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Adaptation to a Fat-Rich Diet

Effects on Endurance Performance in Humans

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Abstract

The focus of this review is on studies where dietary fat content was manipulated to investigate the potential ergogenic effect of fat loading on endurance exercise performance. Adaptation to a fat-rich diet is influenced by several factors, of which the duration of the adaptation period, the exercise intensity of the performance test and the content of fat and carbohydrate in the experimental diet are the most important.

Evidence is presented that short term adaptation, <6 days, to a fat-rich diet is detrimental to exercise performance. When adaptation to a fat-rich diet was performed over longer periods, studies where performance was tested at moderate intensity, 60 to 80% of maximal oxygen uptake, demonstrate either no difference or an attenuated performance after consumption of a fat-rich compared with a carbohydrate-rich diet. When performance was measured at high intensity after a longer period of adaptation, it was at best maintained, but in most cases attenuated, compared with consuming a carbohydrate-rich diet.

Furthermore, evidence is presented that adaptation to a fat-rich diet leads to an increased capacity of the fat oxidative system and an enhancement of the fat supply and subsequently the amount of fat oxidised during exercise. However, in most cases muscle glycogen storage is compromised, and although muscle glycogen breakdown is diminished to a certain extent, this is probably part of the explanation for the lack of performance enhancement after adaptation to a fat-rich diet.

In the 1960s, Bergström et al.^[1,2] introduced the needle muscle biopsy technique and very elegantly demonstrated the association between muscle glycogen and the occurrence of fatigue during endurance exercise. This led to the well known recommendations of how to maximise glycogen storage before exercise in order to obtain optimal endurance performance.^[3,4] However, as the magnitude of muscle glycogen usage is a function of both initial glycogen storage before exercise and rate of utilisation during exercise, it is prudent to consider how muscle glycogen breakdown and/or carbohydrate utilisation can be decreased to achieve optimal performance. Based on the glucose-fatty acid (FA) cycle proposed by Randle and co-workers,^[5] increased availability of fat during exercise should hypothetically limit muscle glycogen breakdown and thus delay the depletion of muscle glycogen stores.

To study this hypothesis, several approaches have been applied to increase fat availability: prolonged fasting, intravenous infusion of lipid-heparin solutions, caffeine intake and increased consumption of dietary fat. In brief, prolonged fasting does increase FA availability; however, at low,^[6] moderate^[7,8] and high^[9] intensity exercise, performance is attenuated compared with the normal condition. Thus, in spite of an increased FA availability, fasting was clearly detrimental to exercise endurance performance and should not be recommended. Another approach to increase FA availability is infusion of lipid-heparin solutions before and during exercise, and obviously this produces a very marked increase in FA availability (a 2- to 5-fold increase). Several studies have applied this protocol and demonstrated decreased glycogen utilisation during submaximal exercise.[10-12] However, performance was not measured in the studies above and it is quite clear that this procedure is not applicable for athletes, but merely a laboratory procedure to manipulate substrate availability. The effect of caffeine, an ergogenic aid that enhances endurance performance,^[13,14] was initially ascribed to a metabolic substrate shift caused by an increase in FA availability and a decrease in glycogen breakdown. However, as reviewed by Graham and colleagues,^[15,16] increased

FA availability during exercise is not always present after caffeine ingestion, and therefore, it is probable that other mechanisms play more important roles in the induced enhancement of performance. Therefore, the only viable approach that might possibly achieve performance enhancement through an increased fat availability is by changing dietary fat intake.

Thus, the aim of this review is to consider the evidence that increased fat intake, or in a more popular term 'fat loading', is beneficial for endurance exercise performance in humans.

1. Short Term Adaptation to Fat-Rich Diets

The concept of fat loading^[17] or consuming a diet rich in fat is by no means a new invention. Even at the beginning of the last century, Zuntz^[18] demonstrated that adaptation to a fat-rich diet led to respiratory exchange ratio (RER) values during mild exercise that suggested an almost exclusive oxidation of fat. In the late 1930s, Christensen and Hansen^[19] performed pioneering work with dietary manipulation that provided evidence for the link between endurance performance and substrate oxidation (as determined by RER). Using themselves and a co-worker as subjects, they were able to demonstrate a lower endurance performance as well as a clearly lowered RER during exercise after 3 days of adaptation to a fat-rich diet compared with 3 days of adaptation to a carbohydrate-rich diet.^[19] In line with these early findings, more recent studies of short term adaptation (in this review defined as <6 days of adaptation) to a fat-rich diet have unequivocally demonstrated a lower endurance performance when compared with a mixed or a carbohydrate-rich diet (table I). Thus, the available evidence quite clearly demonstrates that short term adaptation to a fat-rich diet is detrimental to endurance performance.

As a complement to short term dietary adaptation, studies have also investigated the effects of consuming a fat-rich meal before exercise on performance. Three recent studies demonstrated that a fat-rich meal consumed 4 hours before exercise in-

Study	Duration	Dietary content (% of total energy consumed)		Exercise intensity	Performance
	(days)	fat	carbohydrate	(% of VO _{2max})	(min)
Christensen & Hansen [19]	3	94	4	176W ^a	88 ± 4
	3	3	83	176W ^a	240 (n = 2)*
Bergström et al. ^[1]	3	46	5	75	57 ± 2
	3	0	82	75	$167 \pm 18^*$
Martin et al. ^[20]	3		<10	72	33 ± 3
	3		>75	72	$78\pm5^{*}$
Galbo et al. ^[21]	4	76	10.5	70	64 ± 6
	4	76	10.5	70	59 ± 6
	4	9.5	77	68	$106 \pm 5^*$
Starling et al. ^[22]	1	68	16	75 ^b	117 ± 3
	1	5	83	75	$139\pm7^{*}$
Pitsiladis & Maughan ^[23]	3	65	9	70 (10°C) ^c	89.2 (78-130) ^d
	3	9	82	70 (10°C) ^c	158 (117-166)*
	3	65	9	70 (30°C) ^c	44 (35-51)
	3	6	82	70 (30°C) ^c	53 (50-82)*

Table I. Studies of short term adaptation to fat-rich or carbohydrate-rich diets in humans: effect on endurance performance. Values are means, or means ± SEM for exercise performance

a Exercise performance performed at 1080 kg • m (VO2 during exercise 2.6 L/min).

b Performance was measured as a 1600kJ self paced cycling bout.

c Room temperature.

d Mean and range.

* indicates significantly different from other diets at same exercise intensity (p < 0.05).

creased the plasma FA concentration compared with a carbohydrate-rich meal. However, performance, measured as either a 10km time trial after 90 minutes of exercise at 70% of maximal oxygen uptake (\dot{VO}_{2max}) , continuous exercise until exhaustion at 78% VO2max after 120 minutes at 67% VO2max or continuous exercise until exhaustion at 78% of VO2max after 120 minutes at 67% VO2max, was similar when comparing the meals.^[24-26] Thus, there seems to be little, if any, benefit to endurance performance from increasing FA availability by consuming a fat-rich meal before exercise. A recent study^[27] demonstrated that when a fat-rich meal was consumed before exercise in conjunction with administration of heparin, performance was in fact enhanced in comparison with performance after a carbohydrate-rich meal. However, as the authors concluded, 'Heparin injection to elevate plasma fatty acid concentration would not represent sound medical practice'.^[27] Furthermore, although not unequivocal, there is a rather large amount of evidence that

demonstrates the benefits of carbohydrate consumption before exercise on endurance performance.^[28,29]

2. Long Term Adaptation to Fat-Rich Diets

Unfortunately, the evidence is less clear in intervention studies where dietary fat intake was manipulated over longer durations. In part, the lack of conclusive evidence can be ascribed to markedly different study designs in terms of major factors such as duration of adaptation, choice of exercise intensity and content of fat and carbohydrate in the diets. A very clear example of this is demonstrated in one of the early studies where Pruett^[30] investigated exercise performance at both 50 and 70% VO_{2max} after 10 days of adaptation to a fat-rich or a carbohydrate-rich diet. At the 70% workload, endurance performance was clearly attenuated after the fat-rich diet (table II), whereas at the 50% workload individuals continued until 270 minutes after the fat-rich diet (this was a predetermined maxi-

Study	Duration (days)	Dietary content (% of total energy consumed)		Exercise intensity	Performance
		fat	carbohydrate	(% of VO _{2max})	(min)
Pruett ^[30]	14	59	30	50	270 ± 0
	14	9	87	50	262 ± 6
	14	59	30	70	164 ± 21
	14	9	87	70	193 ± 13*
Phinney et al. ^[31]	28	85	2	64	151 ± 25
•	7	29	57	62	147 ± 13
O'Keeffe et al. ^[32]	7	59	13	80	60 ± 5
	7	25	54	80	98 ± 5
	7	12	72	80	113 ± 11
Williams et al. ^[33]	7	48	37	71	135 ± 5
	7	35	56	71	135 ± 5
Lambert et al. ^[34]	14	67	7	60	$79.7\pm7.6^{\ast}$
	14	12	74	60	42.5 ± 6.8
Muoio et al. ^[35]	7	38	50	75-80 ^a	91 ± 10*
	7	24	61	75-80 ^a	69 ± 7
	7	15	73	75-80 ^a	76 ± 8
Helge et al. ^[36]	49	62	21	69	65 ± 7
	49	20	65	69	$102\pm5^{*}$
	28	62	21	72	79 ± 8
	28	20	65	72	79 ± 15
Pogliaghi & Veicsteinas ^[37]	28	55	36	71	46 ± 5
	28	15	74	71	48 ± 5
Goedecke et al. ^[38]	15	69	19	b	63 ± 6
	15	30	53	b	66 ± 7

Table II. Studies of long term adaptation to fat-rich or carbohydrate-rich diets in humans: effect on endurance performance at moderateexercise intensity. Values are means, or means \pm SEM for exercise performance

a Performance was measured as 30 min at 85% $\dot{V}O_{2max}$ followed by exercise at 75 to 80% $\dot{V}O_{2max}$ until exhaustion.

b Performance was measured as 40km bicycle time trial preceded by 150 min exercise at 70% of VO_{2max}.

* indicates significantly different from other diets at same exercise intensity (p < 0.005).

mum duration) and only 261 ± 4 minutes after the carbohydrate-rich diet (table II). In the literature, muscle glycogen is considered to play a key role in fatigue when exercise intensity ranges between 65 to 85% $\dot{V}O_{2max}$.^[39-41] Thus, one possible explanation for the differential outcome on endurance in the study above is that at 70% of $\dot{V}O_{2max}$ muscle glycogen does plays a role, whereas at 50% of $\dot{V}O_{2max}$ glycogen only plays a minimal role and other factors are responsible for the lower performance. However, alternatively, the higher carbohydrate availability after the carbohydrate-rich diet could have led to a higher glycogen breakdown during exercise at 50% of $\dot{V}O_{2max}$, and thus have induced a restricted fat availability.

Since the rationale behind adaptation to a fatrich diet has primarily been to achieve glycogen sparing and higher fat oxidation, the following overview will primarily focus on studies where exercise intensity was at or above 60% VO_{2max} . To enhance clarity, the studies have been grouped by exercise intensity, where performance was measured at moderate intensities, between 60 and 80% of VO_{2max} , or at higher intensities, between 80 and 95% of VO_{2max} .

2.1 Moderate Exercise Intensity

For the moderate exercise intensities (<80% VO_{2max}), 2 studies, although severely criticised for their design, have actually demonstrated an improved

endurance performance after adaptation to fat-rich diet compared with a carbohydrate-rich diet. Lambert and colleagues^[34] demonstrated that endurance performance until exhaustion at 60% of VO_{2max} was significantly higher after 2 weeks of adaptation to a fat-rich diet containing 70% fat than that achieved after a carbohydrate-rich diet (table II). In a nonrandomised design with 6 male college athletes during the early preseason, Muoio et al.^[35] found that endurance performance and VO_{2max} were improved after consumption of a fat-rich diet for 1 week compared with either a normal or a carbohydrate-rich diet (table II).

However, as indicated above, the validity of these data should be carefully considered, since in one study endurance testing was preceded by a Wingate test and exercise at 90% of VO2max until exhaustion,^[34] and in the other study, in addition to being nonrandomised, endurance performance was measured shortly after participants had endured a determination of VO_{2max}.^[35] Furthermore, 2 studies,^[42,43] presently only available in abstract form, have investigated the effect of 7 days of adaptation to fat- or carbohydrate-rich diets on endurance performance. With a similar design and similar dietary contents as used in the study by Muoio et al.,[35] no effect of fat-rich diet on endurance performance was found in well trained female or male triathletes exercising at 72% and 60% of VO_{2max}, respectively.^[42,43] In these latter studies the fat-rich diet contained only 38% of total energy as fat, a dietary fat content that normally would not be considered 'high fat'. However, in the context of this review, studies that have manipulated dietary fat content between diets and investigated endurance performance hereafter are included.

Most studies in which exercise was performed at moderate intensities do not find any difference in performance between individuals on a fat-rich and those on a carbohydrate-rich diet.^[31,33,36,37] An example is the study by Poglia and Veicsteinas^[37] where endurance performance in untrained men, measured at 71% of $\dot{V}O_{2max}$, was similar after 4 weeks of adaptation to a fat-rich, carbohydrate-rich or normal diet (table II). It is important to note that these studies span durations from 7 to 28 days, and have very marked differences both in the contents of fat and carbohydrate and in the actual differences in dietary fat content between the diets applied (table II). Thus, it would seem that for individuals exhibiting a wide range in training status, adaptation to a fat-rich diet does not lead to an increased performance when tested at a moderate exercise intensity.

On the other hand, few studies have actually demonstrated that a fat-rich diet is detrimental to exercise performance at moderate intensity. As discussed in the example above, Pruett^[30] demonstrated that endurance performance was higher after 14 days of adaptation to a carbohydrate-rich diet compared with a fat-rich diet when performance was measured at 70% of VO_{2max}. In well trained female athletes, a decreased performance at 80% of $\dot{V}O_{2max}$ was found after 7 days of adaptation to a fat-rich diet compared with either a moderate- or a highcarbohydrate diet.^[32] In a more recent study, Helge et al.^[44] demonstrated that when untrained individuals participated in a regular training programme for 7 weeks while consuming either a fat- or a carbohydrate-rich diet, the endurance performance was attenuated after the fat-rich diet (table II, fig. 1). As the study was performed with similar diets, training protocol and participants as the study referenced above,^[36] this later finding indicates that the duration of the adaptation period might be important for the outcome of the dietary change, since performance was attenuated after 7 but not 4 weeks of adaptation to a fat-rich diet.

On the basis of these data and the lack of studies demonstrating a clear positive effect, it is very difficult to argue for a beneficial effect of fat loading. However, with only 3 studies demonstrating a negative effect, further evidence is needed to determine if fat loading is in fact directly detrimental to performance at moderate exercise intensity.

2.2 Higher Exercise Intensity

When considering the higher exercise intensities, the evidence is somewhat clearer. The studies by Sherman^[45] and Pitsiladis and Maughan^[46] dem-



Fig. 1. Endurance exercise performance until exhaustion at 70% of maximal oxygen uptake (\dot{VO}_{2max}) initially and after 7 weeks^[44] adaptation to training and either a fat-rich diet or a carbohydrate-rich diet. Values are means \pm SEM. * indicates p < 0.05 versus initial value; † indicates p < 0.05 versus fat-rich diet.

onstrated that at 80% of VO_{2max} performance after adaptation to a fat-rich diet was not significantly different to that after a carbohydrate-rich diet. Similarly, it was demonstrated that at 90% of $\dot{V}O_{2max}$, performance after adaptation to a fat-rich diet was not significantly different to that after a carbohydrate-rich diet (table III).[34,46] However, in the 2 later studies, although not significant, the high-carbohydrate group exercised 50% and 26% longer than the fat group (table III). Therefore, it would seem that the lack of a significant difference could simply be because of an inadequate number of participants in relation to the power needed. Further support for a detrimental effect of dietary fat (or lack of carbohydrate) on high intensity performance can be gained from the study by Simonsen et al.,^[47] where male and female college student rowers underwent 4 weeks of adaptation to a moderate carbohydrate diet (5g carbohydrate per kg bodyweight, 43% fat) or a carbohydrate-rich diet (10g carbohydrate per kg bodyweight, 17% fat). In this study, rowers trained twice daily, 6 days a week for 4 weeks. Mean power output during three 2500m rowing time trials, separated by 8 minutes, was investigated weekly. At an estimated exercise intensity of 90 to 95% of $\dot{V}O_{2max}$, performance, given as mean power output, was significantly higher after the high-carbohydrate diet than after the moderatecarbohydrate diet (table III, fig. 2). Therefore, the evidence indicates that a fat-rich diet does not have an ergogenic potential for high intensity exercise performance. On the contrary, fat loading is probably detrimental for high intensity exercise performance.

For exercise above 95% of VO_{2max}, Maughan and colleagues^[49] recently reviewed the literature and concluded that after short term adaptation to diets low in carbohydrate, exercise capacity at very high intensities was reduced by 10 to 30% when compared with diets rich in carbohydrates. It was suggested that the explanation for the effect of diet on high intensity performance was not related to the reduced carbohydrate availability, but rather to either an effect on the acid-base status of the body or/and a decreased flux through the pyruvate dehydrogenase (PDH) enzyme complex via an accumulation of acetyl groups after the high fat diet. Another explanation was given by Larson and co-workers,^[50] who used ³¹P-magnetic resonance spectroscopy to demonstrate that after 5 days of adaptation to fat-rich diet, incremental quadriceps performance until exhaustion was impaired compared with that achieved after carbohydrate-rich diet, and that this was probably because of an attenuated phosphorylation potential.

3. Effects of Adaptation to a Fat-Rich Diet

It is well documented that both short and long term adaptation to a fat-rich diet induces a significantly higher fat oxidation at both lower^[51,52] and higher^[31,34,44,53] exercise intensities. Also, it is evident that the consumption of a fat-rich diet leads to an increased availability of plasma FA^[20,21,31] and an increased storage of muscle triacylglycerol when compared with a carbohydrate-rich diet.^[22,36] Less information is available on the adaptations that provide the mechanistic explanation for the observed shift in substrate oxidation. However, there is evidence to suggest that the fat oxidative capacity of β-hydroxyacyl-CoA dehydrogenase (HAD)^[54] and carnitine palmitoyltransferase (CPT)^[55] is enhanced after adaptation to a fat-rich diet compared with a carbohydrate-rich diet. Furthermore, adaptation to a fat-rich diet has been shown to induce a decreased activity of hexokinase (HK)[55] and pyruvate dehydrogenase (PDH).^[56-58] Overall, these adaptations favour fat combustion; however, judging from the lack of ergogenic effect of dietary fat on endurance performance discussed in sections 1 and 2, it would seem that the extent of increase in fat oxidative capacity is insufficient to enhance or, in several cases, even maintain exercise capacity. The rationale for applying a fat-rich diet has traditionally been to increase fat availability and therefore glycogen sparing via an increased fat oxidation. Unfortunately, few studies have actually measured the rate of glycogen breakdown during the endurance bouts, and the results indicate that glycogen sparing occurred in some^[21,31] but not all^[34,44,59] studies. In addition, there is very good evidence that muscle glycogen storage is lower after adaptation to a fat-rich diet after both short term^[1,21] and long term^[31,36,47] adaptation (fig. 2). Furthermore, there is evidence that liver glycogen is also decreased after short term adaptation to a fat-rich diet compared with a carbohydrate-rich diet in humans.^[60] Based on the above, it is tempting to postulate that in spite of a significant increase in the capacity of the fat oxidative system and the storage and supply of FA after a fat-rich diet, the decreased muscle and liver glycogen stores cannot, even with a diminished breakdown rate, sustain the demand for carbohydrate oxidation needed to achieve increased exercise performance when compared with consuming a carbohydrate-rich diet.

The discussion above relies heavily on the assumption that lack of carbohydrates caused by depletion of glycogen stores is closely related to the occurrence of fatigue at exercise intensities between 60 to 90% of \dot{VO}_{2max} , and this may not hold true in all cases.^[1,23,44,61] The inevitable consequence is of course that other physiological variables partake in the events leading to fatigue. It has been shown that increased dietary fat (fat-rich diet) over time was associated with an increased sympathetic activity during exercise.^[21,44] How such an increase in sym-

Study	Duration	Dietary content (% of total energy consumed)	Exercise intensity	Performance
intensity. Values are mea	ans, or means \pm SEM	for exercise performance	·	Ū.

Study	Duration (days)	Dietary content (% of total energy consumed)		Exercise intensity	Performance
		fat	carbohydrate	(% of VO _{2max})	(min)
Simonsen et al. ^[47]	28	43	42	≥90ª	192W
	28	17	70	≥90 ^a	207W*
Sherman ^[45] (cyclists)	7	43-46 ^b	42	80 ^c	9.2 ± 1.4
	7	2-5 ^b	84	80 ^c	10.2 ± 0.8
Lambert et al. ^[34]	14	67	7	90	$\textbf{8.3} \pm \textbf{2.3}$
	14	12	74	90	12.5 ± 3.8
Pitsiladis et al. ^[48]	7	44	40	85 ^d	49 ± 1
	7	25	55	85 ^d	49 ± 1
Pitsiladis & Maughan ^[46]	7	42	40	80	27 ± 7
	7	17	71	80	27 ± 7
	7	44	40	90	11.6 ± 3.8
	7	18	70	90	9.0 ± 2.4

a Three rowing time trials over 2500m separated by 8 min. Performance was measured as average power output.

b Assuming a protein intake of 12 to 15% of total energy consumed.

c After normal training (60 min at 75% of VO_{2max}, followed by 5 × 1 min sprints at 100% of VO_{2max}) performance was assessed as the cumulative time for 2 exercise bouts at 80% of VO_{2max} until exhaustion with 5 min rest in between.

d 10km time trial. Intensity estimated from indirect calorimetry data.

* indicates significantly different from other diets at same exercise intensity (p < 0.005).



Fig. 2. (a) Mean power output for 3×2500 m rowing time trials in 22 male and female college rowers during and after 4 weeks adaptation to training and a high-carbohydrate diet (10g per kg bodyweight) from Simonsen et al.^[47] with permission]. Data are expressed as percentage change from performance at day 1. (b) In the same study, muscle glycogen from vastus lateralis was measured weekly and expressed as percentage change from week 1 (from Simonsen et al.,^[47] with permission). Values are means \pm SEM.

pathetic nervous activity could impair endurance performance is unclear. However, it can be speculated that substrate oxidation could be affected, either by way of a further suppression of insulin secretion during exercise, by the increased sympathetic activity, or by way of an increased cortisol excretion, mediated by a diet-induced increase of central sympathetic activity.^[62,63] This suggests that a detrimental effect of a fat-rich diet could be caused by a higher sympathetic drive at the same relative exercise load. There are, however, other possible variables that potentially could be involved in the fatigue process, such as fat diet–induced changes in fibre type recruitment patterns that would lead to a selective depletion of specific fibre types. Another possibility is fat diet–induced changes in membrane function of the sarcolemma and the sarcoplasmic reticulum because of changes in phospholipid FA membrane composition. The latter could lead to changes in calcium influx and efflux and changes in maintenance of ion balance; however, these possibilities are at present mainly speculative.

4. Adverse Effects of Adaptation to a Fat-Rich Diet

For the general population, it is recommended that fat consumption should not exceed 30 to 35% of total energy consumption in order to maintain good health. Thus, it is imperative to consider the potential health implications of adaptation to fatrich diets in athletes.

Indeed, 70 years ago, McClellan and DuBois^[64] investigated how well humans could endure adaptation to a carbohydrate-free meat diet. In this study, 2 men who had previously experienced such a diet in free living conditions (arctic explorers) tolerated very well a dietary intake consisting of meat, fat, bone marrow, brain and offal (primarily liver and kidney) and occasionally butter and eggs for more than a year in a controlled setting (hospital ward). During the experimental period, the 2 men demonstrated normal physical and mental alertness, normal blood pressure, no vitamin deficiencies and there were no signs of kidney damage. Duplicate analysis of the diet showed that the nutrient composition of the diet resided within the following range, 15 to 25% protein (of total energy), 75 to 85% fat and 1 to 2% carbohydrate. It is interesting that performance on a $2\frac{1}{4}$ mile run (about 3.6km), duration about 20 minutes, was unchanged over the first 2 months of dietary adaptation. Although this is, of course, extreme to the point of ridicule, it nicely emphasises that fat-rich diets can be tolerated over extended periods and that carbohydrates are not essential for human survival.

More recent studies have investigated plasma lipid and lipoprotein profiles after prolonged adaptation to fat-rich diets in well trained athletes who maintained their normal training. It was demonstrated that during and after 12 weeks of adaptation to either a fat-rich diet containing 45% of total energy as fat, or a carbohydrate-rich diet, low density lipoprotein-cholesterol (LDL-C), high density lipoprotein-cholesterol (HDL-C) and apolipoprotein A1 were similar between groups.^[65] In a later follow-up study applying the same design, similar findings were achieved with a fat-rich diet containing slightly more fat, and in this later study, plasma triacylglycerol was higher after the carbohydrate diet than after the fat diet.^[66] Similar findings to these were reported in a group of regularly training runners after 4 weeks of adaptation to diet containing either 30 or 42% of total energy as dietary fat. No adverse effects of dietary fat were found on blood pressure, serum triacylglycerol, LDL-C and apolipoprotein B.[67] Furthermore, it has been demonstrated that even a diet containing 85% of total energy as fat consumed by 5 regularly training individuals did not lead to an unfavourable ratio of total cholesterol to HDL-C when compared with a normal balanced diet.^[68] Therefore, based on this evidence, it would seem that in well trained individuals who maintain training, no adverse effects on plasma lipid and lipoprotein profiles were present when a fat-rich diet was consumed over periods of up to 3 months. However, when training is not maintained while consuming a fat-rich diet and/or when a fat-rich diet is consumed over longer periods, there may be, and probably are, detrimental effects on general health.

If athletes should benefit from consuming a fatrich diet over shorter periods, it is necessary that the training intensity can be maintained at a sufficiently high level to avoid a detraining effect while consuming the fat-rich diet. Almost 80 years ago, Krogh and Lindhard^[51] asked the participants of their study to describe their perception of daily living chores and exercise sessions while eating either fat-rich or carbohydrate-rich foods for 3 to 5 days. Of interest here is the individuals' mostly uniform description of how exercise was performed easily after consumption of the 'carbohydrate diet', while exercise was performed with severe difficulty after consumption of the 'fat diet'. Although the fat diet was almost devoid of carbohydrates and the participants were untrained, this is a potential pitfall when applying fat-rich diets to athletes with high training loads. Unfortunately, only limited published evidence is available on this issue. In one study, the Profile of Mood States (POMS) test was given to 7 well-trained female athletes after 1 week of adaptation to either a low-, moderate- or high-fat diet, just before an endurance test until exhaustion at 80% of VO_{2max}.^[69] The participants continued their normal training through the 3 dietary periods, and the mood state results therefore reflect a combination of dietary changes, training and daily life. It is evident from the results that the score for the mood states tension/anxiety, depression/dejection and anger/hostility were higher after the fat-rich diet than for the 2 other diets; conversely, the vigour/activity score was lower after the fat-rich diet. There was no difference between the dietary treatments in the fatigue/inertia or confusion/bewilderment scores. Although the existing data are sparse, they do indicate that adaptation to diets containing high amounts of fat and/or low amounts of carbohydrate is accompanied by a higher degree of mental stress during exercise.

5. Conclusion

This review has focused on the available evidence for a potential ergogenic effect of fat loading on exercise performance in humans. There is undoubtedly a detrimental effect on exercise performance when a fat-rich diet is consumed over short periods. When the adaptation period is extended to 1 week or longer, the data presented do not indicate that fat loading has an ergogenic potential when exercise performance is measured at moderate or higher exercise intensity. However, since the evidence for a direct detrimental effect of fat loading over longer periods, measured at moderate intensity, is limited to a few studies, and the adverse effects on health do not seem to be critical over these reasonably limited periods, further investigations are needed to draw more final conclusions. Since it is a fundamental issue to athletes that training intensity and duration be maintained, this parameter should be considered and investigated when dietary manipulations towards a higher fat intake are performed in athletes with high training loads.

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