Fat as fuel during exercise

The emphasis in exercise is usually on carbohydrates, but fats are also important.

JULIA GOEDECKE, ***BSc (Med) Hons Nutrition and Dietetics, PhD Exercise Science***
Registered Dietician, University of Cape Town

Julia Goedecke is a registered dietician, employed by the MRC as a Specialist Scientist at UCT. Her research focuses on the regulation of fuel metabolism at rest and during exercise. In addition her research explores the mechanisms underlying the association between obesity and disease risk in South African women.

LIZE HAVEMANN, ***B Dietetics, PhD Exercise Science***
Sports Dietician, Cape Town

Lize Havemann is a registered dietician who was recently awarded her PhD in Exercise Science from UCT. Her thesis examined the effect of different nutritional strategies on ultra-endurance cycling. She is currently employed as a Postdoctoral Fellow at UCT, continuing her work in this area. She is also currently practising as a sports dietician in Cape Town.

Carbohydrate (CHO) and fat serve as the two main substrates for the production of energy during prolonged muscle contraction. Although CHO and fat are oxidised simultaneously, the relative contribution of these substrates to oxidative metabolism during exercise varies, and is dependent on a variety of factors, including exercise intensity and duration and substrate availability and training status, among other factors.

The ingestion of a high-CHO diet (7 - 10 g CHO/kg body mass) 1 - 3 days prior to an endurance event can maximise pre-exercise muscle glycogen stores and improve prolonged endurance time to fatigue.

Endurance (>90 minutes) and ultra-endurance exercise (>5 hours) are typically undertaken at a moderate-to-high exercise intensity during which muscle glycogen is the predominant fuel, especially during the earlier stages of exercise. The ingestion of a high-CHO diet (7 - 10 g CHO/kg body mass) 1 - 3 days prior to an endurance event can maximise pre-exercise muscle glycogen stores and improve prolonged endurance time to fatigue. As a result, endurance athletes are often advised to ingest a high-CHO diet or 'carbohydrate-load' during the few days prior to an endurance event. However, the body's endogenous glycogen stores are restricted to a maximum of approximately 350 - 500 g and are significantly depleted after 2 - 3 hours of moderate intensity (65 - 75% VO_{2peak}) exercise in the fasted state. The potential of endogenous carbohydrate stores alone to fuel endurance events lasting longer than 2 - 3 hours is therefore limited.

In contrast to the limited CHO stores, the body's fat stores are virtually unlimited. Even the leanest athletes have more than 80 000 kCal of potential energy stored as triglycerides in adipose tissue and intramuscular triglyceride stores. This is >40 times more than the energy stored as glycogen in skeletal muscle, and sufficient energy to fuel more than 25 marathon races. However, although fat is potentially an excellent energy source for prolonged exercise, the capacity to oxidise fat is limited, especially during higher-intensity exercise. It has been suggested that an increased ability to utilise fat during exercise may be of particular benefit to performance during longer duration endurance and ultra-endurance events. Therefore, more recent nutritional strategies have not only focused on optimising pre-exercise muscle glycogen stores, but also on increasing fat oxidation during exercise, in an attempt to 'spare' muscle glycogen and improve endurance exercise performance.

Strategies to increase fat oxidation during exercise

Fat ingestion before and during exercise

A high-fat meal containing predominantly long-chain triglycerides is emptied from the stomach very slowly and is therefore not recommended prior to endurance and ultra-endurance events. In contrast to long-chain triglycerides, medium-chain triglycerides (MCTs) contain shorter fatty acid chains (6 - 12 carbons) and can enter the circulation directly through the portal vein. In addition, MCTs do not require the long-chain acylcarnitine transferase system for transport into the mitochondria, the major rate-limiting step of fat oxidation, and are readily oxidised, especially when co-ingested with carbohydrates. MCTs therefore appear to be an ideal energy source during exercise.

Numerous studies examining the effects of MCT ingestion, either prior to or during exercise, on endurance exercise performance have been undertaken. The majority of these studies failed to demonstrate any improvement in fat oxidation or time-trial performance following MCT ingestion. In fact, a recent study demonstrated that the

A high-fat meal containing predominantly long-chain triglycerides is emptied from the stomach very slowly and is therefore not recommended prior to endurance and ultra-endurance events.

ingestion of MCTs actually *compromised* ultra-endurance (5 hours) cycling performance.[1] The decrement in performance with MCT ingestion might relate to the gastrointestinal side-effects associated with MCT ingestion, namely nausea and diarrhoea. Therefore MCT ingestion is not recommended prior to or during endurance and ultra-endurance events.

'Fat loading'

A strategy that has been associated with an increase in fat oxidation and a reduction in muscle glycogen utilisation during exercise is the ingestion of a prolonged high-fat diet. This strategy, also known as 'fat-loading' or 'fat adaptation', is a nutritional strategy whereby well-trained athletes adapt to a high-fat diet for at least 5 days. An example of a high-fat meal plan is given in Table I.

While the ingestion of a high-fat, low-CHO diet for 1 - 4 days reduces resting muscle glycogen stores and compromises the capacity to perform prolonged sub-maximal exercise, there is evidence to suggest that prolonged (>5 days) high fat intakes induce metabolic and hormonal adaptations that 'retool' the muscle to enhance rates of fat oxidation and reduce rates of CHO oxidation during exercise and, to a large extent, compensate for the reduced CHO availability.[2-4] The suggested duration of the fat-loading phase (at least 5 days) is based on the findings from Goedecke *et al.*,[5] who demonstrated that high fat intake for as little as 5 - 10 days is sufficient to maximise fat oxidation during exercise. Most of the early studies used longer time periods, which is unnecessary.

Mechanisms underlying the adaptations to a high-fat diet

Increase intramuscular triglyceride stores and oxidation

A number of studies have consistently demonstrated a substantial increase (37 - 130%) in intramuscular triglyceride stores with diets containing 41 - 65% fat for periods ranging from 2 days to 7 weeks. An increase in intramuscular triglycerides following a high-fat diet may provide an additional available substrate pool, which could account, in part, for the enhanced rates of fat oxidation in response to a high fat intake.

The greater intramuscular triglyceride storage in the trained athlete as opposed to obese and/or type 2 diabetics, represents an adaptive response to endurance training.

Changes in skeletal muscle proteins involved in FFA transport and oxidation

It was previously thought that free fatty acid (FFA) diffused freely into the muscle cell across the lipid membrane. However, more recent studies have demonstrated that FFA uptake into the muscle is facilitated by transport proteins and is highly regulated. Adaptation to a high-fat diet increases the number of FFA transporter proteins, possibly facilitating an increased FFA uptake into the muscle cell for oxidation. Furthermore, the increase in fat oxidation following fat adaptation has also been attributed, in part, to changes in skeletal muscle enzyme activities that increase the uptake and oxidation of fatty acids in the mitochondria (increase CPT-1 and 3-HAD), and reduce CHO oxidation (decrease hexokinase and pyruvate dehydrogenase).

Changes in glucose tolerance and insulin sensitivity/resistance

A high-fat diet has also been shown to induce insulin resistance, suppressing CHO metabolism and increasing fat oxidation. The ingestion of a high-fat diet for only 5 days reduced glucose tolerance, as demonstrated by a significant increase in 30-minute plasma glucose concentrations during an oral glucose tolerance test. It is well documented that increased FFA availability and elevated intramuscular triglyceride stores induce insulin resistance. However, this does not hold true for endurance-trained athletes who are able to fully oxidise the available intramuscular triglyceride stores, and are markedly insulin sensitive. Therefore, the greater intramuscular triglyceride storage in the trained athlete as opposed to obese and/or type 2 diabetics, represents an adaptive response to endurance training, allowing a greater contribution of the intramuscular triglyceride pool as a substrate source during exercise.

Table I. Example of a high-fat meal plan (~68% fat)

Breakfast
- High-fat muesli with added sesame and sunflower seeds
- Full-cream yoghurt with added cream

Snack
- 50 g peanuts

Lunch
- 6 high-fat salt biscuits with butter, cheese, salami and avocado

Snack
- 40 g crisps

Supper
- High-fat lasagne (high-fat meat with cream and cheese sauce)
- Salad with olives, feta cheese, avocado and salad dressing
- Full-cream chocolate milkshake

Effects of fat adaptation on performance

Despite adaptations that favour fat oxidation, and 'spare' muscle glycogen stores, the performance effect of fat loading is not clear. A number of studies have manipulated dietary fat intake over longer periods (>5 days) in trained and untrained subjects. The majority of these investigated the effect of a high-fat diet on moderate-intensity (60 - 85% VO_{2peak}) endurance capacity, measured as exercise time to fatigue.[4,6-9] The findings of these studies are not consistent, with nearly equal proportions of studies showing an improved (3 studies),[4,7,8] no change (2 studies),[6,9] or a decrement in endurance capacity (2 studies) in response to a high-fat diet compared with a moderate-to-high CHO diet. Together these results suggest that the ingestion of a high-fat diet (>55% fat energy) for 7 - 14 days can potentially improve moderate-intensity endurance capacity in trained athletes. However, exercise performance is not typically measured as time to fatigue, questioning the applicability of these results to athletes taking part in endurance races that are typically measured by the time to complete a set distance (time trial).

A few studies have examined the effects of fat loading on time-trial performance. They include aspects of a 'real-life' race situation such as sprinting and pacing and allow subjects to 'compete' in a situation that mimics the demands of a 'real-life' race situation.[5,10,11] However, none of the 3 studies demonstrated a significant change in time-trial performance following 2 - 5 weeks of a high-fat diet (53 - 69% fat energy) compared with moderate[5] or high-CHO diet.[10,11] The failure to demonstrate a time-trial performance benefit might relate to low muscle glycogen levels associated with the diet, as time trials are undertaken at a higher intensity and include sprinting bouts during which muscle glycogen is the predominant fuel. Hence, fat loading is not recommended as a nutritional strategy of choice prior to endurance time-trial performance.

Effects of fat adaptation followed by CHO loading on substrate metabolism and exercise performance

The restoration of muscle glycogen stores following a period of fat adaptation could, theoretically, provide an athlete with the opportunity to enhance fuel provision during exercise from both glycolytic and lipolytic pathways. Therefore researchers have examined the effects of a high-fat diet followed by CHO loading on substrate utilisation and exercise performance.

Studies investigating 5 - 10 days of fat adaptation, followed by 1 - 3 days of high CHO intake in competitive athletes demonstrated reduced muscle glycogen stores following the fat-adaptation period compared with the high-CHO diet. However, 1 day of rest in combination with a high-CHO diet was sufficient to super-compensate muscle glycogen concentrations to similar levels, independent of the preceding diet.[2] Despite the restoration of muscle glycogen levels prior to exercise, this dietary strategy was associated with significantly higher rates of fat oxidation and a 'sparing' of muscle glycogen stores during sub-maximal exercise.[1,3,12,13] However, the available evidence for a potential ergogenic effect of this particular dietary strategy on prolonged endurance exercise is not clear-cut. Of the 6 studies that have examined the effects of fat loading followed by CHO restoration on prolonged (2.5 - 7.5 hours) exercise performance, only 1 study demonstrated an improved time-trial performance following the high-fat, CHO-restoration diet compared with a high-CHO diet.[14] The remaining studies demonstrated no change in overall performance.[1,3,12,13] One of these studies did, however, demonstrate that a fat-loading diet compromised high-intensity sprint performance compared with a high-CHO diet.[13]

However, all 6 studies demonstrated an individual variability in response to the experimental diets. Some athletes improved performance, others demonstrated a decrease in performance and in some athletes performance remained unchanged in response to the high-fat, CHO-restoration dietary strategy. The results suggest that some athletes respond to certain diets, and show true performance benefits, whereas others do not respond. Indeed, there is evidence to suggest that some athletes (i.e. athletes with a 'fat burner' metabolic phenotype) are capable of using fat more effectively than others during exercise,[15] and hence may respond better to a fat-loading diet than those who preferentially burn CHO (i.e. athletes with a 'CHO burner' metabolic phenotype). Indeed, preliminary research from our laboratory demonstrated that the 'fat burners' performed a 200 km time trial faster on a fat-adaptation, CHO-restoration diet compared with a high-CHO diet (data unpublished). In contrast, the 'CHO burners' performed the 200 km cycling time trial faster on the high-CHO diet compared with the fat-loading diet.

Although there is evidence to suggest that a high-fat diet induces adaptations that allow the body to use fat more efficiently during rest and exercise, even after 1 day of CHO loading more evidence is needed to confirm the efficacy of a fat-loading diet prior to ultra-endurance events in athletes with different metabolic phenotypes.

References

1. Goedecke JH, Clark VR, Noakes TD, *et al.* The effects of medium-chain triacylglycerol and carbohydrate ingestion on ultra-endurance exercise performance. *Int J Sports Nutr Exerc Metab* 2005; 15: 15-27.
2. Burke LM, Angus DJ, Cox GR, *et al.* Effect of fat adaptation and carbohydrate restoration on metabolism and performance during prolonged cycling. *J Appl Physiol* 2000; 89: 2413-2421.
3. Carey AL, Staudacher HM, Cummings NK, *et al.* Effects of fat adaptation and carbohydrate restoration on prolonged endurance exercise. *J Appl Physiol* 2001; 91: 115-122.
4. Lambert EV, Speechly DP, Dennis SC, *et al.* Enhanced endurance in trained cyclists during moderate intensity exercise following 2 weeks adaptation to a high-fat diet. *Eur J Appl Physiol Occup Physiol* 1994; 69: 287-293.
5. Goedecke JH, Christie C, Wilson G, *et al.* Metabolic adaptations to a high-fat diet in endurance cyclists. *Metabolism* 1999; 48: 1509-1517.
6. Helge JW, Wulff B, Kiens B. Impact of a fat-rich diet on endurance in man: role of the dietary period. *Med Sci Sports Exerc* 1998; 30: 456-461.
7. Hoppeler H, Billeter R, Horvath PJ, *et al.* Muscle structure with low- and high-fat diets in well-trained male runners. *Int J Sports Med* 1999; 20: 522-526.
8. Muoio DM, Leddy JJ, Horvath PJ, *et al.* Effect of dietary-fat on metabolic adjustments to maximal Vo2 and endurance in runners. *Med Sci Sports Exerc* 1994; 26: 81-88.
9. Pogliaghi S, Veicsteinas A. Influence of low and high dietary fat on physical performance in untrained males. *Med Sci Sports Exerc* 1999; 31: 149-155.
10. Rowlands DS, Hopkins WG. Effects of high-fat and high-carbohydrate diets on metabolism and performance in cycling. *Metabolism* 2002; 51: 678-690.
11. Vogt M, Puntschart A, Howald H, Mueller B, *et al.* Effects of dietary fat on muscle substrates, metabolism, and performance in athletes. *Med Sci Sports Exerc* 2003; 35: 952-960.
12. Burke LM, Hawley JA, Angus DJ, *et al.* Adaptations to short-term high-fat diet persist during exercise despite high carbohydrate availability. *Med Sci Sports Exerc* 2002; 34: 83-91.
13. Havemann L, West SJ, Goedecke JH, *et al.* Fat adaptation followed by carbohydrate loading compromises high-intensity sprint performance. *J Appl Physiol* 2006; 100: 194-202.
14. Lambert EV, Goedecke JH, Zyle C, *et al.* High-fat diet versus habitual diet prior to carbohydrate loading: effects of exercise metabolism and cycling performance. *Int J Sports Nutr Exerc Metab* 2001; 11: 209-225.
15. Goedecke JH, St Clair Gibson A, Grobler L, *et al.* Determinants of the variability in respiratory exchange ratio at rest and during exercise in trained athletes. *Am J Physiol (Endocrinol Metab)* 2000; 279: E1325-E1334.

In a nutshell

- Fat adaptation for 5 - 6 days followed by 1 day of CHO loading should only be considered for ultra-endurance events (>4 - 5 hours) during which muscle glycogen is indeed limiting.
- Fat adaptation should not be considered for shorter events, particularly those that include high-intensity (>85% VO_{2peak}) sprints.
- Since the diet is very high in fat and saturated fat, and results in insulin resistance, it has health consequences and is only recommended for well-trained non-diabetic athletes and athletes without lipid problems.
- The fat-adaptation diet should only be followed for a short period (5 - 6 days) and used a few times per year as a specific pre-race dietary strategy to enhance ultra-endurance performance.
- It is important to realise that not everyone may respond similarly to different dietary strategies, including a fat-adaptation diet. Athletes are therefore encouraged to experiment with different dietary strategies to determine which strategy is most effective for them and the specific event they are participating in.
- Athletes should be encouraged to seek the expertise of sports dieticians who will assist in manipulating their diet according to their individual specified requirements. This is particularly important when an athlete is attempting to fat load, due to the complexity in devising a diet of this nature and the potential health implications.