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Influence of ketogenic diet on athletes' performance and other aspects of body function – review of literature

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ABSTRACT

Introduction and aim. The ketogenic diet (KD) is a high-fat, moderate-protein, and low-carbohydrate dietary regimen that induces a state of ketosis, shifting the body's fuel source from glucose to ketone bodies produced from fatty acids. The aim of this paper is to analyze the influence of the KD on athletes' performance, body composition and other aspects of body function.

Materials and methods. A comprehensive literature search has been conducted through PubMed database using keywords such as "ketogenic diet sport" and "ketogenic diet athletes", "ketogenic diet body".

Analysis of literature. Some studies suggest that a KD can be a viable method for reducing body fat without negatively affecting strength, power, or muscle mass in athletes. It has been found that KD can increase fat oxidation. However, KD may not be optimal for improving performance in high-intensity endurance events or activities that require quick bursts of energy fueled by carbohydrates. Additionally, KD may not have a significant effect on factors such as VO2max, HRmax, time to exhaustion, and perceived exertion in some athletes.

Conclusion. More research is required to understand the effects of the ketogenic diet on athletes' performance. It may aid in weight loss and fat oxidation, but questions remain regarding adaptation time, sport-specific benefits, and impact on various body parameters.
Keywords. ketogenic diet, sport, athletic performance

INTRODUCTION

The ketogenic diet (KD) is a dietary regimen that promotes the metabolic state of ketosis through the consumption of a high-fat, moderate-protein, and low-carbohydrate macronutrient profile. This diet aims to induce a shift in the body's primary fuel source from glucose to ketone bodies, which are produced from the breakdown of fatty acids in the liver.

The typical macronutrient ratio for a ketogenic diet is 70-80% fat, 20-25% protein, and 5-10% carbohydrates. By significantly reducing carbohydrate intake, the body is forced to use fat as its primary source of energy, which is metabolized to ketones in the liver.

Ketone bodies, such as acetoacetate, 3-hydroxybutyrate, and acetone, are produced in the liver through the process of ketogenesis, which involves the conversion of acetyl-CoA. The liver is the primary site of ketone body production, but other organs, including the kidney and the brain, can also generate ketone bodies to a lesser extent.

Once generated, ketone bodies are released into the circulation and can be taken up by other tissues, including the brain, heart, skeletal muscle, and kidneys. In these tissues, ketone bodies are metabolized to generate energy through a process called ketolysis. This involves the conversion of acetoacetate to acetyl-CoA, which can enter the Krebs cycle to produce ATP, the body's primary energy source.

During the initial stages of a ketogenic diet, the body relies on hepatic glycogenolysis and gluconeogenesis to supply the necessary amount of acetyl-CoA for ketone body production. However, after several days of carbohydrate restriction, the body begins to break down stored fat through lipolysis to produce fatty acids that are used as substrates for ketogenesis [1] [2].

Foods commonly consumed on a ketogenic diet include animal proteins, fish, eggs, high-fat dairy products, oils, nuts, seeds, and low-carbohydrate vegetables. Foods high in carbohydrates, such as grains, legumes, and sugary foods, are typically avoided.

Initially developed as a therapeutic approach to manage refractory epilepsy [3], now the ketogenic diet becomes more and more popular among trainees and those who aim in losing weight.

METHODS

In April 2023, we conducted a comprehensive literature review using the PubMed database. The search terms used included "Ketogenic diet sport" and "ketogenic diet athletes", "ketogenic diet body". The objective of this review was to identify meta-analyses of cohort studies and review studies that concern the influence of ketogenic diet on athletes' performance and other parameters concerning the body function.

BODY COMPOSITION

In recent years, ketogenic diet (KD) has gained popularity as a weight-loss strategy and as a dietary intervention for several medical conditions, including type 2 diabetes and metabolic syndrome [4].

There have been conducted some studies which were focusing on comparison between traditional, balanced reduction diet and a novel approach to weight loss which is ketogenic diet. Now the aim of researchers is to assess which of these dietary regimes is more effective and what are the body composition changes induced by diets. In a randomized controlled trial, the ketogenic diet (KD) and a balanced restriction diet (RD) were compared, and it was found that both diets resulted in similar reductions in body weight and body fat in healthy young men. However, the weight loss in the KD group was due to a combination of decreased body fat, body water, and a slight decline in lean body mass, while in the RD group, the weight reduction was predominantly due to body fat loss. Additionally, the KD group exhibited decreased respiratory exchange ratio, indicating a shift towards lipid oxidation after eight weeks of intervention, while no such effect was observed in the RD group. However, there was no significant effect on endurance parameters in the KD group, whereas the RD group demonstrated significant improvements in peak oxygen uptake and peak workload after eight weeks of intervention [5]. Wang et al. show congenial systematic review and meta-analysis which indicate that KD diet when combined with resistance training is likely to result in a decrease in body fat while preserving lean mass and aerobic performance [6]. What is more, Bowler et al. show that following a ketogenic diet (KD) is linked to beneficial effects on body composition, including weight loss and reduced body fat. Additionally, adhering to a KD may lead to improved psychological well-being over the long term. However, there is mixed evidence regarding the impact of a KD on physical health and athletic performance [7]. Another study consisting of 8-week ketogenic diet combined with resistance training proved to be effective in reducing body fat and preserving lean muscle mass in women who engage in strength training. However, the diet appeared not be the best approach for increasing muscle mass [8]. Sjodin et al. in a recent randomized, controlled feeding trial found that healthy, young women who adapted to a ketogenic diet demonstrated a significant increase in fat utilization during submaximal work. While a ketogenic diet did not affect maximal isometric force or muscle fatigue under sustained low-intensity work, the women reported that exercise and daily activities felt more challenging. Additionally, time to fatigue was shortened during incremental exercise. These findings suggest that a ketogenic diet may promote increased fat utilization during submaximal work but may also lead to decreased exercise performance and capacity for high-intensity exercise [9]. Bailey et al. showed congenial significant findings for athletes on a ketogenic diet which included decreased time to exhaustion, higher perceived exertion, and increased peak power in one article each [10].

ANIMAL TESTS

All these findings indicate that ketogenic diet, despite being an effective mean of losing weight, may not be a proper dietary solution for trained ones. Yet, it gained popularity among athletes, especially endurance athletes, in recent years becoming a frequent object of research. Moreover, some studies conducted on rats or mice revealed promising results which may be vital in athletes. Ogura et al. performed a study in which male Wistar rats were randomly assigned to two groups: a control group (CON) and a ketogenic diet group (KD). The extensor digitorum longus (EDL) muscle was then analyzed for twitch force, tetanic force, fatigue, myosin heavy chain composition, protein expression of metabolic enzymes and regulatory factors, and citrate synthase activity. No significant differences were found in muscle function between the two groups, but the KD group showed higher levels of citrate synthase activity and protein expression of certain factors, including Sema3A. The myosin heavy chain composition also shifted from type IIb to IIx in the KD group. These findings suggest that a 4-week ketogenic diet may improve aerobic capacity in male rats without negatively affecting muscle function, and Sema3A may play a role in the myosin heavy chain shift observed in the EDL muscle [11]. Another study aimed to investigate the effects of combining a 10-week low-carbohydrate ketogenic diet (KD) with an 8-week forced treadmill running program on fatty acid oxidation capacity and maximal exercise capacity in mice. The results showed that the KD increased the lipid pool and enhanced fatty acid oxidation capacity, as well as upregulated key genes involved in fatty acid oxidation. However, the 8-week treadmill training program had no effect on fatty acid and ketone body oxidation. Additionally, key genes involved in carbohydrate utilization were downregulated in the KD groups [12]. On the other hand, the research study conducted by Fukazawa et al. aimed to investigate the effects of a long-term ketogenic diet that contains medium-chain triglycerides (MCTs) on the adaptations of ketolytic and glycolytic enzymes in rat skeletal muscle induced by endurance training. Male Sprague-Dawley rats were assigned to three groups: a standard diet group (CON), a group fed a ketogenic diet that contains long-chain triglycerides (LKD), and a group fed a ketogenic diet that contains MCTs (MKD). The results showed that endurance training significantly increased the protein content of 3-oxoacid CoA transferase (OXCT), a ketolytic enzyme, in the epitrochlearis muscle tissue. Furthermore, intake of the MKD diet additively enhanced endurance training-induced increases in OXCT protein content. On the other hand, LKD consumption substantially increased the muscle protein level of PDK4. However, such PDK4 increases were not observed in the MKD-fed rats. The conclusion drawn is that the long-term consumption of ketogenic diets that contain MCTs may enhance the adaptations of ketolytic enzymes induced by endurance training in skeletal muscle without inhibiting carbohydrate metabolism [13].

ATHLETES' PERFORMANCE

Despite mentioned results, studies performed on athletes are still mixed and give no clear solutions.

Paouli et al. indicate that adopting a ketogenic diet for a short period of time can be a viable and safe method for reducing body fat in soccer players without negatively affecting their strength, power, or muscle mass [14]. Similar results have been obtained in a study, where athletes following a ketogenic diet (KD) experienced a decrease in body mass, fat mass, and fat-free mass. Despite similar oxygen consumption, the respiratory exchange ratio (RER) was lower after KD, indicating a greater reliance on fat oxidation for energy. Rates of fat oxidation were higher after KD, with the maximal fat oxidation rate being 1.8-fold higher than before. The crossover point for substrate utilization occurred at a higher relative exercise intensity after KD, and the lactate threshold occurred at a higher exercise intensity. These findings suggest that KD may improve fat oxidation and endurance performance [15].

In the metanalysis [16] different methods have been analysed to measure exercise fat oxidation in athletes following the ketogenic diet, including standardized protocols for measuring maximal rates of fat oxidation (Fatmax) and measuring rates during prolonged exercise. Studies with rigorous dietary control have reported mean values for maximal fat oxidation of around 1.5 g/min, representing a significant increase compared to a high-carbohydrate diet. The shift in the intensity at which maximal fat oxidation occurs has been observed from around 45% to 70% of peak oxygen consumption (VO2peak). Keto-adaptation to the KD appears to reach its maximum effect within 3-4 weeks. Another study also found that the KD led to higher postprandial fat oxidation compared to both the high-carbohydrate diet and habitual diet. However, Shei et al. showed [12] that the KD increased the ability of oxidative muscles to oxidize fatty acids, but this improvement was not enhanced by training. Despite the increase in fatty acid oxidation capacity, there was no improvement in performance during high-intensity exercise. Importantly, the KD did not negatively affect muscle strength relative to body weight.

Noakes et al. [4] showed that adaptation to the KD raises the crossover point to a higher percentage of VO2max (above 80%VO2max) compared to previous reports. Athletes adapted to the LCHF diet exhibit significantly higher FATMAX values (above 1.5 grams per minute). Endurance athletes exercising at intensities above 85%VO2max while performing 6 × 800 m running intervals demonstrated the highest rates of fat oxidation ever recorded in humans. Peak fat oxidation rates measured at an average of 86.4 ± 6.2%VO2max reached 1.58 ± 0.33 grams per minute, with 30% of subjects achieving rates higher than 1.85 grams per minute. These findings challenge the prevailing belief that carbohydrates are the dominant fuel source during high-intensity exercise. Additionally, recent research has shown that 30% of middle-aged competitive athletes on an HCLF diet displayed pre-diabetic glycemic values, which were reversed when they switched to the KD.

The findings suggest that bodybuilder athletes can also benefit from a KD as it can help them maintain muscle mass while reducing body fat. Unlike low-calorie diets, the KD does not lead to a decrease in muscle mass. Additionally, the KD may be helpful in reducing inflammatory cytokines and increasing BDNF, which can aid in managing stress and motivation during weightlifting or other intense physical activities [17]. Another study [16] confirms that showing that KD had positive effects on salivary immunoglobulin A, fat metabolism, body weight, and muscle damage after exercise. Resistance trainers do not show significant differences in strength or hormone profile when compared to controls.Valenzuela et al. after exploring KD effects of strength-trained athletes suggest that KD is effective in reducing total body and fat mass compared to non-KD in the short term. On the other hand, KD may have negative effects on resistance training-induced gains on muscle mass and performance, especially when expressed in absolute values such as total kg lifted or watts [18]. Another study performed in resistance-trained athletes, show similar concern about the potential loss of fat free mass on a KD.[19]

After analyzing the impact of KD on endurance athletes, Cao et al. found that the diet did not have a significant effect on factors such as VO2max, HRmax, time to exhaustion, and perceived exertion. However, they did notice an increase in fat oxidation. While there was not a significant improvement in aerobic capacity, this could be due to the training period not being long enough to yield the desired results [20]. Bailey et al. [10] confirmed no significant effect on VO2max on athletes on a KD. Lee et al. found consistent with preceding results [21]. Another study, which consisted of 3,5-week period of adaptation to a ketogenic, low-carbohydrate, high-fat diet, showed a significant increase in athletes' ability to utilize fat as a source of fuel during intense exercise. However, this dietary intervention also resulted in a decrease in exercise economy, which is the amount of energy required to maintain a given pace or workload. As a result, their overall performance during a real-life endurance event was impaired. These findings suggest that while a ketogenic diet may enhance fat oxidation, it may not be the most optimal approach for improving performance in elite athletes during high-intensity endurance events [16]. There is another study that support this thesis which cyclists were involved in [22].

Other studies have shown that a keto diet may negatively impact high-intensity exercise, such as sprinting or weightlifting, which require quick bursts of energy that are primarily fueled by carbohydrates.

Burke et al. have demonstrated that 5-6 days of adaptation to KD diet appears to decrease the efficiency of exercise at intensities that are relevant to real-life endurance events, even when additional carbohydrate availability is provided. The findings suggest that the process of "muscle retooling" to enhance fat utilization remains intact even when muscle carbohydrate availability increases, which hinders the ability to oxidize carbohydrates during exercise. These adaptations can be reversed within a similar time frame after reintroducing a high-carbohydrate diet. Strategies that aim to combine brief adaptation to a ketogenic diet with enhanced muscle carbohydrate availability appear to have limited efficacy due to the blunted carbohydrate oxidation and continued impairment of endurance performance at high exercise intensities [23].

KETONES SUPPLEMENTATION

There have been conducted few studies concerning the idea of ketones supplementation as an addition to ketogenic diet or habitual diet and its effect on athletes' performance.

The study by Whitfield et al. [24] found that consuming ketone ester (KE) before the KD increased circulating ketone bodies but did not affect oxygen consumption or respiratory exchange ratio (RER). Resting ketone levels were elevated by the KD, but supplementation with KE did not further increase ketone concentrations. Importantly, race performance was impaired by approximately 6% in the KD group compared to baseline, while performance was unaffected in the high-carbohydrate group. Despite increasing endogenous ketone production, the KD did not enhance the metabolic responses to KE supplementation and had a negative impact on race performance.

Another study [25] involved trained endurance athletes who followed different diets during 6 days of laboratory-based cycling. The diets included a carbohydrate-rich control diet, a carbohydrate-rich diet with ketone drink supplementation, and a ketogenic diet. Urinary β-hydroxybutyrate, a marker of ketone production, significantly increased in both the ketone drink and ketogenic diet groups compared to the carbohydrate-rich diet group. Exercise capacity improved by around 5% on the first race day with the carbohydrate-rich diet, while the ketone drink group showed improvements of 6-8% on multiple race days. In contrast, the ketogenic diet group experienced a significant decrease in exercise capacity by 48-57% on all race days. The ketogenic diet led to a three-fold increase in fat oxidation and increased perceived exercise exertion. However, no changes in exercise substrate metabolism were observed in the ketone drink group. Participants in the ketone drink group also showed reduced postprandial insulin sensitivity. The study concludes that dietary carbohydrate restriction and ketone supplementation can both increase ketone levels in the body but have distinct physiological effects. The carbohydrate-rich diet with ketone drink supplementation improved exercise capacity, while the ketogenic diet negatively impacted exercise capacity and resulted in altered metabolic adaptations.

STOOL MICROBIOTA

The research [26] has shown that athletes have different gut microbiota compositions compared to non-athletes, which could be attributed to differences in dietary patterns, particularly increased protein intake common among athletes. A ketogenic diet has been found to significantly decrease the relative concentrations of beneficial bacteria such as Faecalibacterium spp. and Bifidobacterium spp., which play a role in maintaining intestinal balance and have anti-inflammatory effects. Reductions in these bacteria may have implications for the physical health of athletes as the diversity of the gut microbiome is linked to various physiological processes. Interestingly, the same study observed that consumption of a KD was associated with increased levels of Dorea spp. and Enterobacteriaceae in elite race walkers. Elevated levels of Enterobacteriaceae are often linked to disease states, while Dorea spp. has been positively associated with cholesterol and LDL concentrations in hyperlipidemic rats. These findings suggest that adhering to a KD exerts selective pressure on the gut microbiota, which may have many consequences

Mancin et al. [27] conducted a linear discriminant analysis in the post-intervention period identified several genera that differentiated the two groups – western diet (WD) and ketogenic diet (KD) group. Bifidobacterium, Butyricicoccus, and Acidaminococcus were more abundant in the WD group, while Clostridia UCG-014, Butyricimonas, Odoribacterter, and Ruminococcus were more abundant in the KDP group. Additionally, the study reveals that changes in microbial taxa before and after the intervention are significantly associated with environmental variables, such as the macronutrient intake of athletes. Carbohydrate intake showed a strong positive association with changes in respiratory exchange ratio (RER), indicating that players in the KD group with lower carbohydrate intake had a greater decrease in RER, suggesting an increased reliance on oxidative metabolism. Carbohydrate intake was also inversely correlated with changes in Odoribacter genus abundance, which aligns with the higher abundance of Odoribacter in the KD group. Fat intake, on the other hand, was negatively associated with variations in RER, visceral adipose tissue (VAT), extracellular water (ECW), and Fusicatenibacter genus abundance. Reductions in weight were associated with a decreased abundance of Ruminococcus torques and Lachnospira genera, while being inversely correlated with Parabacteroides genus abundance. Importantly, the KD did not significantly alter the overall composition of the gut microbiome. This suggests that the diet can be implemented without disrupting the stability of the gut microbiome, which is known to play a crucial role in maintaining gut health and enhancing athletic performance.

HAEMATOLOGICAL

In the study by Durkalec-Michalski et al. [28] comparing the effects of a ketogenic diet (KD) and a conventional diet (CD) on exercise-related physiological parameters, several significant findings were observed. After exercise, lactate concentration was significantly lower in the group that consumed a KD compared to those on a CD. Males on a KD showed significant changes in post-exercise blood acid-base balance. Indices such as pH, BE, and HCO3- were increased, while H+, anion gap, and lactate were decreased. No substantial changes were observed in females. In the entire group, pre-exercise bilirubin concentration was higher after consuming a KD compared to a CD. In males, both pre- and post-exercise AlAT activities were significantly increased after consuming a KD. Post-exercise glucose and bilirubin concentrations were higher after consuming a KD compared to a CD. After consuming KD there was a significant increase in pre-exercise monocyte (MON) count in the entire group and in females. Post-exercise MON count increased in the entire group and in males. Pre- and post-exercise hemoglobin concentrations, mean corpuscular hemoglobin (MCH), and mean corpuscular hemoglobin concentration (MCHC) decreased after consuming a KD in the entire group and in females. Overall, these findings suggest that a KD may have negative effects on bilirubin concentration, hematological parameters in females, and liver health in males. However, the impact on acid-base balance appears to be minor or inconclusive. It is important to consider these potential drawbacks when considering a KD for athletes or individuals engaged in high-intensity training like CrossFit. Another study [29] showed that athletes consuming ketogenic diets performed a significant decrease in total cholesterol levels compared to control athletes. However, there were no significant changes observed in HDL cholesterol, triglyceride levels, glucose levels, or insulin levels between athletes on ketogenic diets and control athletes. Lee et al. presented similar results when it comes to changes in

HDL cholesterol, triglycerides, glucose levels and insulin levels following the ketogenic diet, which is promising regarding the individual's cardiovascular risk.

When it comes to lipidaemia, it was known [30] that medium-chain fatty acids (MCFAs) are efficiently transported to the liver through the portal vein and promote the production of ketone bodies. Incorporating medium-chain triglycerides (MCTs), which exclusively contain MCFAs, into ketogenic diets appeared to allow for higher carbohydrate consumption and lower fat intake while maintaining ketosis. Previous research has shown that consuming MCTs in a ketogenic diet enhances ketone body utilization in skeletal muscle. However, the long-term safety of such a diet, known as an MCT-containing ketogenic diet (MKD), remains uncertain. There have been concerns about potential liver function impairment due to the accumulation of triacylglycerols induced by MCT intake.

These concerns about hepatic triacylglycerol accumulation with MCT intake were not supported by the newest findings [31]. Contrary to expectations, 24-week intake of MKD, with a higher MCT content, decreased liver triacylglycerol concentration and liver weight in rats, while long-chain triacylglycerol (LKD) increased liver triacylglycerol concentration compared to the control group. No significant differences were observed in serum markers for liver disorder.

The MKD group did not show significant differences in glucose, total protein, and albumin concentrations compared to the control group, and these markers were within normal ranges. Serum creatinine was significantly lower in the MKD group, suggesting no unfavorable effects on kidney function.

HIGH ALTITUDE

The study [32] found that a 4-week ICKD combined with hypoxia exposure had variable effects on performance and physiological parameters. While some participants showed improvements, others did not respond positively or experienced worsening performance. The KD influence on athletes training in high altitudes remains uncertain and requires more research.

BONES

The study [33] examined the effects of a KD on markers of bone health. After adaptation to the KD, fasting concentrations of CTX (a marker of bone resorption) increased, while levels of P1NP (a marker of bone formation) and OC (a marker of bone turnover) decreased. During exercise, KD further increased CTX concentrations and decreased P1NP and OC concentrations compared to both baseline and a high-carbohydrate diet. The area under the curve (AUC) for CTX during exercise was also higher with KD after adaptation, while AUC for P1NP and OC decreased.

The restoration of carbohydrate levels post-exercise (CHO) helped recover CTX levels and CTX exercise-related AUC, but P1NP and OC concentrations and their exercise-related AUC remained suppressed in the KD group compared to the adaptation phase. These findings suggest that short-term KD impairs markers of bone modeling/remodeling, and only the marker of bone resorption (CTX) recovered after acute CHO restoration.

In another study [34], impact of different dietary interventions on serum osteonectin levels, an acidic extracellular matrix glycoprotein crucial for bone mineralization and collagen binding was examined. It was found that in the RD group (following a reduction diet), serum osteonectin levels decreased. This suggests that the regular diet may have had a negative effect on osteonectin regulation, potentially impacting bone health. On the other hand, in the ketogenic diet group, serum osteonectin levels remained unaffected.

CONCLUSION

Based on the research provided, there is not enough data concerning the influence of ketogenic diet on athletes' performance. It is proven that the KD leads to weight loss and increased fat oxidation but there needs to be done a further investigation when it comes to time needed to a total adaptation to KD, type of sport in which KD would be the most efficient, its impact on muscles, bones, lipid levels and other parameters which raise doubts. The study groups should be more abundant to draw proper conclusions.

DISCLOSURES

Author's contribution

Conceptualization: Siekierko N., Lewandowski M.; Methodology: Żołnierek M., Kotusiewicz W.; Software: Świętochowski J.; Check: Świętochowski J.; Formal analysis: Siekierko N., Kucharski J.; Investigation: Gacoń E., Zembala J.; Resources: Zapała B., Ząber A.; Data curation: Kotusiewicz W., Żołnierek M.; Writing – rough preparation: Siekierko N., Lewandowski M.; Writing – review and editing: Kucharski J., Ząber A.; Visualization: Zapała B.; Supervision: Siekierko N.; Project administration: Siekierko N.

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