生酮饮食对体重管理、肌肉合成以及运动表现的影响

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摘　要：自20世纪20年代以来，极低碳水化合物饮食或生酮饮食疗法被应用于癫痫的治疗，甚至在某些情况下能够完全取代药物治疗。1970年以后，这种饮食疗法作为一种肥胖治疗手段而被广泛知晓 。生酮饮食(Ketogenic Diets，KD)是指碳水化合物减少(通常小于20 g/d或低于每天摄入总能量的5%)而蛋白质和脂肪含量相对增加的饮食。目前认为这三大营养物质的重排可以诱导生理性酮症，进而减轻体重。近年来，许多运动员也希望通过生酮饮食减脂以取得更好的运动表现。尽管生酮饮食在体重管理方面作用显著，但它是否能够维持或提高体能表现仍不明确。文章讨论了生酮饮食的代谢效应和潜在风险，以及近期关于生酮饮食对体重减轻、肌肉合成和运动表现影响的研究进展。

关键词：生酮饮食；减重；肌肉合成；运动表现

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Effects of Ketogenic Diets on Weight Management, Muscle Development, and Sports Performance

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Abstract: Very-low-carbohydrate diets or ketogenic diets have been in use since the 1920s as a therapy for epilepsy and can, in some cases,completely remove the need for medication.Since 1970, they have also become widely known as one of the mostcommon methods for obesity treatment.Ketogenic diets are characterized by a reduction in carbohydrates (usually <20 g/day or 5% of total daily energy intake) and a relative increase in the proportions of protein and fat. It has been suggested that this macronutrient rearrangement can produce physiological ketosis, therefore reducing body mass. More recently,ketogenic diets have alsodrawn attention to athletes who desire to reduce body fat and thus to obtain the extra performance edge. Despite its appealing role in weight management, the efficacy of using ketogenic diets as a tool to maintain or improve sports performance remains to be determined.This review will discuss metabolic consequences and potential risks of ketogenic diets as well as recent research progress with regard to the effects of ketogenic diets on weight loss, muscle mass development, and athletic performance.

Key Words: Ketogenic Diets, Weight Management, Muscle Development, Sports Performance

0　绪论

近年来，大量文献报道极低碳水化合物生酮饮食在许多疾病起到治疗作用，这类饮食可以导致称为酮症的特殊代谢状态。生酮饮食应用在癫痫治疗中已有数十年历史[1]，而在20世纪70年代，这类饮食因可以减轻体重而被广泛知晓，特别是著名的“阿特金斯饮食法”[2]。最近，生酮饮食在治疗其他

Introduction

During recent years, an increasing amount of evidence has accumulated in the literature, suggesting that very-low-carbohydrate ketogenic diets could have a therapeutic role in numerous diseases. These types of diets result in a metabolic state of ketosis. The use of ketogenic diets in treating epilepsy has been well estab-

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疾病的研究中也取得了较好的结果，鉴于目前美国每年的医药费用达到 7 500 亿美元[3]，如果饮食干预可以减少对药物使用的依赖，它将带来显著的社会以及经济效益，这也将成为今后一个重要的研究方向。

最近生酮饮食疗法也在许多运动项目中流行，希望通过生酮饮食疗法减轻体重，获得更好的运动表现。然而，生酮饮食对提高运动表现是否有功效并没有得到一致的认可。耐力运动员的主流营养理念强调高碳水化合物、低脂肪的饮食方式。在这种饮食模式下，运动员主要依赖碳水化合物产能来完成大量的有氧运动[4]。生酮饮食对于耐力运动员的吸引力在于它改变了运动员利用能量的方式，从以利用碳水化合物为中心转变为利用脂肪产能为主。与有限的碳水化合物相比（如肌糖原），脂肪在体内的储存更丰富。经过一段时间的饮食改变后，机体会产生代谢的变化。这种变化通常被称为“脂肪适应”。20 世纪 80 年代以来这种代谢变化在研究中得到了充分的证实[5,6]。尽管在运动中利用脂肪作为能量来源具有生理上的优势，然而至今为止并没有确凿的证据表明这会提高运动能力[7]。

本文将讨论生酮饮食的代谢效应和潜在风险，以及近期关于生酮饮食对体重减轻、肌肉合成和运动表现影响的研究进展。本文还将为那些有兴趣尝试这种饮食方法的人提供正确的饮食指导。

1 什么是生酮饮食？

生酮饮食是指低碳水化合物（通常小于 20 g/d 或低于每天总摄入能量的 5%）而蛋白质和脂肪相对增加的饮食[8]。碳水化合物的不足使得机体主要的能量来源为脂肪。最初的生酮饮食规定每天摄入脂肪与非脂肪的比例为 4:1，80%的能量来源于脂肪，15%来源于蛋白质，碳水化合物仅占 5%。随后生酮饮食也做了许多改进，如减少脂肪与非脂肪的比例或不限制每天摄取的能量，随意进食蛋白质和脂肪。

2 历史背景

关于经典生酮饮食的代谢效应的知识，来源于 Cahill 等人在 20 世纪 60 年代在禁食方面的开拓性工作[9,10]。他们的研究发现在 12 h 至 3 周的时间内禁食或仅摄取最少量的食物和含有热量的饮料，可以诱导称为酮症的特殊代谢状态。近年来，许多研究调查了在伊斯兰教斋戒月期间每日禁食对机体的影响，在这 1 个月内从日出到日落，需完全禁食禁水。尽管这种间歇性禁食对久坐人群的影响不大，但对

lished for many decades[1] and these diets have become even more widely known, as they became popular in the 1970s for weight loss - especially as the ‘Atkins Diet’[2]. More recently, the therapeutic use of ketogenic diets in other diseases has been studied with positive results - it is an important direction for research because, clearly, if nutritional intervention can reduce reliance on pharmaceutical treatments it would bring significant benefits from an economic as well as a social point of view given the current $750 billion annual cost of pharmaceuticals in United States[3].

Ketogenic diets have recently become popular dietary regimes for athletes who desire to reduce body mass and to obtain the extra performance edge. However, there is no consensus regarding the efficacy of ketogenic diets on sports performance. The overarching mainstream nutrition philosophy for endurance athletes is one that emphasizes a carbohydrate-dominant, low fat paradigm. Under these dietary conditions, athletes utilize carbohydrate as their predominant fuel source to fuel high volumes of aerobic exercise[4]. The appeal of ketogenic diets for endurance athletes is likely due to the shift in fuel utilization, from a carbohydrate-centric model to one that utilizes fat predominantly, of which stores are unlimited compared to carbohydrate (i.e., muscle glycogen). This metabolic shift, seen after a period of dietary alteration is often referred to as being ‘fat-adapted’, which has been well-documented in studies since the 1980s[5,6]. Despite the physiological advantage of utilizing fat as a fuel source during sub-maximal exercise, to date there is no conclusive evidence to suggest that this would result in subsequent performance enhancement[7].

This review will discuss metabolic consequences and potential risks of ketogenic diets as well as recent research progress with regard to the effects of ketogenic diets on weight loss, muscle mass development, and athletic performance. This article will also provide some practical guidelines for those who are interested to be able to carry out this dietary approach correctly.

What Is the Ketogenic Diet?

Ketogenic diets are characterized by a reduction in carbohydrates (usually <20 g/day or 5% of total daily energy intake) and a relative increase in the proportions

于运动员的训练和表现，特别是在夏季日照时间长的情况下会有重要的影响。斋戒月期间观察到运动员体内的血糖和组织水分从日出到日落逐渐降低。然而,如果运动员能够保持足够的能量、营养物质的摄入及良好的睡眠并调整训练负荷的时间，他们的整体表现不会受到影响[11,12]。

斋戒禁食是一种间歇性禁食模型，但禁食时间太短不能诱发酮症。而因纽特人（北美的爱斯基摩人)案例(Inuit Case)则是一个比较好的长期的酮症模型,这是由 Schwatka 探险队报道的第一个有据可查的禁食案例。Frederick Schwatka 中尉是一支探险队的领队，他在 1879 年至 1880 年前往寻找失踪的皇家海军“富兰克林探险队”(Franklin Expedition)的过程中,与其他参与者包括 12 名极地土著人完成了超过 5 000 km 的雪橇旅程[13]。在最初携带的食物消耗完之后,探险队唯一的食物来源就是狩猎和捕鱼,因为沿途没有其他的食物供应来源。Schwatka 中尉在他的日记中提到：当第一次完全通过进食驯鹿肉充饥时,整个机体似乎并没有得到满足,身体感到虚弱以致无法继续艰苦而险峻的旅程。但是这种感受在 2 到 3 周内就会消失[14]。这是关于酮适应的第一个有据可查的描述,这段文字被多次引用。

多年以后,一位名叫 Vilhajalmur Stefansson 的人类学家前往北极学习因纽特人的语言和文化。在他的旅程中,体验了典型的因纽特人饮食,其中约 80%~85%的能量来源于脂肪,15%~20%来自蛋白质,他的身体没有发现任何问题[15]。随后,因他的报道引起了争议,Stefansson 同意在贝尔维尤医院的 DuBois 医生的监督下再次采用因纽特饮食，证实了之前的观察，即采用脂肪 / 蛋白质饮食对身体没有任何损害,也不会导致营养缺乏。

在这些报道之后，生酮饮食的研究似乎就被人们所遗忘,直到 20 世纪 20 年代,它作为一种癫痫疗法受到关注。然而随着癫痫治疗药物的问世,生酮饮食又受到冷落，而近年来因药物疗法具有严重的副作用,生酮饮食疗法再次引起人们的兴趣[16]。近几年，有关生酮饮食的研究主要集中在减重或减脂方面。至今为止,仅有个别研究关注生酮饮食与运动表现之间的关系。生酮饮食在体育运动中具有两种可能的应用价值:第一,在有重量级别的体育项目中具有减轻体重的作用[17];第二,在提高耐力方面具有潜在的作用[6]。

3 生酮饮食的生理学基础

经过几天的禁食或至少大幅减少膳食中碳水化

of protein and fat[8]. Such insufficient levels of carbohydrates can then force the body to use fat as a main fuel source. The original ketogenic diet was designed as a 4:1 lipid:nonlipid ratio, with 80% of daily energy intake from fat, 15% protein, and 5% carbohydrate. Many modifications subsequently have been introduced to the original ketogenic diet, for example, lowering the lipid:nonlipid ratio or no restrictions in daily energy intake with ab libitum protein and fat.

Historical Background

The knowledge regarding the metabolic effects of classic ketogenic diets originates from the pioneering work of Cahill and colleagues in the 1960s on fasting [9,10]. In these studies, ingesting no or minimal amounts of food and caloric beverages for periods that ranged from 12 h to 3 weeks has been found to induce a particular metabolic state called ketosis. In recent years, many studies have investigated the effects of the daily fasting used during Ramadan that requires a total abstention from food and drink from sunrise to sunset for 1 month. Although such ritual intermittent fasting has only minor effects on the sedentary population, it can have important consequences for the training and performance of the athlete especially during summer when daylight hours are long. In general, studies have found that, in athletes observing Ramadan, the glycemia and tissue hydration decrease progressively from sunrise to sunset. However, overall performance seems to be unaffected if athletes are able to maintain an adequate total energy and macronutrient intake and a sound sleep and to adjust the timing of the training load[11,12].

Ramadan fasting is an interesting model for intermittent fasting but is too short to induce ketosis; instead, a good model for prolonged ketosis is the Inuit case in which the first well-documented fasting was reported by the Schwatka expedition. Lt. Frederick Schwatka was the leader of an expedition that set out to find the missing Royal Navy "Franklin Expedition." Lt. Schwatka and the other participants including 12 indigenous circumpolar people completed a more than 5000-km sled journey from 1879 to 1880[13]. It is worth noting that, once they finished their initial provisions, the expedition's only source of food was hunting and fishing because there were no other sources of supply a

合物含量（即小于 20 g/d 或低于每天总能量摄入的 5%），同时通过增加其他营养物质维持机体总的能量摄入，此时葡萄糖储备不足使得三羧酸循环中的草酰乙酸供应减少，不足以维持正常的脂肪氧化过程以及向中枢神经系统供应葡萄糖。在正常体温下，草酰乙酸不稳定，因此不能被积累和储存，但三羧酸循环的持续运作需要草酰乙酸，可通过葡萄糖转化为丙酮酸，然后再生成草酰乙酸（图 1）而不断补充。由于生酮饮食导致草酰乙酸生成减少，通过三羧酸循环的脂肪氧化将大大减少，并伴随一定程度的乙酰辅酶 A 的堆积。此外，中枢神经系统需要葡萄糖作为能量来源，而在生酮饮食中过量乙酰辅酶 A 的生成使得酮体成为替代能源发挥作用。

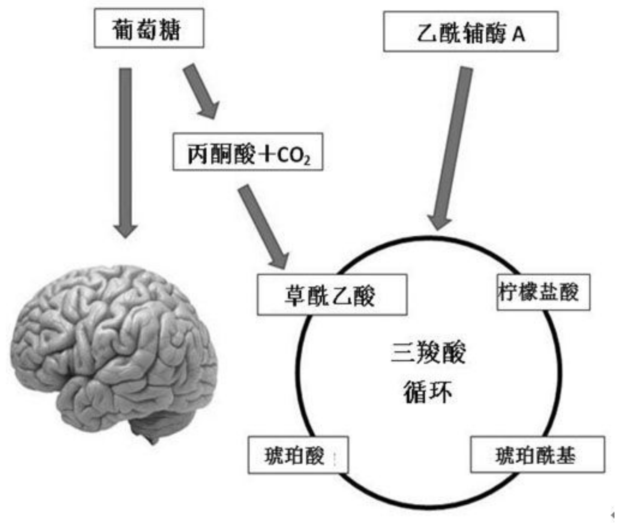

图 1 葡萄糖对大脑供能和维持三羧酸循环正常运作示意图

Figure 1 Glucose is essential as an energy supply for the brain and also for the production of oxaloacetate, the levels of which need to be maintained for the functioning of the Krebs cycle.

酮体由乙酰乙酸、β- 羟基丁酸和丙酮组成。酮体生成主要在肝脏进行（图 2）。在正常饮食条件下，体内酮体浓度低于 0.3 mmol/L，中枢神经系统不利用酮体供能；而当酮体浓度达到 4 mmol/L，与葡萄糖浓度相似时，机体所有组织均可利用酮体供能。β- 羟基丁酸转化为乙酰辅酶 A 然后分解成 2 分子的乙酰辅酶 A，可进入三羧酸循环产生 ATP。与葡萄糖相比，利用酮体可产生更多的线粒体 ATP 从而增加能量生成。例如，利用弹式热量计计算，在相同碳单位的情况下，β- 羟基丁酸燃烧产生的热量较丙酮酸燃烧高 31%[18]。生酮饮食后体内酮体浓度最大可达到 8 mmol/L[19]。

long their route. Lt. Schwatka reported in his diary this often-cited sentence: When first thrown wholly on the diet of reindeer meat, it seems inadequate to properly nourish the system, and there is an apparent weakness and inability to perform severe, exertive, fatiguing journeys. But this soon passes away in the course of 2 to 3 weeks[14]. This is the first documented description of the so-called keto-adaptation.

Years later, an anthropologist named Vilhajalmur Stefansson set out to travel throughout the Arctic mainland to study the Inuit language and culture. During his journeys, Stefansson experimented on himself with the typical Inuit's diet, consisting of about 80-85% of energy from fat and 15%-20% from protein, and he reported no observed problems[15]. Pressed by the controversy raised from his reports, Stefansson agreed to recreate the Inuit diet under the scientific supervision of Dr. DuBois at the Bellavue Hospital, he confirmed his earlier observations that the adoption of a fat/protein diet was without any impairment or signs of nutrition deficiency.

After these earlier reports, however, the study of ketogenic diets seems to have sunk into oblivion until the 1920s when it experienced a "renaissance" as a therapy for epilepsy. Interest in this dietary therapy again waned with the introduction of pharmaceutical therapy for epilepsy, but it has been reawakened recently because of the severe side effects of pharmacological treatments[16]. In more recent years, ketogenic diets mostly have been studied from a weight/fat loss point of view. Interestingly, up until now, only a few studies have investigated the relationship between ketogenic diets and sports performance. There are two main possible applications of ketogenic diets in sport: one is the more intuitive weight reduction for sports that involve weight classes[17] and the second is a potential for improving endurance performance[6].

A Closer Look at the Ketogenic Diet

After a few days of fasting or at least a drastically reduced dietary carbohydrate content (i.e., <20 g/day or 5% of daily energy intake) while maintaining usual energy intake through macronutrient redistribution, glucose reserves become insufficient both for normal fat oxidation via the supply of oxaloacetate in the Krebs cycle (which gave origin to the phrase 'fat burns in the

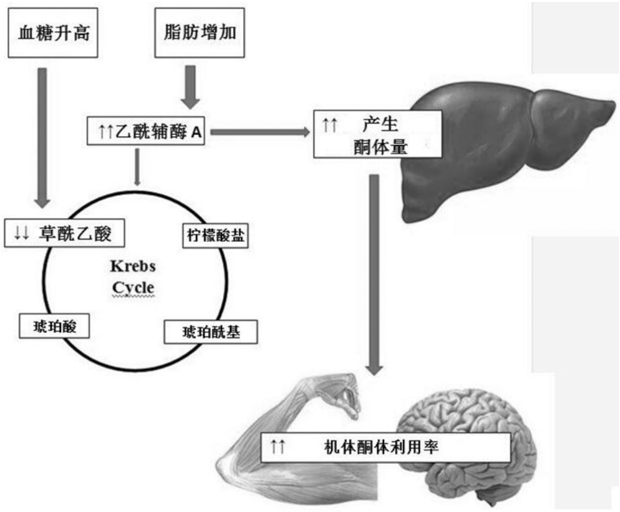

图 2 肝脏生酮生成路径

Figure 2. Ketone bodies production in the liver increases in response to low carbohydrates and/or high lipids in ketogenic diet

肝脏中生成的酮体主要是乙酰乙酸，但循环中的酮体以 β- 羟基丁酸为主。在正常富含碳水化合物的饮食中，游离乙酰乙酸的生成可忽略不计，且会被许多组织特别是骨骼肌和心肌快速代谢。而在乙酰乙酸过量生成时，乙酰乙酸富集并分解成其他两种酮体，导致酮血症和酮尿症（血液和尿液中存在酮体）。丙酮作为一种易挥发的化合物，可通过呼吸从肺内排出，使得呼出的气体有酮症特征性的烂苹果气味。

尽管血液中的葡萄糖水平降低，但通过生糖氨基酸以及甘油三酯分解产生甘油的糖异生，血糖仍可维持在生理水平[20]。禁食以及极低碳水化合物饮食导致的“生理性酮症”，尽管酮体水平可达到 7~8 mmol/L，但机体 PH 水平不变。生理性酮症是为应对长期食物缺乏所导致的营养不足的一种进化适应。这些饥饿阶段是生酮过程，使得血糖和胰岛素水平降低，而为了维持生理性血糖水平，胰高血糖素增加。在病理性的糖尿病酮症酸中毒中，酮体水平可超过 20 mmol/L 并伴有血液 PH 值降低。由于中枢神经系统可有效利用酮体取代葡萄糖作为能量来源，正常人体内酮体水平不会超过 8 mmol/L。还有一点需要强调的是，尽管血糖水平降低，但仍维持在生理性水平，因为葡萄糖生成有两个主要的来源：(1)生糖氨基酸；(2)甘油三酯水解释放的甘油[21]。

4 生酮饮食与体重管理

自 1980 年以来，全世界肥胖人口迅速增加，几乎翻了一番[22]。据统计，2016 年，全世界 18 岁以上成年

flame of carbohydrate') and for the supply of glucose to the central nervous system. At normal body temperature, oxaloacetate is not stable and so cannot be accumulated and stored, but it is required for the continued functioning of the Krebs cycle and is replenished continually by the conversion of glucose to pyruvate and then to oxaloacetate (Figure 1). Due to the lack of production of oxaloacetate following ketogenic diets, fat oxidation through Krebs cycles will be reduced drastically. Moreover, the central nervous system requires glucose as an energy source and thus following a ketogenic diet will cause the need for an alternative energy source which is derived from the overproduction of acetyl-CoA namely ketone bodies.

Ketone bodies are made up of acetoacetate, 3-hydroxybutric acid and acetone. This whole process occurs in the liver and is called ketogenesis (Figure 2). Under normal diet, the concentration of ketones bodies is less than 0.3 mmol/l and ketone bodies will not be used as an energy source by the central nervous system until this concentration reaches 4 mmol/l, similar to the glucose concentration. At that point, ketone bodies are then used as a source of energy by the all tissues. Specifically, 3-hydroxybutric acid is transformed into acetoac etyl-coA which is then transformed into two molecules of acetyl-coA and acetyl-CoA are then used in Krebs cycle in generating ATP. Utilization of ketone bodies creates more energy than glucose because of greater mitochondrial ATP production. For example, the energy liberated by burning 3-hydroxybutric acid in a bomb calorimeter is 31% higher per two-carbon unit compared with the combustion of pyruvate[18]. The maximum ketone bodies concentration in individuals following the ketogenic diet will reach up to~8 mmol/l[19].

The main ketone bodies produced in the liver is acetoacetate, but the primary circulating ketone is 3-hydroxybutyrate. Under normal conditions of adequate dietary carbohydrate, the production of free acetoacetic acid is negligible and it is rapidly metabolized by various tissues, especially the skeletal and heart muscles. In conditions of overproduction of acetoacetic acid, it accumulates above normal levels and part of it is converted to the other two ketone bodies leading to ketonemia and ketonuria (presence of KBs in the blood and urine). The characteristic 'sweet' breath odor of keto sis is

人有超过19亿人超重，其中肥胖人口超过6.5亿[23]。饮食作为一种肥胖的干预措施一直是一个富有争议的话题，尽管目前许多类型的饮食主张可以减轻体重，但并没有科学依据表明其中某种饮食优于其他饮食方法。目前最普遍接受的是一种高碳水化合物、低脂肪的饮食策略，但有研究表明，低脂肪饮食对于减轻体重效果甚微。另外，鉴于大多数肥胖人群偏爱高脂肪食物，他们对于高碳水化合物/低脂肪饮食的依从性也是一个问题。实际上，低脂肪饮食可能导致糖以及碳水化合物的摄入增加，进一步加剧体重问题，同时低脂肪饮食也可能导致血脂异常，尤其是在胰岛素抵抗的人群中[24]。考虑到以上的问题，近年来对于极低碳水化合物生酮饮食或单纯的生酮饮食关注增加。

有强有力的证据表明生酮饮食是一种有效的减肥疗法，但生酮饮食对减轻体重的作用机制仍待进一步研究。阿特金斯起初认为机体通过排泄酮体而失去能量供应来减轻体重[2]，但最近有人提出了几种不同的假设，其中一种认为在生酮饮食中利用蛋白质产能实际上是耗能过程，可导致卡路里丢失从而减轻体重[25]。在生酮饮食的最初阶段，机体每天需要消耗60~65 g葡萄糖，16%的葡萄糖来源于甘油而大部分来源于饮食或组织蛋白的糖异生[26]。糖异生是一个耗能的过程，每天大约消耗400~600 kcal。但并没有直接证据支持这个假设。相反的，最近有研究报道生酮饮食后静息能量消耗没有改变[27]。

也有研究者认为生酮饮食导致的体重减轻可能归因于蛋白质的饱腹感效应或酮体对食欲的抑制效应，因为酮体也可作为一种饱食信号减少饥饿感[28,29]。已有文献表明与基础值相比，生酮饮食后个体的饥饿感减少，食欲下降[28]。有些研究发现，生酮饮食过程中主观食欲测量的绝对改变虽然很小，但即使参与者摄入限制能量的饮食，他们的饥饿感也不会增加，从而导致显著的体重减轻[30]。因此，对于想要寻求一种方法既可以有效减肥而又不增加饥饿感的临床医生来说，生酮饮食可以满足这一需求。

目前很难确定生酮饮食导致的食欲下降是由酮症引起还是由其他因素（如饮食中蛋白质或脂肪含量增加、碳水化合物含量减少）导致。这是因为在总能量不变的情况下，一种营养物质的膳食摄入量的改变必然会影响其他营养物质的摄入量。有研究认为生酮饮食导致的食欲抑制归因于饮食中高蛋白质含量[31]。事实上，相对于正常饮食，生酮饮食中蛋白质绝对含量只轻度增加或几乎不增加。尽管生酮饮食中蛋白质相对比例增加，但蛋白质的绝对摄入量

caused by acetone, which, being a very volatile compound, is eliminated mainly via respiration in the lungs.

It is important to note that, although the blood level of glucose drops, it still remains at a physiological level through gluconeogenesis involving glucogenic amino acids and also glycerol released from triglycerides[20]. Fasting and very low carbohydrate diets lead to what is known as "physiological ketosis" where ketone body levels may rise to 7 to 8 mmol/l, but without any pH change. Physiological ketosis is an evolutionary adaptation to counter long periods of undernutrition because of unreliable food supplies. These periods of near starvation are ketogenic, leading to decreases in blood glucose and insulin, along with increases in glucagon as the body attempts to maintain physiological levels of glucose. In "pathological diabetic ketoacidosis", on the other hand, ketonemia can exceed 20 mmol/l with a concomitant lowering of blood pH. In healthy people, the levels do not rise above 8 mmol/l because of the efficient use of ketone bodies instead of glucose for energy by the CNS. A further point to underline is that glycaemia, even though reduced, remains within physiological levels because of the fact that glucose is formed from two sources: 1. glucogenic amino acids and 2. glycerol liberated via lipolysis from triglycerides[21].

Ketogenic Diet and Weight Management

Obesity is a rapidly growing epidemic worldwide that has nearly doubled since 1980[22]. In 2016, more than 1.9 billion adults, 18 years and older, were overweight and of these over 650 million were obese[23]. Regarding obesity interventions, diet is one of the more controversial issues and many different types have been advocated for weight loss, but there is little scientific evidence to recommend one diet over another. The most commonly accepted dietary strategy is based on relatively high levels of carbohydrates and low fat content, but according to some studies these low fat diets yield only modest weight losses. In addition, adherence of obese individuals to high carbohydrate/low fat nutrition is often a problem because the majority have been shown to have dietary preferences for foods with a rich fat content. In fact, a low fat diet may actually encourage the consumption of sugars and refined carbohydrates that can worsen weight problems and also facilitate dyslipi-

仅为 50~60 g/d。此外,蛋白质摄入的增加并不能解释饥饿或禁食状态下饥饿感消失的现象[32,33]。进一步研究发现,当蛋白质摄入量相同时,不管在肥胖[28]或正常体重[34]的受试者中,生酮高蛋白饮食较非生酮高蛋白饮食抑制食欲作用更明显,表明酮症是主要的影响因素。

总的来说,生酮饮食导致的体重减轻机制有以下几点:(1)糖异生导致的代谢性消耗增加以及蛋白质的热效应;(2)酮体导致的食欲抑制;(3)蛋白质的饱腹感效应和/或4)脂肪生成减少以及脂解或脂肪利用增加。

5 生酮饮食的潜在风险

有人也许会质疑低碳水化合物、高蛋白、高脂肪饮食是一种不健康的饮食方式,因为它可能会增加体内低密度脂蛋白胆固醇(LDL-C)和甘油三酯的含量,这个问题在肥胖人群中尤其重要。然而,有证据表明,生酮饮食对心血管危险因素具有保护作用。目前大多数研究均发现碳水化合物摄入减少有利于降低总胆固醇水平,提高高密度脂蛋白(HDL-C)含量,降低血甘油三酯水平[24,35]。此外,生酮饮食可增加LDL-C颗粒的大小和体积[26],由于LDL颗粒越小其致动脉粥样硬化作用越高,因此认为这可降低心血管疾病风险。生酮饮食对内源性胆固醇合成的影响具有生物化学基本原理支持。3-羟基-3甲基戊二酸单酰辅酶A(HMG-CoA)还原酶是胆固醇合成过程中的关键酶,可被胰岛素活化。当血液中葡萄糖水平增加时,胰岛素分泌增加可促进内源性胆固醇合成。因此,膳食中碳水化合物减少并保证适量胆固醇摄入可抑制内源性胆固醇合成。

另一个需要考虑的问题是潜在的肾脏副作用。蛋白质代谢过程中,氮排泄增多可增加肾小球压力和超滤过[18]。在肾功能正常的受试者中,高蛋白饮食可导致肾脏功能以及形态的适应性改变但没有明显的副作用[36]。考虑到肾功能改变对血压的影响,研究发现,在肾功能正常时,生酮饮食不会导致血压升高[37]。关于生酮饮食中可能出现的酸中毒问题,在胰岛素功能正常的受试者中,由于酮体浓度不会超过8 mmol/L,这一风险几乎不存在[38]。有关生酮饮食对健康的总体影响,目前也有许多不同意见。在最近的一篇基于有限观察例数的研究中,Noto等人提出低碳水化合物/高蛋白质饮食对健康可能有害:即全因死亡率风险增加,但对心血管疾病死亡率没有影响[39]。而一项大型的欧洲研究表明,蛋白质含量的增加和随后血糖指数的下降可以更好地维持体重减轻且没

demia, especially in insulin resistance individuals[24]. As a consequence of these concerns, there has been increased interest in recent years in very low carbohydrate ketogenic diets or simply ketogenic diets.

There is strong supportive evidence that the use of ketogenic diets in weight-loss therapy is effective; however, the mechanisms underlying the effects of ketogenic diets on weight loss is still a subject of debate. Atkins' original hypothesis suggested that weight loss was induced by losing energy through excretion of ketone bodies[2], but more recently different hypotheses have been proposed: one hypothesis is that the use of energy from protein in ketogenic is an "expensive" process for the body and so can lead to a "waste of calo ries" and therefore increased weight loss[25]. During the first phase of a ketogenic diet, 60-65 g of glucose per day are needed by the body, 16% of this is obtained from glycerol while the major part is derived via gluconeogenesis from proteins of either dietary or tissue origin. Gluconeogenesis is an energy-demanding process calculated at approximately 400-600 kcal/day[26]. There is though no direct experimental evidence to support this intriguing hypothesis. On the contrary, a recent study reported that there were no changes in resting energy expenditure after a ketogenic diet[27].

Some authors claim instead that the weight loss obtained with ketogenic diets could be attributed to a reduction in appetite due to higher satiety effect of protein or the suppressant action of the ketone bodies because ketone bodies can also act as a satiety signal to reduce hunger[28,29]. The existing literature demonstrated that individuals adhering to ketogenic diets are less hungry and have a reduced desire to eat compared with baseline measures. Although in some studies the absolute changes in subjective appetite measures during ketogenic diet were small and not significant, there was a clear lack of increase in hunger despite participants consuming an energy-restricted diet that resulted in a significant weight loss[30]. Hence, for clinicians seeking an effective method of weight loss that does not increase hunger, ketogenic diets can achieve this target.

It is difficult to determine whether the appetite suppression seen with ketogenic diet is indeed due to ketosis or other factors such as an increased content of protein or fat in the diet or the restriction of carbohy

有负面效应[24]。

需要再次强调的是，严格来说生酮饮食并不是低碳水化合物 / 高蛋白质饮食。生酮饮食是指极低碳水化合物但蛋白质含量正常的饮食，可产生特定的代谢状态，而不应等同于低碳水化合物 / 高蛋白质饮食。

6 生酮饮食在体育运动中的应用

与其他限制能量的饮食不同,生酮饮食是具有丰富蛋白质(至少 1.3~1.5 g/kg 体重)且能量充足的饮食,不会导致必需营养素(即维生素、矿物质、必需脂肪酸和氨基酸等)以及帮助机体控制氧化应激和炎症过程的其他营养物质的缺失。因此,尽管碳水化合物含量非常低,但生酮饮食不会导致那些因长期服用减肥饮食而引起的代谢失衡。基于生酮饮食对身体产生极少副作用以及它的减肥效果,越来越多的研究旨在发现生酮饮食在体育运动中的潜在应用,特别是摔跤、举重、柔道等涉及重量级别的运动。

运动员渴望减肥的目的包括:(1) 增加力量体重比;(2)在更有利的体重级别比赛;(3)与健身配合,达到审美上高度欣赏的极度瘦身状态。然而目前运动员采用的许多常见的减肥方法会有许多副作用,进而影响到他们的运动表现。这些快速减肥方法通常是在比赛前临时进行的,包括大幅减少能量摄入,通过桑拿浴、利尿剂或呕吐造成脱水,或使用促进体重减轻的药物。这些减肥法会导致电解质紊乱、脱水以及糖原贮存减少[17]。运动员对蛋白质需求很高,严重的能量限制也意味着蛋白质(以及其他必须营养素)摄入的减少,使得运动员肌肉量下降,从而影响到体力、爆发力以及耐力。限制能量饮食[40]与利用桑拿浴或利尿剂导致脱水[41]的减肥方法对运动表现的影响类似,除了会增加长期的健康风险外,这些运动员到中年后体重增加以及肥胖的风险也会上升[42]。

快速减肥法在有体重要求的运动中的使用不容忽视。Franchini 等最近的一项报道显示,快速减肥在诸如摔跤运动员(60%~90%)和柔道运动(~90%)等对抗性运动中使用率很高[43]。Brito 等人也发现其在柔道运动员(62.8%)、柔术(56.8%)、空手道 (70.8%)和跆拳道(63.3%)中的应用有相似的比例[41]。在举重方面,即使没有确切的数据,快速的体重减轻也很常见。这些运动员通常采用大幅减少能量摄入并通过脱水来达到快速减肥的目标，但他们的运动表现往往会受到负面影响。然而,生酮饮食,因能保证足够

drate. This is because the dietary intake of one particular macronutrient cannot be varied independently of the other macronutrients without affecting the total energy. For instance, the appetite suppression of ketogenic diets has been attributed to their high protein content [31]. However, ketogenic diets involve only modest or no increases in absolute protein intake relative to normal diets. For example, while relatively high in protein, ketogenic diets typically provide absolute protein intakes of only ~50-60 g/day. Additionally, increased protein intake cannot explain the observation of an 'absence of hunger' during starvation or fasting regimes[32,33]. Further, well-controlled studies have shown that when protein intake is matched, a ketogenic high-protein diet suppresses appetite more so than a nonketogenic high-protein diet in obese[28] and in lean subjects[34], highlighting ketosis as a plausible contributing factor.

In considering all literature, the weight-loss effect of ketogenic diets may be ascribed to 1. increased metabolic costs of gluconeogenesis and the thermic effect of proteins, 2. appetite-suppressant action of the ketone bodies, 3. reduced appetite due to higher satiety effect of proteins, and/or 4. decreased lipogenesis and increased lipolysis and fat utilization.

Potential Risks of Ketogenic Diets

One may argue that a low carbohydrate, high protein and fat diet is potentially unhealthy as it may cause a rise in LDL cholesterol and triglycerides and this issue is of special importance in obese individuals. However, there are evidence that point to beneficial effects of ketogenic diets on these cardiovascular risk factors. The majority of recent studies seem to demonstrate that the reduction of carbohydrate intake can actually lead to significant benefits in total cholesterol reduction, in creases in HDL and reduction of blood triglycerides [24,35]. Furthermore, ketogenic diets have been reported to in crease the size and volume of LDL-C particles [26], which is considered to reduce cardiovascular disease risk since smaller LDL particles have a higher atherogenicity. There is a biochemical rationale behind the effects of ketogenic diets on endogenous cholesterol synthesis. A key enzyme in cholesterol biosynthesis is HMG-CoA reductase, which is activated by insulin. This means that an increase in blood glucose and consequently of

的能量和蛋白质摄取，可以避免因其他减肥方法所引起的负面效果。

7 生酮饮食对肌肉代谢的影响

与严格限制能量饮食不同，生酮饮食为运动员提供了足够的能量和蛋白质[25]，避免了蛋白质的缺乏。与此同时，生酮饮食通过诱导空腹样状态导致代谢途径、自噬和应激抵抗等过程的改变。生酮饮食模拟限制能量效应，通过磷酸化激活腺苷单磷酸激活蛋白激酶（Adenosine Monophosphate-activated Protein Kinase ，AMPK）、去乙酰化酶 1（Sirtuin-1，SIRT-1）和过氧化物酶体增殖物激活受体 γ 辅激活物 1-α（Peroxisome Proliferator-activated Receptor Gamma Coactivator 1-alpha ，PGC-1α ）[44]。PGC-1α 转移到细胞核内，作为转录因子上调编码脂肪酸转运、脂肪氧化以及氧化磷酸化等蛋白的基因的表达。AMPK 一方面通过磷酸化激活 PGC-1α，另一方面可促进骨骼肌氧化代谢相关酶的表达。研究发现肥胖人群在禁食状态下 AMPK 活性降低，同时伴有机体氧化能力下降 [45]。

与禁食相似，生酮饮食削弱了胰岛素样生长因子 1 （Insulin-like Growth Factor 1，IGF-1） 的作用。IGF-1 是肌肉合成代谢中的主要介质，在阻抗运动中机械应力的增加可促进局部肌组织 IGF-1 的释放。雷帕霉素靶蛋白（Mammalian Target of Rapamycin，mTOR）信号通路是正常细胞生长和增殖过程的关键调节因子[46]，也参与了 IGF-1 促进的合成代谢过程。因此，尽管生酮饮食能量摄入充足，但肌肉含量增加的可能性较小。

尽管生酮饮食对提高耐力表现有作用，但并不适合想要增加肌肉的运动员。鉴于生酮饮食抑制肌肉肥大的潜在作用，健身爱好者在增肌期间广泛采用这种饮食似乎不妥，因为所有的生化以及分子机制等数据均表明生酮饮食期间肌肉含量很难增加。

8 生酮饮食与肌肉力量

如前所述，对于在有体重级别的项目中参赛的运动员来说，一种安全的且不影响其运动表现的减肥方法至关重要。遗憾的是，仅有一项研究报道了这一课题。在该研究中，Paoli 等观察到，与正常饮食相比，30 d 的生酮饮食对一组高水平的体操运动员的爆发力和耐力表现没有负面影响[47]。这一发现表明对于力量型运动员来说，生酮饮食可以在维持力量水平的同时满足相应的体重级别。由于竞技运动员运动量大，对蛋白质的需求较高，因此该研究采用的生酮饮食中蛋白质含量达到 2.8 g/kg/d [25]。

insulin levels will lead to increased endogenous cholesterol synthesis. Thus, a reduction in dietary carbohydrate together with a correct intake of cholesterol will lead to a inhibition of cholesterol biosynthesis.

Another concern relates to potential negative renal effects. It is suggested that high levels of nitrogen excretion during protein metabolism can cause an increase in glomerular pressure and hyper-filtration[18]. In subjects with intact renal function, nevertheless, higher dietary protein levels have caused some functional and morphological adaptations but without negative effects[36]. It is important to also take into account the renal related ef fects on blood pressure [37]. However, the potential hypertensive effect of this diet has not been evidenced in individuals with normal renal function. With regard to possible acidosis during ketogenic diet, since the concentration of ketone bodies never rises above 8 mmol/L, this risk is virtually non-existent in subjects with normal insulin function[38]. Regarding the overall effects of ketogenic diet on health there are differences in opinion. In a recent systematic review based on limited observational studies, Noto et al.[39] suggested a possible harmful effect of low carbohydrate/high protein diet on health: i.e., an increase of all-cause mortality risk whilst there was no effect on cardiovascular disease mortality. On the other hand, a large European study demonstrated that an increase in protein content and a subsequent reduction in the glycemic index led to better maintenance of weight loss without adverse effects[24].

It is important to underline once again that a ketogenic diet is not, strictly speaking, a low carbohydrate/high protein diet. A ketogenic diet is mainly a very low carbohydrate diet with a normal amount of protein that produce an unusual metabolic state that should not be assimilated to a low carbohydrate/high protein diet.

Utility of Ketogenic Diets in Sports

Unlike many other types of energy restricted diets, which can create situations of undernutrition for essential nutrients, i.e., vitamins, minerals, essential fatty acids, and amino acids, as well as depriving the body of other macronutrients that help control oxidative stress and inflammatory processes, a ketogenic diet is energy-sufficient diet with an adequate amount of protein (minimum 1.3-1.5 g/kg of body weight). Thus, despite the fact that

Davis 和 Phinney 发现在 3 个月的生酮饮食期间，给予1.1 g/kg/d 蛋白质的受试者较给予 1.5 g/kg/d 蛋白质的受试者的最大摄氧量($\dot{V}O_{2max}$)显著降低，表明蛋白质含量降低可能会影响到运动表现[48]。

在禁食的早期阶段，肌蛋白分解为氨基酸前体，参与糖异生过程，此时中枢神经系统依赖于糖异生所产生的葡萄糖供能。但这只是暂时的过程，因为利用肌肉分解供能不是机体最佳选择也不利于长期生存。生酮饮食可通过来自大量脂肪的酮体抑制糖异生来保存肌肉量。生酮饮食不会增加肌肉含量，但它也不会导致肌肉损失以及肌力下降。在酮症状态下，利用酮体和游离脂肪酸供能可减缓肌蛋白的分解代谢，保留肌肉含量，而这种利用脂肪作为能量的"肌肉节约效应"仍待进一步研究。目前还不清楚长期生酮饮食是否会阻碍肌肉形成，从而使得需要增加肌肉含量的运动员适得其反。

9 生酮饮食与耐力表现

生酮饮食在不经常锻炼或久坐者中的研究结果相互矛盾，有些报道表明生酮饮食可以改善体能[49]，而有些则认为生酮饮食后体能降低[12]。例如，Phinney 等指出，轻度肥胖且不锻炼的受试者在 60%的最大耗氧量下长时间运动，即使 6 周内饮食几乎不含碳水化合物(小于 10 g/d)，他们依然能够维持这一运动量。此外，在平均减重 7.1 kg 后，与基础值(168~259 min)相比，他们的跑步时间提高了 1.5 倍[50]。而 White 等[51]报道生酮饮食(碳水化合物提供 5%的能量)增加了 9 min 行走的疲劳感。该研究仅报道受试者主观疲劳程度增加，但平均心率以及运动强度无明显改变，并且 $\dot{V}O_{2max}$ 和血乳酸水平也都没有分析。最近研究发现，在肥胖人群中，与高碳水化合物饮食相比，8 周的生酮饮食增加脂肪氧化，且对有氧运动表现以及肌肉力量等指标没有负面效应[52]。

生酮饮食对耐力运动员影响的研究也很少，最早是由 Phinney 等人报道，他们发现 4 周的生酮饮食对于自行车运动员的耐力表现没有负面作用[8]。最近 Zajac 等发现生酮饮食可增加山地自行车运动员的最大耗氧量以及乳酸阈值[53]。作者将该发现归因于体重以及脂肪含量的减少和脂肪利用率的增加，同时生酮饮食也使得最大运动负荷以及达到乳酸阈值的运动负荷明显提高。

尽管研究报道结果不一致，有几个原因可以解释这些矛盾。首先，生酮饮食不利于运动表现的研究只进行不到两周时间，这不足以使得酮适应完全发挥作用。尽管 Sawyer 等的文章中表明 7 d 生酮饮食

it entails very low carbohydrate levels, the diet does not lead to metabolic imbalances that can have irreversible effects if nutrient-deficient weight loss diets are repeated on a regular basis. In this context and based on weight loss effect of ketogenic diets, there has been growing research aimed to examine the potential application of ketogenic diets in sports, especially those involving weight classes such as wrestling, weight lifting, judo, etc.

Motivations that lead athletes to desire weight loss include 1. improving power-to-weight ratio, 2. competing in a more favorable weight category, and 3. in case of an activity like bodybuilding, to achieve an extreme leanness that is highly desirable for aesthetic purposes. Unfortunately, many common methods that athletes use to reduce weight also may have some negative side effects that can be detrimental to actual sports performance. These methods that produce rapid weight loss are typically carried out immediately before competition. The weight loss is created through cutting energy intake drastically, creating dehydration by using saunas, diuretics, and spitting, or using medications that facilitate weight loss. This can lead to electrolyte imbalance, dehydration, and reduced glycogen stores [17]. Severe energy restriction also means a reduction of protein intake (as well as other essential nutrients) that, considering the higher needs of athletes, could induce loss of skeletal muscle mass and, in consequence, impairment of strength, power and endurance performance. There are several generally harmful effects on performance resulting from such a very restricted energy intake[40] as well as harmful effects from methods such as dehydration using sauna or diuretics[41]. Apart from increasing risks of long-term health problems, there also is an increased risk of weight gain and obesity in athletes who reach middle age[42].

The practice of rapid weight loss in weight dependent sports is not to be underestimated. A recent review by Franchini and colleagues[43] showed that rapid weight loss has a high prevalence in combat sport practitioners such as wrestlers (60%-90%) and in judo (~90%). Brito et al. (41) reported a similar percentage in judo athletes (62.8%), jujitsu (56.8%), karate (70.8%), and taekwondo (63.3%). Also in weightlifting, rapid weight loss appears to be common even though no precise data are available.

(5.4%碳水化合物,35.1%蛋白质,53.6%脂肪)对 31 名训练者的力量没有任何负面效应，仍建议运动员在比赛前至少 2 周即开始采用生酮饮食减重[54]。其次,受试者是否摄入足量电解质尚不明确。在生酮饮食中,需要摄入钠和钾来维持组织功能及氮平衡[6]。最后,在生酮饮食期间,糖异生增加使得蛋白质需求增加,因此 蛋白质摄入不足可能会影响到运动员的肌肉量。

10 生酮饮食与心理问题

除了会增加困倦、疲惫感以及抑郁等症状外,快速减肥还可能导致注意力不集中、短期记忆力减退以及自尊心降低[55]。所有这些改变均可能影响到运动员的表现。注意力不集中会影响到运动员的技术水平发挥。短期记忆障碍可能会造成技术或战术缺陷。自尊心的降低可能会导致信心的丧失和消极的态度,这两者都可能导致整体表现不佳。鉴于生酮饮食伴有足够的能量摄入，与常见的快速减肥饮食有关的这些负面影响可能不会出现。与简单而极端的限制能量摄入的机制不同，生理性酮症是一种特殊的代谢状态。生酮饮食对情绪以及认知影响的少数研究表明,对于心理健康的超重及肥胖人群,短期适度限制能量的低碳水化合物饮食与相同能量的传统饮食具有相似的作用效果[52]。同时该研究小组也发现 1 年的低脂肪饮食较低碳水化合物饮食对超重和肥胖人群的情绪具有更有利的作用[56]。因此至少短期生酮饮食应用可缓解运动员抑郁症状并减轻主观疲劳感。

11 实际应用

近年来,对生酮饮食的研究逐渐增加。然而仅有个别研究报道生酮饮食对运动表现的影响，且结果不一致,有部分原因是由于未正确使用生酮饮食。以下是有关如何正确进行生酮饮食的几个关键点。

(1)为有效诱导生理性酮症,生酮饮食中碳水化合物含量需低于每天摄入总能量的 5%或小于 20 g/d。

(2)为维持运动员的肌肉量,每天摄入蛋白质含量需在 1.2~1.7 g/kg 范围内(不超过 2.5 g/kg)。这一含量可以确保至少维持机体蛋白质补充以及糖异生消耗量。而过量蛋白质摄入(超过 2.5 g/kg 或每天消耗总能量的 25%~30%)则可能抑制酮症状态。

(3)脂肪是达到每天总能量需求的基础营养物质,因此,运动员可随意摄取脂肪。

(4)应确保受试者足够的矿物质以及每天 3~5 g 钠和 2~3 g 钾的摄入来维持组织功能和氮平衡。

Effect of Ketogenic Diets on Muscle Metabolism

Unlike sev ere energy restriction, ketogenic diets provide adequate amounts of energy and protein to athletes[25], avoiding protein deficiency but, at the same time, the diet, by inducing a “fasting-like” state, leads to alterations in metabolic pathways and processes such as autophagy and stress resistance. Ketogenic diets “mimics” the energy restriction effect that is to activate adenosine monophosphate-activated protein kinase (AMPK), sirtuin-1 (SIRT-1), and peroxisome proliferator-activated receptor gamma coactivator 1-alpha (PGC-1α) by phosphorylation[44]. In this state, PGC-1α moves to the nucleus and acts as a transcription factor, increasing the expression of genes that code for proteins involved in fatty acid transport, fat oxidation, and oxidative phosphorylation. AMPK works in two ways, either by activating PGC-1α by phosphorylation or by promoting the expression of enzymes involved in skeletal muscle oxidative metabolism. It has been demonstrated that obese individuals have lower AMPK activation coupled with less oxidative capacity during fasting[45].

On the other hand, ketogenic diets, similar to fasting, blunts the action of insulin-like growth factor 1 (IGF-1). IGF-1 is considered to be the primary mediator for the anabolic response in muscle and its release from local muscle tissue increases as muscle undergoes mechanical stress such as by resistance exercises. IGF-1 accelerates anabolic process that involves mammalian target of rapamycin (mTOR) signaling pathway, which is a key regulator of normal cellular processes in volved in cell growth and proliferation[46]. In this context, ketogenic diets can reduce the possibility of gaining muscle mass despite energy sufficiency.

So while ketogenic diets may be useful in endurance performance, it is an oxymoron when the athlete seeks muscle hypertrophy. Given the potential that ketogenic diets can suppress muscle hypertrophy, it appears somewhat contradictory that there is widespread use of this diet in bodybuilders also during “bulk up” periods, while all data regarding biochemical and molecular mechanisms suggest that it is very difficult to increase muscle mass during a ketogenic diet.

Ketogenic Diets and Muscle Strength and Power

As previously mentioned, for athletes competing in

（5）受试者应具有依从性，饮食计划应受专业营养师或注册营养师监督以确保坚持生酮饮食。

（6）通过血液分析确保受试者处于酮症状态，血液检查较尿液检查效果更好，因为尿中酮体缺乏并不一定意味着非酮症状态。

（7）受试者需记住在生酮饮食的前几天，体重减轻的主要原因是糖原和水分的丢失，因为每储存 1 g 糖原会附带 3 g 水分。随着时间延长，脂肪的消耗逐渐增加，在 5~7 d 后，脂肪氧化显著上升。

（8）如果在涉及体重级别的比赛中采用生酮饮食，为避免对运动表现产生副作用，建议至少提前两周开始。

（9）生酮饮食只适用于成年运动员，在青少年时期使用需谨慎。尽管有证据证明其在癫痫发作的儿童中的有效性和耐受性，但生酮饮食在青少年运动员中的应用必须在医疗指导下进行。

12 结论

生酮饮食是指碳水化合物含量减少（通常小于 20 g/d 或低于每天总能量摄入的 5%）而蛋白质和脂肪的比例相对增加的饮食。生酮饮食与其他类型的减肥饮食不同，它的特点是能量充足但碳水化合物含量非常低，蛋白质含量能够满足日常消耗且提供丰富的微量营养素及必需营养素。生酮饮食诱导的代谢性酮症可抑制饥饿感并增加脂肪氧化，从而减轻体重。尽管有待进一步研究，但短期生酮饮食不会引起任何重大的健康问题。已有研究表明生酮饮食在某些运动，特别是在有体重级别，涉及审美以及耐力运动中具有重要作用，但训练者、体育医生以及营养师也必须充分了解采用这种饮食方法的正确步骤以及它的优势与不足之处。目前有关这种相对新的饮食方法的研究仍然有限，因此有关生酮饮食在治疗肥胖及其并发症中的潜在作用，以及在不影响运动员运动表现的情况下控制体重的特殊功效还尚待更多研究数据的积累。

weight categ ory sports, a safe method of weight loss that does not impair performance can be a legitimate and important tool. Surprisingly, only one study has reported on this topic. In this study, Paoli et al.[47] demonstrated that, compared with a standard ad libitum diet, a 30-d ketogenic diet did not affect explosive and strength performance negatively in a group of high-level gymnasts. This finding suggests that ketogenic diets could be useful for power athletes to meet weight categories while maintaining power output. Because of the intense physical activity of competitive athletes, there is an increased demand for protein, and this was reflected in the ketogenic diet administered in the study, which provided approximately 2.8 g protein/kg/day[47]. In fact, a lower quantity of protein may impair performance as demonstrated by Davis and Phinney [25] who showed that subjects consuming 1.1 g of protein/kg of body weight experienced a significant reduction in $\dot{V}O_{2max}$ during a 3-month period during a ketogenic diet compared with subjects given 1.5 g/kg body weight.

In the early phase of fasting, the CNS is kept supplied with glucose for energy via gluconeogenesis, a process of breaking down muscle tissue to the amino acid precursors. Clearly, this is only a temporary measure as muscle wasting is compatible with neither optimal performance nor long-term survival. However, ketogenic diets are able to spare muscle mass by producing ketone bodies, a fat-based source of energy, at a high level. Ketogenic diets may not lead to a gain in muscle mass, but they normally don't cause muscle loss nor decreased muscle performance either. It appears that during a ketotic state, the use of ketone bodies and free fatty acids for energy slows muscle protein catabolism, so lean body mass is generally conserved, although this "sparing effect" of the use of fats as an energy source remains to be evidenced. It is unclear if a long-term use of ketogenic diet can interfere with muscle development and thus be counterproductive especially when the aim of the athlete is to gain muscle mass.

Ketogenic Diets and Endurance Performance

The available data on the use of ketogenic diets in untrained/sedentary subjects have shown contradictory results, with some reports of improvement[49] and others of reduction[12] in physical performance. For example, in mildly obese untrained individuals, Phinney et al. [50]

noted that, while undergoing prolonged exercise at 60% $\dot{V}O_{2max}$, they can sustain this even with almost no carbohydrate in the diet (<10 g/day) across a period of 6 weeks. Furthermore, after a mean weight loss of 7.1 kg, there was a significant 155% increase compared with baseline in treadmill time (from 168 to 259 min). On the other hand, White et al.[51] reported that a ketogenic diet (5% of energy provided by carbohydrates) increased perception of fatigue during a 9-min walk. However, it was only the rating of perceived exertion that was significantly higher and there was no actual change in average heart rate or exercise intensity, whereas other measures of performance such as $\dot{V}O_{2max}$ and blood lactate levels were not analyzed. Recent studies demonstrated that, in obese subjects, 8 weeks of a ketogenic diet enhanced fat oxidation and had no detrimental effect on maximal or submaximal markers of aerobic exercise performance or muscle strength compared with a high-carbohydrate diet[52].

Very few studies have analyzed the effect of ketogenic diets in endurance athletes. The earliest is the study by Phinney et al.[8] who found that 4 weeks of ketogenic diet did not have any negative effects on endurance performance in cyclists. A more recent study by Zajac et al. [53] reported a significant increase in $\dot{V}O_{2max}$ and improvement in the lactate threshold in off-road cyclists after a ketogenic diet. The authors attributed their findings to the reduction body mass and fat mass and increase in fat utilization even though the maximal workload and the workload at lactate threshold were both reduced significantly on the ketogenic diet.

Although these studies report divergent results, there are several factors that could explain the contradictory findings. First, studies showing a detrimental effect of a ketogenic diet on performance were performed for less than 2 weeks and this is not sufficient for the effects of full keto-adaptation to be seen. It is recommended that athletes should program a ketogenic diet for weight loss at least 2 weeks before competition, even though a recent article by Sawyer et al.[54] reported that power output was not affected negatively in 31 trained individuals after only 7 days of a ketogenic diet (5.4% carbohydrate, 35.1% protein, and 53.6% fat). Second, it is unclear whether subjects consumed adequate amount of electrolytes. During a ketogenic diet, sodium and potassium need to be supplied to maintain tissue function and nitrogen balance[6]. Finally, during a ketogenic diet, the need for protein is higher because of gluconeogenesis; thus, a low intake of protein may affect negatively the athlete's muscle mass.

Ketogenic Diets and Psychological Issues

It must be noted that rapid weight loss may cause decreased concentration, short term memory loss, and lower self-esteem, as well as increasing confusion, fatigue, and depression traits[55]. All these modifications can contribute to impaired performance in athletes. A lack of concentration could affect the ability of the athlete to focus on technique that would result in loss of performance. Impairment in short-term memory can cause a technical/tactical disadvantage. A reduction of self-esteem can result in a loss of confidence and negative attitudes, both of which can contribute to an overall subdued performance. Given that a ketogenic diet is accompanied by a sufficient energy intake, these negative observations associated with common rapid weight loss diets may not apply. This is because physiological ketosis is a specific metabolic state that is quite different from the mechanisms induced by simple but extreme energy restriction. The few studies available about the effects of a ketogenic diet on mood and cognition suggest that a short-term consumption of a moderately energy-reduced low-carbohydrate diet has similar effects on the psychological well-being of overweight and obese individuals compared with an isoenergetic conventional diet[52]. This same research group also reported a more favorable effect on mood of low-fat diets compared with a low-carbohydrate diet after 1 year in overweight and obese individuals[56]. It appears that ketogenic diets at least in the short-term such as that might be used by athletes can help alleviate depressive symptoms and also diminish perceptions of fatigue.

Practical Application

An increasing amount of research has been carried out on ketogenic diets during recent years. However, only a few studies are available on ketogenic diets and sport performance, and results are mixed in part because of an incorrect use of ketogenic diets. The following are the key points with regard to how ketogenic diets should be carried out adequately:

* A ketogenic diet shall contain less than 5% of total daily energy from carbohydrates or less than 20 g of carbohydrate daily in order to effectively induce physiological ketosis.

* In athletes, to preserve lean body mass, the daily requirement for protein should be in the range of 1.2 to 1.7 g/kg body weight (up to 2.5 g/kg body weight). This amount is needed to ensure the minimum quantity for body protein replacement and for gluconeogenesis. On the other hand, an excessive protein intake (>2.5 g/kg body weight or more than 25-30% of daily energy expenditure) might suppress ketogenesis.

* Fats are fundamental to reach the total daily energy requirement; thus, for athletes, fat should be provided ad libitum.

* Subjects must insure an adequate mineral intake and supplementation with 3 to 5 g/day of sodium and 2 to 3 g/day total potassium can maintain tissue function and nitrogen balance.

* Subjects should be compliant, and the diet plan should be checked by an expert nutritionist or registered dietician to confirm adherence to a ketogenic diet.

* Blood analysis should be performed to confirm that subjects are in ketosis; blood examinations using a device that uses capillary blood are preferable to urine examinations because often a lack of ketone bodies in urine does not mean necessarily a nonketotic state.

* Subjects should keep in mind that during the first days of ketogenic diet, the main contributor to weight loss is muscle glycogen and, thus, water - it is well known that there are about 3 g of water stored with each gram of glycogen. In addition, the contribution of fat increases gradually overtime and it should be expected that a signifi cant increase in fat oxidation could be observed after 5-7 days.

* If a ketogenic diet is used for weight category sports, it is recommended that it begins early, at least 2 weeks prior to the competition in order to avoid any negative effects on performance.

* Ketogenic diets may only be applied to adult athletes and their use in youth needs caution. Even though there are convincing data about its efficacy and tolerability in children with seizures in epilepsy, the use of ketogenic diets in young athletes must require a medical supervision.

Conclusions

Ketogenic diets are characterized by a reduction in carbohydrates (usually <20 g/day or 5% of total daily energy intake) and a relative increase in the proportions of protein and fat. The diet is fundamentally different from many other weight loss diets. The key feature of this diet is an energy sufficiency while with a very low carbohydrate intake and its compatibility with normal protein consumption and a rich nutrition that provides full complements of micronutrients and essential macronutrients. By inducing physiological ketosis, the diet can help control hunger and improve fat oxidative, thereby reducing body weight. Although more research is needed, the short term use of ketogenic diets has not been associated with any major health issues. There are some encouraging data that suggests a useful role of ketogenic diets in certain sports, especially those with weight categories and aesthetic and endurance sports, but it is necessary that trainers, sports physicians, and dieticians are aware of the proper procedure and strengths and limitations associated with this nutritional strategy. As data are still quite limited with regard to this relatively "new" dietary approach, further studies are warranted to further investigate the potential role ketogenic diets play in treating obesity and its comorbidities and in helping athletes manage their body weight without sacrificing performance.

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