Fats in sports nutrition

Position of the working group sports nutrition of the German Nutrition Society (DGE)

Alexandra Schek, Hans Braun, Anja Carlsohn, Mareike Großhauser, Daniel König, Alfonso Lampen, Stephanie Mosler, Andreas Nieß, Helmut Oberritter, Klaus Schäbethal, Peter Stehle, Kiran Virmani, Rainer Ziegenhagen, Helmut Heseker

Abstract

This position statement represents the current state of scientific knowledge regarding the recommended fat intake in ambitious recreational and high-level sports. It also addresses dietary strategies (fat-loading methods) and food supplements that are designed to influence fat metabolism during physical exercise.

So far, no recommendation has been established for sports-specific fat intake in absolute numbers (g/kg body weight/d), in line with international practices regarding carbohydrates and proteins. However, there is consensus among scientific sports medicine associations that fat consumption should not exceed 30% of the energy intake (En%), nor fall below 20 En%, particularly in endurance sports.

Before competitions, some endurance athletes practice fat-loading strategies which include a ketogenic diet. This procedure is not advisable, as there is no scientific evidence of improvement in performance. Moreover, this is an unbalanced diet according to DGE recommendations.

The current use of dietary supplements which are supposed to improve the availability/oxidation of fatty acids is also generally discouraged.

Keywords: sports nutrition, fat, fat loading, ketogenic diet, caffeine, carnitine, fish oil, MCT

Citation
Schek A, Braun H, Carlsohn A, Großhauser M, König D, Lampen A, Mosler S, Nieß A, Oberritter H, Schäbethal K, Stehle P, Virmani K, Ziegenhagen R, Heseker H (2019) Fats in sports nutrition. Position of the working group sports nutrition of the German Nutrition Society (DGE). Ernahrungs Umschau 66(9): 181–188
This article is available online:
DOI: 10.4455/eu.2019.042

Peer-reviewed
reviewed during preparation

Reference values for fat intake and food-related dietary recommendations

Compared to the significance of carbohydrates in endurance sports and proteins in resistance training, the amount of consumed fats and their quality play a rather subordinate role with regard to performance and health of ambitious recreational and high-level athletes. This is why essentially the same recommendations as for the healthy general public apply.

While there are recommended intakes in absolute values (g/kg body weight/d) for carbohydrates and proteins in endurance and strength sports on an international level, there is only a guideline for fat intake: not to exceed 30% of the energy intake (En%), nor fall below a rate of 20 En% [1]. The lower limit is meant to ensure that:
1. an adequate amount of essential fatty acids and fat-soluble vitamins is supplied/absorbed,
2. the person feels satiated between meals,
3. the intramuscular triglycerides are replenished after long-lasting physical exercise.

The reference value of 30 En% for healthy adolescents and adults is considered the upper limit of fat intake in ambitious recreational and high-level sports to prevent food-related illnesses [2, 3]. Persons with increased energy expenditure (physical activity level [PAL] > 1.7) may require more than 30 En% [3]. However, especially in regards to endurance sports, reputable international associations encourage limiting fat intake to 30 En%, which takes into account the fact that deriving energy from carbohydrates takes precedence [1].
For a fat intake up to 30 En%, the proportions of fatty acid fractions should ideally be as follows:
- 7–10 En% saturated fatty acids (max. one third of energy supplied as fat),
- 7 En% polyunsaturated fatty acids (sum of

Fatty acids	Foods (content in En%)
Polyunsaturated fatty acids	
Linoleic acid (n-6, essential)	wheat germ oil (57), soybean oil (54), sunflower seeds (31), pumpkin seeds (30)
α-linolenic acid (n-3, essential)	linseed oil (54), walnuts (13), walnut oil (12), canola oil (9)
Eicosapentaenoic acid (EPA; n-3)	herring (8), sprat (6), tuna (6), salmon (4)
Docosahexaenoic acid (DHA; n-3)	tuna (9), sprat (8), salmon (7), mackerel (5)
Monounsaturated fatty acids	olive oil (72), hazelnuts (71), peanut oil (57), avocado (56), canola oil (50), cashews (44), pumpkin seeds (27)
Saturated fatty acids	coconut fat (88), butter (65), cream, 30% fat in dry matter (56), Gouda, 45% fat in dry matter (49), palm oil (47), lard (40), bacon (39), milk chocolate (34), liverwurst (33), nut nougat cream (32), Hollandaise sauce (32), salami (31), egg yolk (23)
Trans fatty acids	are often contained in variable proportions in e.g.: deep-frying oil, baked products, biscuits, crackers, potato chips, instant soups, margarine made from one type of oil

Tab. 1: **Foods with high proportions of individual fatty acids or different types of fatty acids** (calculated with DGExpert version 1.9.3.1)

n-3 and n-6 fatty acids) or up to 10 En% if the energy supply from saturated fatty acids exceeds 10% of the total energy intake,
- monounsaturated fatty acids make up the difference to the total fat content,
- the proportion of trans fatty acids should be less than 1 En%.

For adolescents and adults, the recommended intake of essential fatty acids that cannot be formed in the human body is 2.5 En% for linoleic acid (n-6) and 0.5 En% for α-linolenic acid (n-3) [3]. The latter can only be converted in the body to a limited extent into the long-chain n-3 fatty acids eicosapentaenoic (EPA) and docosahexaenoic acid (DHA) [3].

A wholesome diet according to the nutritional recommendations of the DGE [4, 5] includes a high proportion of plant-based food and – bearing in mind a healthy energy balance – a supply of oils with a high amount of α-linolenic acid (linseed, walnut, canola oil) and fish with a high amount of eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) (herring, salmon, mackerel). If possible, fish from a sustainable source should be consumed once to twice per week [4, 5]. Additionally, the consumption of foods with a high proportion of saturated (coconut oil, palm oil, animal-derived products) and trans fatty acids (convenience foods) should be reduced and replaced with food containing high levels of monounsaturated fatty acids (olive oil, canola oil, nuts and seeds). ♦ Table 1 shows foods containing high levels of the above-mentioned fatty acids.

Fat consumption

Data about fat consumption in ambitious recreational sports are sparse, as illustrated by the compilation in ♦ Table 2. Most (cross-sectional) studies were performed with high-level athletes. The latter mostly adhere to the reference value of 30 En% fat, as documented in detail by Schek (2018, p. 15–22) [6], in endurance as well as (high-speed) strength and team sports, while the intake of carbohydrates is often in the lower range of the recommended intake. This also seems to apply for the endurance disciplines in ambitious recreational sports (♦ Table 2). However, the available data do not allow for any estimates beyond this. Given the popularity of city marathons and high-intensity fitness classes, there is a need for further research.

Disputable strategies before competition (fat loading)

Studies have been conducted for about 35 years on whether the availability or oxidation rate of fatty acids in the active muscles can be increased by varying the fat content in food or using dietary supplements. The aim is to protect the glycogen reserves [9], which *hypothetically* leads to an improvement in endurance performance.

Fat loading is a pre-competition strategy that is practiced either three to four hours before the start (acute) or five and more days before the competition (chronic). Chronic fat loading can be further distinguished into ketogenic and non-ketogenic low-carb, high-fat (LCHF) diets.

	n	Age (years)	Training (min/d)	Energy (kcal/d)	CHO (g/kg BW/d)	Proteins (g/kg BW/d)	Fats (En%)
Set values of the ACSM [1]				sufficient to meet requirements	5–12	1.2–2.0	20–30
Endurance sports							
Modern pentathlon [7]	12 m+f	39.8	64	2,739	5.5	1.6	32
Triathlon [7]	22 m+f	37.4	111	2,925	5.5	1.7	31
Ironman [7]	39 m+f	41.4	143	3,703	7.3	2.1	28
"Ultradistance" [8]	55 m 12 f	46.4 44.3	87 86	2,681 2,205	4.5 4.8	1.3 1.3	30.4 31.1
Fitness sports							
CrossFit [8]	5 m 6 f	25.6 31.5	41 90	3,308 2,609	3.4 3.8	1.8 2.1	39.6 38.5

Tab. 2: **Energy and macronutrient intake determined to date in ambitious recreational athletes to illustrate the nutrient distribution in practice**
ACSM = American College of Sports Medicine; BW = body weight; CHO = carbohydrates; d = day; f = female; m = male; n = number

The interest in fat loading resurged during the past five years [10–13], although not many new studies have been conducted. Since fat loading is getting increasing exposure on internet platforms and blogs with the key phrase "ketogenic diet" (40,300,000 search results on google.de on July 7, 2019), the different strategies are briefly introduced and critically examined below.

Acute fat loading

Acute fat loading involves eating a high-fat meal (60–90 En% fat) three to four hours before a strenuous endurance exercise bout. Studies involving competitive athletes show that a high-fat loading meal does not positively influence the time to exhaustion, but instead may even shorten it:

- Okano et al. (1996; 1998) and Whitley et al. (1998) were able to show a slightly higher proportion of fatty acids in the energy supply, but only at an early stage of the exercise and without any effect on endurance capacity [14–16].
- Wee et al. (1999) determined a negative influence of a high fat intake compared to a high carbohydrate intake on the time to exhaustion (–14%), which the authors attributed to delayed gastric emptying [17].
- In the context of intermittent (Hulton et al., 2013) or high-intensity exercise (Hawley et al., 2000), only a slightly higher availability and oxidation of fatty acids could be determined after a high-fat meal. The performance was not improved [18, 19].

Concerns about gut comfort after ingesting a high-fat loading meal were not addressed in any of the mentioned studies. However, a correlation between high fat intake and gastrointestinal distress can be observed particularly in endurance sports [20].

Ketogenic LCHF diet (short: ketogenic diet)

The ketogenic diet, which is carried out particularly with the goal of weight reduction, sometimes for weeks, although there is no proof that it is superior to energy restricted types of diets, is characterized by a fat content of 75–85 En%, a protein content of 15–25 En% and a carbohydrate content of < 50 g/d. The studies which were mostly performed in the realm of endurance sports reveal no positive effects on performance capacity, but may even show negative effects:

- Phinney et al. (1983) were not able to prove any influence on the time to exhaustion with bicyclists, which led them to conclude: *"The price paid for the conservation of CHO during exercise appears to be a limitation of the intensity of exercise that can be performed"* [21].
- Zajac et al. (2014) did see a minor increase in the relative oxygen intake, but this was attributed to the weight loss by 1.8 kg (in four weeks). The maximum work load on the bicycle ergometer was lower [22].
- Zinn et al. (2017) showed a weight loss of 4 kg (in ten weeks) on the one hand, and a decrease in time to exhaustion in a bicycle ergometer step test on the other hand [23].
- Heatherly et al. (2018), despite demonstrably lower glucose oxidation rates, found no influence on various performance parameters during five 10-minute running bouts at multiple individual race paces and a 5 km

time trial. They assume that possible performance reductions were offset by the observed weight loss of 2.5 kg (in three weeks) [24].

- McSwiney et al. (2018) did not find any influence on the result in a 100 km time trial. The increase in relative power in a simulated final sprint can be attributed to an improved power-to-mass ratio resulting from a weight reduction by 5 kg (in three months) [25].
- Burke et al. (2017) showed that under competitive conditions, the time for a 10 km race walk could not be improved after a three-week ketogenic diet – in contrast to the results after diets providing chronic or periodized high carbohydrate availability. The authors propose that the low-carbohydrate diet prevented a positive training effect, which could partially be attributed to a reduced exercise economy [26].
- Mujika (2018), in the scope of an individual case study, states that during an eight-month reduction in carbohydrate intake to < 52 g/day, a world-class triathlete dropped from the top ranks to the 18th and 14th position and had to cancel a competition. Five weeks after switching to a diet rich in carbohydrates, he finished second and fourth in two Ironman events separated by only three weeks. Moreover, there was a positive impact on the athlete's subjective psychological well-being [27].
- As part of high-intensity interval training (Cipryan et al., 2018) and in three studies involving strength disciplines (overview by López Laval & Sitko, 2019), no influence on performance could be shown [28, 29].

A striking observation, when considering the food selection in a ketogenic diet, is that it is at odds with the food-related recommendations by the DGE for a balanced diet [4, 5]. Micronutrient-dense foods, such as fruit, potatoes, or cereal products, can only be consumed in very limited amounts. It is therefore possible that long-term use can lead to negative effects on health, nutrient supply and performance.

Non-ketogenic LCHF diet

This diet, which also limits the food selection so severely that it is no longer wholesome, involves the consumption of 60–70 En% fat and 15–20 En% of each proteins and carbohydrates for one to several weeks before a competition. Based on endurance-oriented studies, it can be inferred that the non-ketogenic LCHF diet does not have a significant influence on performance or may even have a negative influence:

- In the study by O'Keeffe et al. (1989), to date the only study performed on women, a decline in endurance capacity was evident [30].
- Lambert et al. (1994) did find an increase in endurance time to exhaustion, but this was after a prior supramaximal exercise test, which heavily strained the muscle glycogen reserves and has little in common with real-life conditions [31].
- Two additional studies (Rowlands & Hopkins, 2002; Vogt, 2003) were unable to show any influence on the maximum oxygen intake, distance, duration or power output in a time trial or on the half-marathon time [32, 33].

What has been shown so far about fat-loading strategies leads to the conclusion that a fatty acid oxidation rate that has been moderately increased by a higher fat intake [34] has no benefit with respect to (endurance) performance. A possible cause of this could be that the low carbohydrate intake is accompanied by a reduced availability of glycogen/glucose [35]. It can be assumed that the disadvantage of reduced muscular glycogen reserves outweighs the benefit of a glycogen-sparing effect during physical exercise.

LCHF diet in combination with carbohydrate loading

In an attempt to avoid the possible disadvantage of suboptimal glycogen storage due to an LCHF diet, several studies were conducted in which a five- to 11-day non-ketogenic LCHF diet was followed by one to three days of carbohydrate loading with 7–11 g of carbohydrates/kg body weight/day. However, the study results suggest that the combination of an LCHF diet with carbohydrate loading does not have a positive effect on endurance performance:

- In five studies, no effect on cycling performance could be determined in a time trial following an endurance exercise bout at moderate intensity [31, 36–39]; one study showed a 4% improvement [40].
- The realistic study of competitive cyclists by Havemann et al. (2006) showed decreased performance in the final sprint. The authors conclude: *"Adaptation to the LCHF diet followed by CHO restoration increased fat oxidation during exercise (…), but it reduced high-intensity sprint power performance, which was associated with increased muscle recruitment, effort perception and heart rate"* [41].

In summary, it can be assumed that during intermediate and final sprints, glycolysis is limited owing to a downregulation of the pyruvate dehydrogenase activity caused by an LCHF diet [34]. This means that the upregulation of fatty acid oxidation is ultimately more likely to result in a limitation of glycogen use than to have a glycogen sparing effect [35]. In addition, it is possible that during an exercise bout after fat loading, the higher concentrations of free fatty acids and ammonium ions in blood plasma promote general fatigue [42]. This is why high-fat dietary practices are discouraged.

Dietary supplements for the alleged increase of fatty acid oxidation

The influence of various dietary supplements on the availability or oxidation rate of fatty acids has been studied repeatedly. The hypothesis underlying these studies is that an increase in energy supply from fatty acids could spare glycogen and thus enhance endurance performance. To what extent it does make sense to use food supplements is discussed below.

Caffeine

Caffeine was on the list of banned drugs until 2004. Heretofore, it was assumed that the alkaloid stimulates the release of adrenaline, thereby increasing the mobilization of fatty acids from adipocytes and myocytes, which can be used as energy sources [43]. Graham et al. (2000), however, showed that caffeine does neither enhance the uptake of fatty acids by the working muscles, nor does it influence fat or carbohydrate metabolism [44]. Nor could Greer et al. (2000) determine any influence on the breakdown of muscle glycogen, although an increased time to exhaustion [45] was shown. This is why the metabolic theory was discarded.

The European Food Safety Authority (EFSA) certifies that caffeine, as an adenosine receptor antagonist, has a positive effect on alertness and concentration with a single serving of 75 mg (about one cup of coffee) [46] or a favorable influence on endurance performance and capacity with a consumption of 3 mg/kg body weight [47]. The health risks of caffeine are clarified by the “Position of the working group sports nutrition of the DGE: Safety aspects of dietary supplements in sports” [48].

Carnitine

During exercise of moderate intensity, carnitine functions as a carrier of long-chain fatty acids through the inner mitochondrial membrane. In the case of high work loads, carnitine buffers excess acetyl residues, thereby preserving the pool of free coenzyme A, an essential factor in oxidation reactions (pyruvate dehydrogenase, citrate cycle enzymes) [34, 49, 50]. All studies that investigated the effect of carnitine supplementation of 2–6 g/day over a period of one to 16 weeks showed that carnitine per se does not influence the proportion of fats and carbohydrates in the energy supply, nor does it improve endurance performance or reduce body fat [49, 51]. This is because orally ingested carnitine does not increase the carnitine concentration in the myocytes [49, 50]. This is only possible if carnitine is administered with large amounts (2 x 80 g/day) of readily available carbohydrates [50, 52, 53], which is not desirable from a nutritional and physiological perspective.

According to the EFSA, carnitine does not favorably influence endurance capacity or recovery [54]. In the scope of testing carnitine tartrate for use in particular foods, the EFSA has rated an intended daily supply corresponding to 2 g of carnitine as well tolerated, and assured that gastrointestinal distress was only reported for consumptions of 4–6 g of carnitine or more per day in tolerance studies [55].

Fish oil

Fish oil, which contains high amounts of EPA and DHA, was first recommended specifically for athletic purposes by Simopoulos (2007) [56]. In vitro, EPA results in an induction of the gene expression of acetyl-CoA carboxylase which regulates the fatty acid oxidation in the mitochondria [57]. However, human studies have not verified any influence of long-chain n-3 fatty acids on the proportionate energy supply from fat and carbohydrates, either at rest [58] or during exercise [59]. This explains why fish oil has no effect on endurance performance, as Da Boit et al. (2017) presented in their review [60].

For adults, the EFSA does not note any health concerns for a combined supplemention of EPA and DHA with amounts of up to 5 g per day or, if only EPA is supplemented, of up to 1.8 g/day. If only supplemented with DHA, this applies to doses of up to about 1 g/day for the general population [61].

Medium-chain triglycerides (MCT)

Medium-chain triglycerides (MCT) are fatty acids with a medium chain length (6–12 C atoms). They can contribute to energy production in the skeletal muscles, but only at an extent of 3–8% of all oxidized fatty acids [62–64]. The maximum oxidation rate of 0.12 g/min is reached after strenuous exercise lasting approx. two to three hours [62–64]. Most of the few studies that have examined the influence of a combined intake of MCT and carbohydrates before and during endurance exercise show no indication of a glycogen sparing or performance enhancing effect [65–69]. Only van Zyl et al. (1996), who administered 86 g of MCT to their study subjects during an endurance exercise bout, found an improvement in their performance in the subsequent time trial [70]. However, Goedecke et al. (2005) identified a performance impairment in the scope of a simulated ultra-endurance competition during which a total of 148 g of MCT had been supplied. The authors speculated that the gastrointestinal symptoms (especially intestinal cramps) reported by some participants contributed to the impaired performance [71]. Ivy et al. first outlined in 1980 that gastrointestinal distress had occurred in 100% of their study subjects after a bolus of 50 or 60 g of MCT. When the dose was reduced to 30 g, gastrointestinal discomfort was reported by only 10% of the participants [72]. Décombaz et al. (1983) used single dosages of 25 g of MCT, because preliminary studies had not shown any adverse effects for this amount [73]. Jeukendrup et al. [62, 74] consider a single administration of approx. 30 g of MCT prior to physical exercise to be the upper limit. This amount is too low to influence performance, however.

Coconut oil

MCT in the form of coconut oil are currently experiencing a revival as part of the ketogenic diet for weight reduction. Coconut oil contains about 54% medium chain fatty acids, of which only 12% with 8 and 10 carbon atoms are rapidly converted into ketones by the liver [76]. The use of MCT to support weight loss is not to be recommended [2, 77]. This is because only 80–120 kcal can be saved, owing to the average tolerable intake level of about 60 g per day, which is reached when an initial MCT supply of 20 g/day is slowly increased by 5–10 g/day [77]. It can thus be assumed that coconut oil is not an effective means of reducing weight, for example as part of competition preparation.

Conclusion

In contrast to carbohydrates and proteins, for which recommended intakes were internationally derived in g per kg of body weight and day for various types of sports, the reference value for fat intake is specified in terms of a percentage of energy supply. The diet of ambitious recreational and high-level athletes should provide a maximum of 30 and a minimum of 20 En% fat and prioritize a health-promoting fatty acid pattern.

Attempts to increase fatty acid availability by means of acute or chronic fat loading strategies (with or without subsequent replenishing of glycogen stores) failed to show improvements in endurance performance, although fatty acid oxidation was enhanced. In the worst case, fat loading may even result in performance impairment in intermediate or final sprints, which is why low-carb, high-fat (LCHF) diets are not recommended.

The use of dietary supplements which are supposed to increase the availability/oxidation of fatty acids does not result in performance enhancing effects and is thus not recommended.

Acknowledgement
For the critical review of this manuscript the authors thank Dr. Angela Bechthold and Birte Peterson-Sperlich from the Science Department at the DGE.

Corresponding author
Klaus Schäbethal
schaebethal@dge.de

Dr. Alexandra Schek[1]
Hans Braun[2]
Prof. Dr. Anja Carlsohn[3]
Dr. Mareike Großhauser[4]
Prof. Dr. Daniel König[5]
Prof. Dr. Dr. Alfonso Lampen[6]
Dr. Stephanie Mosler[7]
Prof. Dr. Andreas Nieß[8]
Dr. Helmut Oberritter[9]
Klaus Schäbethal[9]
Prof. Dr. Peter Stehle[10]
Dr. Kiran Virmani[9]
Dr. Rainer Ziegenhagen[6]
Prof. Dr. Helmut Heseker[11]

[1] Redaktion Leistungssport (DOSB)
[2] Institut für Biochemie
Deutsches Forschungszentrum für Leistungssport – Momentum Deutsche Sporthochschule Köln
[3] Fakultät Life Sciences/Department Ökotrophologie
Hochschule für Angewandte Wissenschaften Hamburg
[4] Olympiastützpunkt Rheinland-Pfalz/Saarland
[5] Institut für Sport und Sportwissenschaft
Arbeitsbereich Ernährung Albert-Ludwigs-Universität Freiburg
[6] Abteilung Lebensmittelsicherheit (Abt. 5)
Bundesinstitut für Risikobewertung (BfR)
[7] Institut für Gesundheitswissenschaften
Abteilung Ernährung, Konsum und Mode
Pädagogische Hochschule Schwäbisch Gmünd
Olympiastützpunkt Stuttgart
[8] Abteilung Sportmedizin
Medizinische Klinik
Universitätsklinikum Tübingen
[9] Deutsche Gesellschaft für Ernährung e. V. (DGE)
[10] Institut für Ernährungs- und Lebensmittelwissenschaften Ernährungsphysiologie
Rheinische Friedrich-Wilhelms-Universität Bonn
[11] Institut für Ernährung, Konsum und Gesundheit
Fakultät für Naturwissenschaften Universität Paderborn

Conflict of Interest
The authors declare no conflict of interest.

References

1. Thomas DT, Erdmann KA, Burke LM (2016) American College of Sports Medicine joint position statement: nutrition and athletic performance. Med Sci Sports Exerc 48: 543–568
2. Deutsche Gesellschaft für Ernährung (Hg). Fettzufuhr und Prävention ausgewählter ernährungsmitbedingter Krankheiten – Evidenzbasierte Leitlinie. 2. Version 2015. Bonn (2015) URL: www.dge.de/wissenschaft/leitlinien/leitlinie-fett/ Zugriff 19.11.17
3. Deutsche Gesellschaft für Ernährung, Österreichische Gesellschaft für Ernährung, Schweizerische Gesellschaft für Ernährung (Hg). Referenzwerte für die Nährstoffzufuhr. 2. Aufl., 3. aktualisierte Ausgabe, Bonn (2017)
4. Deutsche Gesellschaft für Ernährung (Hg). Vollwertig essen und trinken nach den 10 Regeln der DGE (2017) URL: www.dge.de/ernaehrungspraxis/vollwertige-ernaehrung/10-regeln-der-dge/ Zugriff 19.08.18
5. Deutsche Gesellschaft für Ernährung (Hg). Der DGE-Ernährungskreis – Beispiel für eine vollwertige Lebensmittelauswahl (2019) URL: www.dge.de/ernaehrungspraxis/vollwertige-ernaehrung/ernaehrungskreis/ Zugriff 19.08.18
6. Schek A. Top ernährt im Sport. BoD, Norderstedt (2018)
7. Masson G, Lamarche B (2016) Many non-elite multisport endurance athletes do not meet sports nutrition recommendations for carbohydrates. Appl Physiol Nutr Metab 41: 728–734
8. Wardenaar F, Brinkmans N, Ceelen I et al. (2017) Macronutrient intakes in 553 Dutch elite and sub-elite endurance, team, and strength athletes: does intake differ between sport disciplines? Nutrients 9: 119
9. Spriet LL (2014) New insights into the interaction of carbohydrate and fat metabolism during exercise. Sports Med 44(Suppl 1): 87S–96S
10. Brukner P (2013) Challenging beliefs in sports nutrition: are two 'core principles' proving to be myths ripe for busting? Brit J Sports Med 47: 663–664
11. Helge JW (2017) A high carbohydrate diet remains the evidence based choice for elite athletes to optimise performance. J Physiol 595: 2775
12. Noakes T, Volek JS, Phinney SD (2014) Low carbohydrate diets for athletes: what evidence? Brit J Sports Med 48: 1077–1078
13. Volek JS, Noakes T, Phinney SD (2015) Rethinking fat as a fuel for endurance exercise. Eur J Sport Sci 15: 13–20
14. Okano G, Sato Y, Murata Y (1998) Effect of elevated FFA levels on endurance performance after a single fat meal ingestion. Med Sci Sports Exerc 30: 763–768
15. Okano G, Sato Y, Takumi Y, Sugawara M (1996) Effect of 4-h pre-exercise high carbohydrate and high fat meal ingestion on endurance performance and metabolism. Int J Sports Med 17: 530–534
16. Whitley HA, Humphreys SM, Campbell IT et al. (1998) Metabolic and performance responses during endurance exercise after high-fat and high-carbohydrate meals. J Appl Physiol 85: 418–424
17. Wee SL, Williams C, Garcia-Roves P (1999) Carbohydrate availability determines endurance running capacity in fasted subjects. Med Sci Sports Exerc 31(5), Suppl (abstract 299): 91S
18. Hulton AT, Edwards, JP, Gregson W et al. (2013) Effect of fat and CHO meals on intermittent exercise in soccer players. Int J Sports Med 34: 165–169
19. Hawley JA, Burke LM, Angus DJ et al. (2000) Effect of altering substrate availability on metabolism and performance during intense exercise. Br J Nutr 84: 829–838
20. Hoogervorst D, van der Burg N, Versteegen JJ et al. (2019) Gastrointestinal complaints and correlations with self-reported macronutrient intake in independent groups of (ultra) marathon runners competing at different distances. Sports (Basel) 7: E140
21. Phinney SD, Bistrian BR, Evans WF (1983) The human metabolic response to chronic ketosis without caloric restriction: preservation of submaximal exercise capacity with reduced carbohydrate oxidation. Metabolism 32: 769–776
22. Zajac A, Poprzecki S, Maszczyk A et al. (2014) The effects of a ketogenic diet on exercise metabolism and physical performance in off-road cyclists. Nutrients 6: 2493–2508
23. Zinn C, Wood M, Williden M et al. (2017) Ketogenic diet benefits body composition and well-being but not performance in a pilot case study of New Zealand endurance athletes. JISSN14: 22 ff
24. Heatherly AJ, Killen LG, Smith AF et al. (2018) Effects of ad libitum low-carbohydrate high-fat dieting in middle-age male runners. Med Sci Sports Exerc 50: 570–579
25. McSwiney FT, Wardrop B, Hyde PN et al. (2018) Keto-adaptation enhances exercise performance and body composition responses to training in endurance athletes. Metabolism 81: 25–34
26. Burke LM, Ross ML, Garvican-Lewis LA et al. (2017) Low carbohydrate, high fat diet impairs exercise economy and negates the performance benefit from intensified training in elite race walkers. J Physiol 595: 2785–2807
27. Mujika I (2019) Case study: long-term low-carbohydrate, high-fat diet impairs performance and subjective well-being in a world-class vegetarian long-distance triathlete. Int J Sport Nutr Exerc Metab 29: 339–344
28. Cipryan L, Plews DJ, Ferretti A et al. (2018) Effects of a 4-week very low-carbohydrate diet on high-intensity interval training responses. J Sport Sci Med 17: 259–268
29. López Laval I, Sitko S (2019) Dietas bajas en hidratos de carbon y rendimiento deprotivo: revision sistemática. J Neg No Pos Results 4: 634–643
30. O'Keeffe KA, Keith RE, Wilson GD, Blessing DL (1989) Dietary carbohydrate intake and endurance exercise performance of trained female cyclists. Nutr Res 9: 819–830
31. Lambert EV, Speechly DP, Dennis SC, Noakes TD (1994) Enhanced endurance in trained cyclists during moderate intensity exercise following 2 weeks adaptation to high fat diet. Eur J Appl Physiol 69: 287–293
32. Rowlands DS, Hopkins WG (2002) Effects of high-fat and high-carbohydrate diets on metabolism and performance in cycling. Metabolism 51: 678–690
33. Vogt M, Puntschart A, Howald H et al. (2003) Effects of dietary fat on muscle substrates, metabolism, and performance in athletes. Med Sci Sports Exerc 35: 952–960
34. Purdom T, Kravitz L, Dokladny K, Mermier C (2018) Understanding the factors that effect maximal fat oxidation. JISSN 15: 3 ff
35. Burke LM (2015) Re-examining high-fat diets for sports performance: did we call the 'nail in the coffin' too soon? Sports Med 45(Suppl 1): S33–S49
36. Burke LM, Angus DJ, Cox GR et al. (2000) Effect of fat adaptation and carbohydrate restoration on metabolism and performance during prolonged cycling. J Appl Physiol 89: 2413–2421
37. Burke LM, Hawley JA, Angus DJ et al. (2002) Adaptations to short-term high-fat diet persist during exercise despite high carbohydrate availability. Med Sci Sports Exerc 34: 83–91
38. Carey AL, Staudacher HM, Cummings NK et al. (2001) Effects of fat adaptation and carbohydrate restoration on prolonged endurance exercise. J Appl Physiol 91: 115–122

39. Noakes T (2004) Fat adaptation and prolonged exercise performance. J Appl Physiol 96: 1243–1244
40. Lambert EV, Goedecke JH, van Zyl CG et al. (2001) High-fat versus habitual diet prior to carbohydrate loading: effects on exercise metabolism and cycling performance. Int J Sport Nutr Exerc Metab 11: 209–225
41. Havemann L, West SJ, Goedecke HJ et al. (2006) Fat adaptation followed by carbohydrate-loading compromises high-intensity sprint performance. J Appl Physiol 100: 194–202
42. Chang CK, Borer K, Lin PJ (2017) Low-carbohydrate-high-fat diet: can it help exercise performance? J Hum Kinet 56: 81–92
43. Costill DL, Dalsky GP, Fink WJ (1978) Effects of caffeine ingestion on metabolism and exercise performance. Med Sci Sports Exerc 10: 155-158
44. Graham TE, Helge JW, MacLean DA et al. (2000) Caffeine ingestion does not alter carbohydrate or fat metabolism in human skeletal muscle during exercise. J Physiol 529(Pt 3): 837–847
45. Greer F, Friars D, Graham TE (2000) Comparison of caffeine and theophylline ingestion: exercise metabolism and endurance. J Appl Physiol 89: 1837–1844
46. EFSA (2011) Scientific opinion on the substantiation of health claims related to caffeine and increased fat oxidation (…). EFSA Journal 9: 2054
47. EFSA (2011) Scientific opinion on the substantiation of health claims related to caffeine and increase in physical performance (…). EFSA Journal 9: 2053
48. Ziegenhagen R, Braun H, Carlsohn A et al. Safety aspects of dietary supplements in sports. Position of the working group sports nutrition of the German Nutrition Society (DGE). Ernahrungs Umschau [submitted]
49. Schek A (1994) L-Carnitin: Sinn und Unsinn der Substitution einer körpereigenen Substanz (Teil 1 + 2). Ernährungs Umschau 41(1 + 2): 9–15 + 60–67
50. Stephens FB, Constantin-Teodosiu D, Greenhaff PL (2007) New insights concerning the role of carnitine in the regulation of fuel metabolism in skeletal muscle. J Physiol 581(Pt 2): 431–344
51. Brass EP (2000) Supplemental carnitine and exercise. Am J Clin Nutr 72(2 Suppl): 618S–623S
52. Stephens FB, Wall BT, Marimuthu K et al. (2013) Skeletal muscle carnitine loading increases energy expenditure, modulates fuel metabolism gene networks and prevents body fat accumulation in humans. J Physiol 591: 4655–4666
53. Wall BT, Stephens FB, Constantin-Teodosiu D et al. (2011) Chronic oral ingestion of L-carnitine and carbohydrate increases muscle carnitine content and alters muscle fuel metabolism during exercise in humans. J Physiol 589(Pt 4): 963–973
54. EFSA (2011) Scientific opinion on the substantiation of health claims related to L-carnitine (…). EFSA Journal 9: 2212
55. EFSA (2003) Opinion of the Scientific Panel on food additives, flavourings, processing aids and materials in contact with food (AFC) on a request from the commission related to L-carnitine-L-tartrate for use in foods for particular nutritional uses. EFSA Journal 19: 1–13
56. Simopoulos AP (2007) Omega-3 fatty acids and athletics. Curr Sports Med Rep 6: 230–236
57. Hessvik NP, Bakke SS, Frederiksson K et al. (2010) Metabolic switching of human myotubes is improved by n-3 fatty acids. J Lipid Res 51: 2090–2104
58. Noreen EE, Sass MJ, Crow ML et al. (2010) Effects of supplemental fish oil on resting metabolic rate, body composition, and salivary cortisol in healthy adults. J Int Soc Sports Nutr 7: 31
59. Bortolotti M, Tappy L, Schneiter P (2007) Fish oil supplementation does not alter energy efficiency in healthy males. Clin Nutr 26: 225–230
60. Da Boit M, Hunter AM, Gray SR (2017) Fit with good fat? The role of n-3 polyunsaturated fatty acids on exercise performance. Metabolism 66: 45–54
61. EFSA (2012) Tolerable upper intake level of EPA, DHA and DPA. EFSA Journal 10: 2815
62. Jeukendrup AE, Saris WHM, Schrauwen P et al. (1995) Metabolic availability of medium-chain triglycerides co-ingested with carbohydrates during prolonged exercise. J Appl Physiol 79: 756–762
63. Jeukendrup AE, Saris WHM, van Diesen R et al. (1996) Effect of endogenous carbohydrate availability on oral medium-chain triglyceride oxidation during prolonged exercise. J Appl Physiol 80: 949–954
64. Massicotte D, Péronnet F, Brisson GR, Hillaire-Marcel C (1992) Oxidation of exogenous medium-chain free fatty acids during prolonged exercise: comparison with glucose. J Appl Physiol 73: 1334–1339
65. Angus DJ, Hargraeves M, Dancey J, Febbraio MA (2000) Effect of carbohydrate or carbohydrate plus medium chain triglyceride ingestion on cycling time trial performance. J Appl Physiol 88: 113–119
66. Goedecke JH, Elmer-English R, Dennis SC et al. (1999) Effects of medium-chain triacylglycerol ingested with carbohydrate on metabolism and exercise performance. Int J Sport Nutr 9: 35–47
67. Jeukendrup AE, Saris WHM, Brouns F et al. (1996) Effects of carbohydrate (CHO) and fat supplementation on CHO metabolism during prolonged exercise. Metabolism 45: 915–921
68. Jeukendrup AE, Thielen JJ, Wagenmakers AJM et al. (1998) Effect of MCT and carbohydrate ingestion on substrate utilization and cycling performance. Am J Clin Nutr 67: 397–404
69. Vistisen B, Nybo L, Xu X et al. (2003) Minor amounts of medium-chain triglyceride ingestion on carbohydrate metabolism and cycling performance. J Appl Physiol 95: 2434–2443
70. Van Zyl CG, Lambert EV, Hawley JA et al. (1996) Effects of medium-chain triglyceride ingestion on carbohydrate metabolism and cycling performance. J Appl Physiol 80: 2217–2225
71. Goedecke JH, Clark VL, Noakes TD, Lambert EV (2005) The effects of medium-chain triacylglycerol and carbohydrate ingestion on ultra-endurance exercise performance. Int J Sport Nutr Exerc Metab 15: 15–27
72. Ivy JL, Costill DL, Fink WJ, Maglischo E (1980) Contibution of medium and long chain triglyceride intake to energy metabolism during prolonged exercise. Int J Sports Med 1: 15–20
73. Décombaz J, Arnaud MJ, Milon H et al. (1983) Energy metabolism of medium-chain triglycerides versus carbohydrates during exercise. Eur J Appl Physiol 52: 9–14
74. Jeukendrup AE, Saris WHM, Wagenmakers AJM (1998) Fat metabolism during exercise: a review. Part III: Effects of nutritional interventions. Int J Sports Med 19: 371–379
75. Fife B. The Coconut Ketogenic Diet. Piccadilly Books, Colorado Springs (2014)
76. Vandenberghe C, Castellano CA, Maltais M et al. (2016) A short-term intervention combining aerobic exercise with medium-chain triglycerides (MCT) is more ketogenic than either MCT or aerobic exercise alone: a comparison of normoglycemic and prediabetic older women. Appl Physiol Nutr Metab 44: 66–73
77. Deutsche Gesellschaft für Ernährung (Hg). Mittelkettige Triglyceride für die Adipositastherapie nicht empfehlenswert (2011) URL: www.dge.de/wissenschaft/weitere-publikationen/fachinformationen/mittelkettige-triglyceride-adipositastherapie/ Zugriff 03.02.18

DOI: 10.4455/eu.2019.042