REVIEW

Ketogenic diets, exercise performance, and training adaptations

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Purpose of review

The ketogenic diet has been proposed as a nutritional strategy in sports. This review was undertaken to provide an overview of the recent literature concerning the effects of ketogenic diet on exercise performance and training adaptations.

Recent findings

Most recent literature on the ketogenic diet and exercise performance showed no beneficial effects, especially for trained individuals. During a period of intensified training, performance was clearly impaired during the ketogenic intervention, while a diet with high carbohydrates maintained physical performance. The main effect of the ketogenic diet resides in metabolic flexibility, inducing the metabolism to oxidize more fat for ATP resynthesis regardless of submaximal exercise intensities.

Summary

The ketogenic diet is not a reasonable nutritional strategy, as it has no advantage over normal/high carbohydrate-based diets on physical performance and training adaptations even when used only in a specific training/nutritional periodization stage.

Keywords

athletes, endurance sports, interval training, metabolic flexibility, obese

INTRODUCTION

There are several types of diets based on different assumptions. Graybeal *et al.* [1] verified that ketogenic, low-carbohydrate, and Atkins are the most followed diets among athletes (51.1% of 169 athletes) of several sports modalities, such as cycling, running, triathlon, rowing, swimming, wheelchair running, aqua bike, and snowshoeing. The ketogenic diet, in particular, was used by 25.6% of interviewed athletes. Such a diet is proposed as a nutritional strategy based on the predominance of calories from fat (70–85% calories), an adequate quantity of protein (15–25% calories), and minimal carbohydrate consumption for metabolic needs (<50 g per day or 5% calories) [2]. Thus, it induces the body to utilize fat as the primary substrate source [3,4▪,5], which produces ketone bodies in the liver, namely acetoacetate, beta-hydroxy-butyrate (βHB), and acetone. The ketogenic diet is defined by its ability to elevate circulating ketone bodies, the so-called nutritional ketosis, evaluated mainly from increased levels of blood βHB (>0.5 mmol/l) [6]. Adherence to the ketogenic diet also causes a shift in the reliance on lipid-based fuels while decreasing glucose oxidation, leading to a keto-adaptation [6], the primary physiological mechanism supporting its utilization in sports practice.

Beyond physical and technical/tactical training, diet is paramount in nearly all sports modalities. In endurance sports, adherence to different diets can adapt the body to utilize more carbohydrates or fats as fuel. In contrast, diet is essential to controlling body composition in other sports with weight-based categories (i.e. fights, lifts). Briefly, using the ketogenic diet in sports comes from the 1980s with the pioneer study by Phinney *et al.* [2] on the effects of this diet on endurance performance. In that study, five cyclists performed a time-to-exhaustion (TTE) test during cycling exercise at ~63% maximal oxygen uptake

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KEY POINTS

- This diet leads to an accentuated shift in the substrate oxidation for ATP resynthesis during moderate-to-high submaximal intensities (i.e. <$\dot{V}O_{2max}$), changing the use of carbohydrates to fat as the main source.
- The fat as the main source of the substrate leads to an impairment in the movement economy, that is, a high oxygen uptake for the same absolute intensity of exercise.
- For endurance performance, there were more impairments for trained individuals than for less-trained ones.

($\dot{V}O_{2max}$) after 1 week under a habitual carbohydrate intake (57% calories) and after 4 weeks under an isocaloric ketogenic diet composed of minimal carbohydrate (<20 g/day) and high fat (80% calories) contents. In summary, there was no difference at the group level in the TTE after the habitual no-restricted carbohydrate diet (147 ± 13 min) and the ketogenic diet (151 ± 25 min). Over the decades, several studies have been conducted about the effects of the ketogenic diet on exercise performance in different modalities and exercise modes, and on the body composition in diverse populations. Concerning this issue, there were several studies with meta-analyses published recently [7▪,8–10]. They all showed no advantage of the ketogenic diet over normal/high carbohydrate-based diets on physical performance. In contrast, they showed beneficial effects on fat and total body mass loss. The present article aimed to review the most recent publications regarding the ketogenic diet's impact on exercise performance and training adaptations.

EXERCISE PERFORMANCE

Regarding exercise performance, the most recent systematic reviews, including or not meta-analysis, showed that the ketogenic diet does not produce better effects compared with carbohydrate-based diets in both aerobic (e.g. cycling and running) and strength performances [7▪,9] and seems to have no effect in improving endurance performance even when combined with concurrent training [8].

Most endurance performance events are performed at intensities greater than 70% of $\dot{V}O_{2max}$, in which the main source for the substrate to ATP resynthesis comes from the carbohydrates [11]. The ketogenic diet is a powerful strategy to shift primary substrate source from carbohydrates to fat, regardless of the submaximal exercise intensity [3,4▪,5]. A recent study by Dearlove *et al.* [12▪▪] tested the effects of the ketogenic diet against a rich-carbohydrate-based diet and normal carbohydrate plus exogenous hyperketonemia via weight-adjusted ketone drinks consumption on exercise performance pre, post, and during six consecutive days of performance tests. For that, 14 trained male cyclists were divided into diet groups. They performed an incremental exercise test pre-intervention and post-intervention and during the six consecutive days, which consisted of a preload of 90 min at 70% $\dot{V}O_2$max followed by an incremental test to exhaustion. Overall, groups with normal (+ exogenous hyperketonemia) and high carbohydrate consumption did not change TTE (which accounted for the 90 min preload and the incremental test) in the posttest, and during the six consecutive days, the changes were minor. On the other hand, the ketogenic group reduced the TTE by ~50% in all testing sessions. In another investigation [5], four female and one male cyclist were randomized in cross-over trials of 2 weeks, each composed of a high carbohydrate or a ketogenic diet. The performance was assessed by a 30 km cycling time-trial (TT) after each diet, and a significantly lower power output (~ -14%) was observed in all cyclists during the ketogenic intervention [5].

In another study, Wachsmuth *et al.* [13] implemented a nonrandomized cross-over design in a group of 18 (13 female individuals) active individuals to a high carbohydrate or ketogenic diet, performed in that order with a wash-out of 3 weeks. The physical performance measured as peak workload ($\dot{W}_{max}$) from an incremental test was lower after the ketogenic than high carbohydrate (~-4%; $P = 0.0001$), even with lower calories at high carbohydrate weeks (1739 ± 606 vs. 1939 ± 430 kcal/day; $P = 0.02$). The control group ($n = 6$, 1 female) that performed two times in a 3-week period, also separated by 3 weeks of a wash-out, did not change $\dot{W}_{max}$ (change ~-1%).

Somewhat contradictory to these studies, Paoli *et al.* [14] studied 16 young semi-professional soccer players and verified an average augmentation of 28 and 44% in the distance covered during an incremental field test, namely the Yo-Yo intermittent recovery test, after 30 days of ketogenic or no restricted carbohydrate diets ($n = 8$ for each), respectively. Despite apparent disproportional changes, the results were not different between groups at a statistical threshold of P less than 0.05. Additionally, in a group of CrossFit practitioners, nonsignificant changes were observed under 6 weeks of ketogenic or no restricted carbohydrate diets in both groups for a 500 m rowing TT, cycling Wingate test (i.e. 30 s all-out), and three maximal repetitions on deadlift exercise [15]. Although in overweight individuals, Cipryan *et al.* [16▪] verified a performance improvement in the incremental test after 12 weeks under ketogenic ($n = 25$, 17 female individuals), which was greater than the improvement in the control group that followed their habitual diet ($n = 19$, 13 female individuals).

Importantly, the criteria for assessing performance should be looked with attention. Most studies have evaluated exercise performance through incremental tests, with the outcomes $\dot{W}_{max}$ or TTE [12▪▪,13,14,16▪]. Instead, other utilized a cycling TT of 30 km [5] and Wingate test [15], or a rowing 500 m TT [15]. Both $\dot{W}_{max}$ and TTE from an incremental test are interchangeable measures and are correlated with the most varied TT durations [17]. Nevertheless, they did not simulate the demands of 'real world' endurance events. On the other hand, they provide more reliable data for untrained individuals, as pacing strategy control is not required. For soccer physical performance evaluation, the Yo-Yo incremental shuttle-running test, intending to simulate the physical behavior of matches.

Concerning the majority of cited studies, small sample sizes were utilized. This limits the statistical power for the dichotomous 'statistical significance' given by P value less than 0.05. The studies in athletes or physically active individuals showed impairment or equal effects for ketogenic against control carbohydrate-based diets regardless of the diet duration or performance task [5,12▪▪,13,14,15]. The only study that verified effects slightly more favorable to ketogenic was in a sample of overweight individuals following 12 weeks of intervention [16▪]. Regarding this issue, a recent systematic review with meta-analysis using Bayesian probabilistic inferences verified by using meta-regressions that the magnitude of effects of ketogenic diets against carbohydrate-based diets is modulated by the diet and performance (for aerobic activities) durations [7▪]. Also, the meta-regression showed that the ketogenic diet impairs endurance performance to a greater extent in participants with higher aerobic fitness (measured by relative VO_2max) [7▪]. Therefore, a ketogenic diet could be more suitable for long performance tasks and when followed by a long period in untrained individuals. Nevertheless, studies demonstrating this are still incipient, so carbohydrate-based diets are still the best approach for endurance performance events [11]. Finally, no evidence is available about the ultra-endurance performance: events exceeding more than 6 h.

TRAINING ADAPTATIONS

In endurance sports, some periods focus on low, moderate, or high-intensity training, depending on the season. A big unresolved question concerning the ketogenic diet and performance is whether it is possible to use a ketogenic protocol only in a specific stage of the training/nutritional periodization, aiming to stimulate a greater supply of fat and returning to a no-restricted carbohydrate diet just before the competitions for improving or without impairing performance [18]. This concept is termed as metabolic flexibility. From the recent studies, we focus on interval and 'functional' training [16▪,19] and congested performance tests [12▪▪] in conjunction with a ketogenic diet.

Concerning interval training during a ketogenic diet, Cipryan *et al.* [16▪] compared the interval training + ketogenic, interval training only, ketogenic diet only, and a control condition in overweight individuals for 12 weeks. Interval training consisted of two to three sessions per week performed at nearly maximal perceptions of effort. Incremental test TTE significantly increased at week 12 in relation to pre-intervention by 12, 16.9, and 5.9% in the interval training only, interval training + ketogenic, and ketogenic only groups, respectively. The changes in the two groups that followed the interval training were significantly higher than in the ketogenic-only and control groups. In contrast, changes were not different between the two interval training groups. In another report, Camajani *et al.* [19] investigated the effects of 'functional training' following a 'normal' and a ketogenic diet for 6 weeks in a sample of obese with sarcopenia. The two groups had no differences in the 'chair stand test' performance. As these studies were conducted on untrained individuals, it is not possible to extrapolate the findings to the athletic population's performance. Nevertheless, the ketogenic diet appears to be an efficient strategy for total body mass and fat mass loss [7▪,16▪,19,20], improves the levels of HDL-c, VLDL-c, and triglycerides [21], and the mitochondrial mass and function in skeletal muscle (in mice) [22,23].

The study by Dearlove *et al.* [12▪▪] provides interesting insights regarding high training load periods or competitions performed over multiple days. The authors utilized a period of six consecutive days, performing 90 min at 70% $\dot{V}O_2$max followed by an incremental test. In the participants that followed the ketogenic diet already on the first day, the 90 min was not completed in nearly all subjects, and also in the subsequent days until the sixth. While in the other groups that ingested normal (with ketone drinks) and high carbohydrate diets, the 90 min was completed, and the following incremental test performance improved. It seems evident that the ketogenic group was in a state of overreaching, an undesirable performance state [24]. Those findings reinforce the importance of carbohydrate ingestion in periods of intensified or high training load demands. For instance, a recent case report from an elite cross-country skier presented one of the main reasons for the season of underperformance, the excessive use of training sessions without proper carbohydrate ingestion [25].

Several studies have verified a metabolic shift under the ketogenic diet. Kreutzer *et al.* [5] verified an augmentation of fat and a decrease of carbohydrate oxidation during a cycling 30 km TT. Prins *et al.* [4▪] verified during a running 5 km TT that fat and carbohydrate accounted for 3–7 and 93–97% of the energy supply, respectively, during a high carbohydrate diet. On the other hand, during a ketogenic intervention, the energy supply was 36–52 and 48–64%, respectively. According to the authors, the 5 km TT race time was not different between the diets [4▪]. Nonetheless, most previous studies found an impairment of performance. The main reason is based on the body's efficiency in producing energy because fat oxidation demands a greater oxygen uptake (i.e. worse movement economy) [3]. Burke *et al.* [3] observed that 5–6 days following a ketogenic diet was enough to impair the running economy in elite race walkers. The authors also observed that 24 h eating carbohydrates after the ketogenic intervention could not restore the previous state, possibly because of a decrease in the active form of pyruvate dehydrogenase and glycogenolysis, causing glycogen impairment. But, interestingly, 5–6 days of eating a no-restricted carbohydrate diet was enough to reverse the adaptations promoted by ketogenic (i.e. more utilization of fat as fuel during exercise). So, in addition to reducing performance in athletes, the ketogenic diet does not promote adaptations when used in a specific period of nutritional periodization. Moreover, in this same population, a ketogenic diet, regardless of energy availability, appears to lead to symptoms of relative energy deficiency in sport (RED-S), such as impaired bone metabolism [26], iron, immune, and stress responses to exercise [27]. Corroborating with performance issues, Kreutzer *et al.* [5] observed that 14 days following a ketogenic diet impaired performance because of reduced muscle glycogen availability before TT, measured using skeletal muscle ultrasound. All this evidence suggests caution not only for performance issues but also for athletes' health too.

LIMITATIONS AND FUTURE PERSPECTIVES

The most recent literature is still incipient on the interaction of a ketogenic diet and different training structures or periodization, especially in samples composed of highly trained individuals. Therefore, future studies could address the unresolved question of periods interchanged by ketogenic and normal/high carbohydrate diets that could produce the best metabolic flexibility. Also, the ketogenic diet and ultra-endurance performances should be focused of future studies.

CONCLUSION

Based on recent evidence, there is no doubt that athletes aiming for performance should not follow a ketogenic diet, even when used only in a specific training/nutritional periodization stage. In addition, for untrained individuals, ketogenic diets also have no performance advantage over carbohydrate-based diets. However, in this group of people, the ketogenic diet appears to induce desired effects on body composition and health measures.

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Conflicts of interest

There are no conflicts of interest.

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Papers of particular interest, published within the annual period of review, have been highlighted as:

▪ of special interest
▪▪ of outstanding interest

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