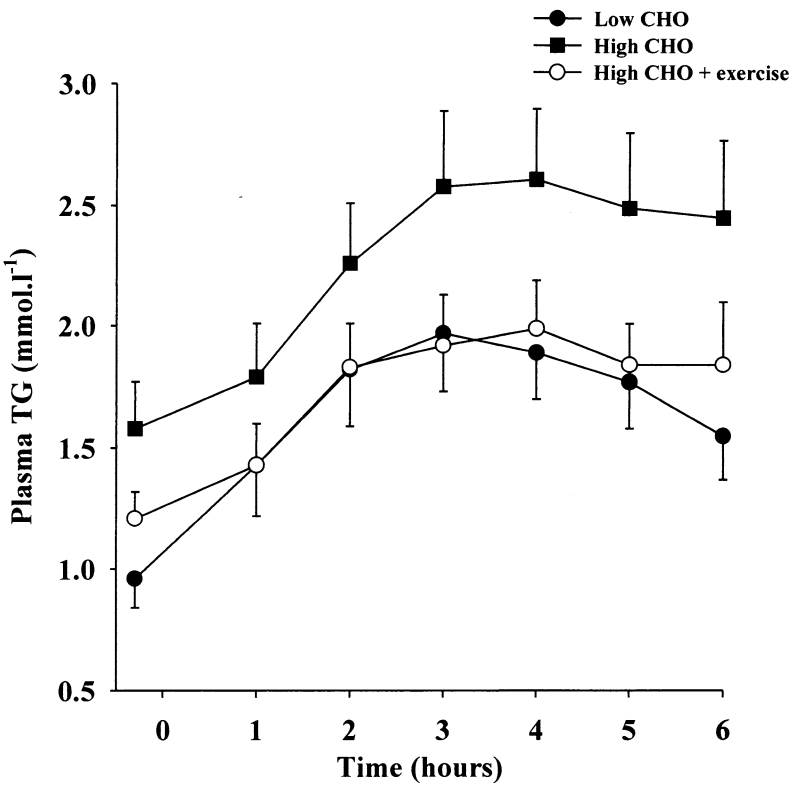

Fig. 3. Plasma TG responses to high fat test meals administered after a three-day low-carbohydrate diet (35% energy from carbohydrate) (Low CHO, ●), after a three-day high-carbohydrate diet (70% energy from carbohydrate) (High CHO, ■), and after a three-day high-carbohydrate diet with 60 min of daily walking at 60% maximal oxygen uptake (High CHO + exercise, ○). Subjects were post-menopausal women. Area under the TG *vs* time curve was 36% higher after the high-carbohydrate diet than the low-carbohydrate diet ($p < 0.01$), but area under curve after the high-carbohydrate diet with daily walking was not significantly different from the low-carbohydrate diet. Values are mean ± SEM, n = 8. Reproduced from reference [103] with permission by *Arteriosclerosis Thrombosis and Vascular Biology.* © Lippincott Williams & Wilkins.

consistent with data from the postprandial state showing increased circulating concentrations of VLDL-TG [95] and VLDL apolipoprotein B100 [86] after high carbohydrate diet interventions. It has also been suggested that TG clearance is impaired following a high carbohydrate diet [96,97], possibly mediated by decreased LPL activity [98,99], although reports are inconsistent on this point [100,101]. As exercise, even at moderate levels, has been shown substantially to reduce postprandial TG concentrations, by increasing TG clearance and/or reducing VLDL production, there is a strong theoretical rationale for proposing that regular physical activity could oppose the adverse effects of high carbohydrate ingestion on postprandial TG metabolism. However, to date, only two studies have been undertaken specifically to address this hypothesis.

In one study of young men, a three-day high-carbohydrate diet (70% energy from CHO) increased the postprandial TG response to a standard high-fat test meal by 35% compared with an isoenergetic three-day mixed diet (46% energy from carbohydrate) [102]. However, 30 min of daily moderate exercise during the high-carbohydrate diet intervention prevented the carbohydrate-induced augmentation in postprandial lipemia, with postprandial TG concentrations on this diet being similar to the mixed diet. The three-day high-carbohydrate diets, both with and without daily exercise, significantly reduced LDL cholesterol concentrations by ~0.2 mmol.l^{-1}, compared with the mixed diet. In a second study of post-menopausal women, fat tolerance was assessed after three-day low (35% carbohydrate) or high (70% carbohydrate) carbohydrate diets [103]. When subjects performed no exercise during the dietary interventions, postprandial concentrations of TG were 36% higher after the high carbohydrate diet and concentrations of apolipoproteins B48 and B100 in the triglyceride-rich lipoprotein fraction and remnant-like lipoprotein cholesterol were also significantly elevated. However, the addition of daily exercise (60 min of brisk walking) during the high-carbohydrate diet significantly reduced all these concentrations, virtually to the level seen during the low-carbohydrate diet (Fig. 3).

In both these studies, daily exercise completely opposed the postprandial hypertriglyceridaemia induced by a short-term high-carbohydrate diet. However, postprandial lipemia after a high-carbohydrate diet plus daily exercise was no lower than that observed after low-carbohydrate or mixed diets. This might be interpreted by some as demonstrating that, other than LDL lowering—which can be achieved by switching to a diet high in unsaturated fat—there is no

'net-gain' associated with adopting a low-fat, high-carbohydrate diet, even with the addition of daily exercise. This, however, may not be true under free-living conditions. The high-carbohydrate diets utilized in the two above studies were extreme and designed to maximize any potential hypertriglyceridaemia, with 70% of energy intake from carbohydrate and half to two-thirds of this provided by simple sugars. This level of carbohydrate ingestion would be extremely difficult to achieve in the free living population and 'low-fat' diet guidelines usually recommend ingestion of <30% energy from fat, which corresponds to ~50-55% energy from carbohydrates, typically with an emphasis on complex carbohydrates rather than simple sugars [104]. Such 'real-life' diets would have a much smaller hypertriglyceridemic effect than the experimental diets above [105,106]. Thus, it is likely that adopting this recommended form of 'low-fat, high-carbohydrate' diet, together with 30-60 min of daily exercise, would result in levels of postprandial lipemia which were in fact lower than observed following a typical 'mixed' diet, although this requires formal investigation. Switching from a 'Western' diet to an AHA 'Step I' diet (<30% energy from fat, <10% energy from saturated fat) lowers LDL cholesterol by an average of 7-12% [83,107]; thus this type of diet combined with regular exercise could favorably modify a number of features of the lipoprotein profile, without adverse consequences.

One additional point warrants discussion. In the two studies described above, the high-carbohydrate and the low/moderate carbohydrate diets were designed to be isoenergetic. Under free-living conditions, *ad libitum* high carbohydrate diets often lead to reduced energy intake and weight loss compared with diets containing greater proportions of fat [83,108,109] which, alongside many other health benefits, is associated with a reduction in plasma TG concentration [83]. Thus, regular exercise (which is also associated with weight loss and the prevention of weight gain, among many other health benefits), together with a 'low-fat, high-carbohydrate diet' may well provide the optimal lifestyle strategy to achieve a favorable lipid profile. Long-term studies of the effects of low-fat, high-carbohydrate diets combined with regular exercise on postprandial lipoprotein metabolism are clearly needed to address this issue.

However, although the level of exercise required for the beneficial effects of a high-carbohydrate diet to be enjoyed without any adverse changes appears to be relatively modest, it is inevitable that some individuals will not be prepared to alter their sedentary lifestyles. In these people, replacing dietary saturated fats with unsaturated fats, rather than carbohydrate, may be a preferable option. However, high fat intakes are associated with increased body weight irrespective of the quality of dietary fat ingested [83]. Thus, this dietary approach—taken together with a physically inactive lifestyle—could make maintenance of a healthy body weight difficult and may result in trading one set of risk factors (hypertriglyceridaemia and low HDL cholesterol) with another (obesity and associated co-morbidities). Thus, without undertaking regular exercise, it is probable that compromises would need to be made with respect to management of the atherosclerotic risk profile.

6. Conclusions

Exercise is a potent regulator of postprandial lipid metabolism, with the weight of evidence suggesting that the majority of exercise's hypotriglyceridemic effect is due to acute metabolic changes following individual exercise sessions, rather than long-term adaptations to training. The energy expended during exercise is an important determinant of the exercise-induced TG reduction which is independent of exercise intensity, format and nature of substrates used while exercising. The TG-lowering effect of exercise cannot be replicated by a dietary-induced energy deficit of similar magnitude. The mechanisms responsible for exercise-induced TG reductions require further elucidation but it is probable that increased LPL-mediated TG clearance and reduced hepatic VLDL secretion both contribute. The relative importance of these two mechanisms is likely to depend on a number of factors including the energy expended during the exercise session and characteristics of the individual (i.e. training status, body fatness etc). In addition, exercise can oppose carbohydrate-induced postprandial hypertriglyceridemia and therefore levels of physical activity should be taken into account when considering nutritional strategies for reducing the risk of cardiovascular disease.

Acknowledgments

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