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Fueling performance: Determining the efficacy of low-carbohydrate diet models for athletic populations

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Abstract

Advocates of low-carbohydrate (LC) diets assert that these diets help lessen dependence on sugar while aiding in the metabolism of fat tissue. Additionally, it is believed that lipolysis helps dieters feel more energetic, lose weight, and improve physical performance. For these reasons, many athletes and active people are drawn to diets such as the Atkins Diet, the South Beach Diet, the Paleo Diet, and the Zone Diet. According to current evidence, excessive weight loss, ketosis, reduced glycogen availability, dehydration, and increased stress hormone levels make LC diets that severely limit carbohydrates disadvantageous for athletes. Although LC diets are widely followed, their long-term effects are still not thoroughly understood. The purpose of this review is to examine the current research on substrate utilization during exercise as well as the diet patterns in question to determine whether they are appropriate for athletes and active people.

Introduction

The first LC diet was described in the 1860s by William Banting, but this type of diet truly gained popularity with the emergence of the Atkins Diet.[1] In the Atkins Diet, foods high in carbohydrates are replaced with foods high in fat and protein. This nutritional strategy promises weight loss, fat burning, and improved energy.

LC diet patterns developed more recently share some characteristics with Atkins principles. These diets vary greatly in the types of foods they allow as well as macronutrient ratio recommendations, but they have a common guiding principle. Proponents of these diets assert that diets low in carbohydrates and high in protein assist in the metabolism of adipose tissue for energy, contributing to rapid weight-loss[1]. Although LC diets such as Atkins were originally intended for weight loss, many active individuals and athletes have adopted them in an effort to become stronger, leaner, and more energetic. Atkins, South Beach, Paleo, and Zone diets have all become popular for frequent exercisers and athletes alike.

Despite the proposed benefits of LC diets, several concerns have been raised regarding their safety and efficacy. Ketogenesis (the conversion of fatty acids to ketones) brought on by very low-carbohydrate (VLC) diets is associated with alterations in metabolic function, which can be dangerous for certain populations. High fat and low fiber intakes that often accompany LC diets raise concerns that these diets may adversely affect cardiovascular disease risk. As there are few studies about the long-range safety and efficacy of LC diets, it is difficult to determine if these diets will help dieters maintain positive changes the diets helped them make initially, or if the diet will have any adverse effects[1].

Purpose

Although LC diets are widely followed, their long-term effects are still not thoroughly understood. Most studies on LC diets are conducted with participants who are obese or have diabetes, and are used to study the effect of these diets as they relate to weight loss or hormonal function. There is a need for a compilation of the existing data on varied LC diet models to help athletes and active individuals in particular determine which nutritional pattern is most appropriate for their goals. The purpose of this review is to examine the current research on substrate utilization during exercise as well as the diet patterns in question to determine whether they are appropriate for athletes and active people.

Methods

To address the research goal, a literature search was conducted using the databases Science Direct, Medline Plus, PubMed, and Web of Science. Search terms included: "low-carbohydrate diet" AND "athletes," "ketogenic diet" AND "athletes," "Atkins diet" AND "athletes," "South Beach diet" AND "athletes," "Paleo diet" AND "athletes," "Zone diet" AND "athletes." Studies included were limited to those written in English and performed using human subjects.

Biochemistry

The body can utilize various substrates and pathways to produce energy. Fat, in the form of adipose tissue, plasma fatty acids, and intramuscular triglycerides (IMTGs), makes up an overwhelming majority (about 98%) of the body's energy stores. Carbohydrates, such as glucose in blood and glycogen in muscle and liver comprise the smaller remainder of energy stores.

There are three basic pathways that the body can use to utilize stored energy during exercise: the creatine phosphate pathway (ATP-CP), glycolysis, or aerobic metabolism. The ATP-CP system rapidly produces limited amounts of energy in the form of adenosine triphosphate (ATP) from stored creatine phosphate in working muscle. Glycolysis also produces small amounts of ATP energy quickly, but it uses blood glucose and glycogen to accomplish this. Aerobic metabolism produces energy slowly, but this pathway is capable of yielding far more energy. Blood glucose and glycogen, as well as fat in the form of adipose tissue and IMTGs can be used to fuel this form of metabolism. During intense exercise, the need for ATP to produce energy is immediate, requiring quick production of it. After ATP stores from muscle glycogen are exhausted by aerobic glycolysis, the body turns to the ATP-CP pathway. CP stores are exhausted after 5-10 seconds of intense activity, and then the body turns to anaerobic glycolysis. This process can sustain several minutes of intense activity. After this, aerobic metabolism contributes the energy needed to power prolonged exercise (Figures 1 and 2).

Using fats to produce ATP requires a larger amount of oxygen than when using carbohydrates. Converting amino acids to glucose is the body's last resort when carbohydrates and fats are not available to provide energy. When both carbohydrates and fats are available for fuel, carbohydrates are preferred because they have double the potential to transfer energy than do fatty acids.Increasing intensity of activity from rest increases the percentage of energy derived from carbohydrates.Long-duration moderate-intensity exercise is fueled largely by lipolysis. Low-intensity bouts of exercise can be powered by aerobic metabolism, while longer bouts or intense bursts of energy rely on anaerobic pathways. By employing the concepts of substrate utilization, the generalization can be made that the type of fuel needed to fuel activity depends on the type of activity itself.[3]

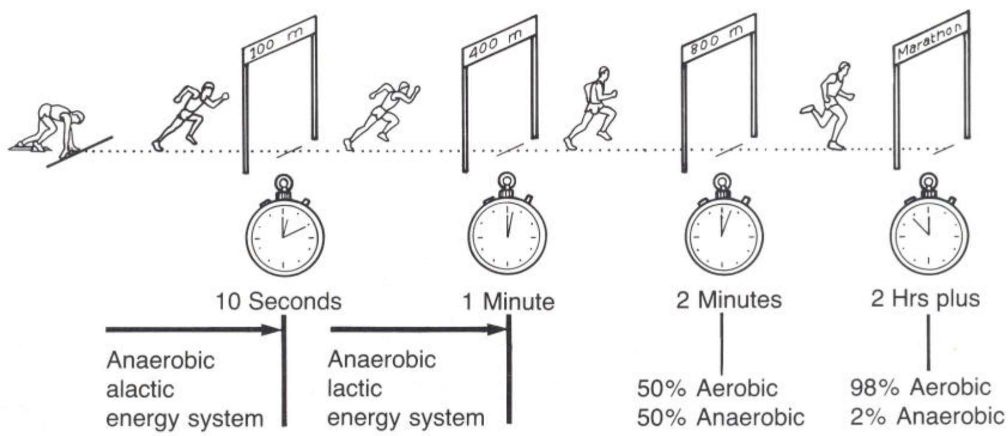


Figure 1. Energy system use during exercise[2]

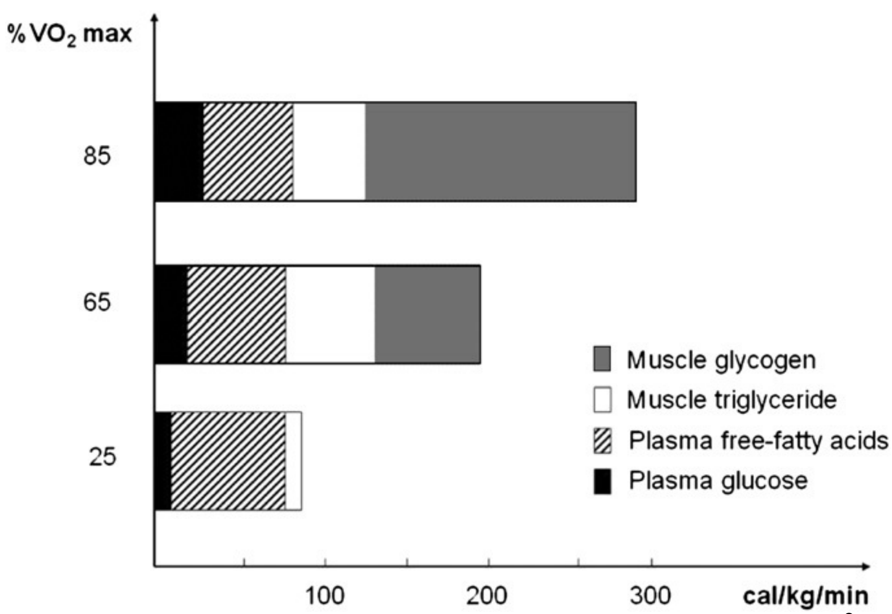


Figure 2. Energy substrate use relative to exercise intensity[3]

Under starvation conditions or when carbohydrate intake is extremely low, glucose is unavailable to provide fuel, so the body can convert fatty acids into ketones. These ketones can also be used to provide fuel for the brain as well as muscles, which spares muscle protein from being catabolized. This condition is called ketosis, and it is the basis for some LC diets. To be truly ketogenic, a diet of less than 10% of energy from carbohydrate and 50-80% fat should be followed for at least 7 days.[4] The shift from primarily glucose utilization to ketones is said to elicit improvements in weight loss, blood lipid profile, and endurance. Critics of ketogenic diets question the efficacy of the diet to elicit these factors, as it would seem that “running on empty” (i.e. ketosis) would lead to fatigue, a poor lipid profile, and improbable weight loss. Additionally, it is interesting to note that ketogenic diets are most commonly used as a therapy to lessen the frequency of epileptic seizures in children, as the brain’s shift from using glucose to using ketone bodies for fuel proves to improve symptoms and reduces seizure occurrence.

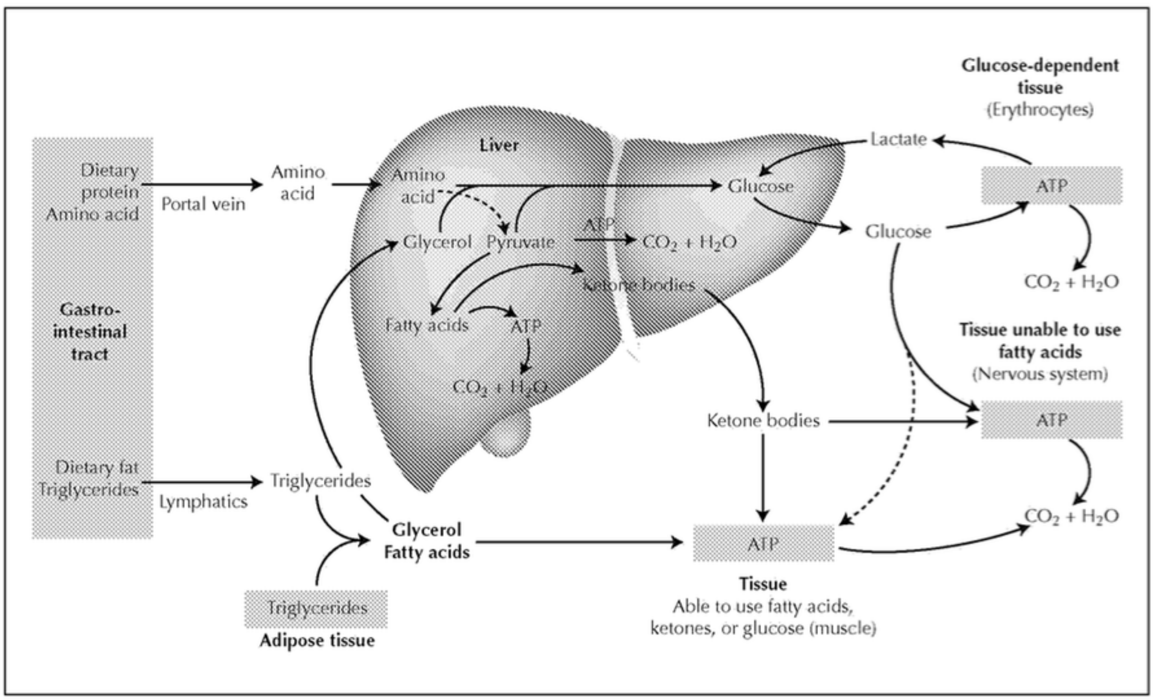


Figure 1. Projected fuel utilization for a low-carbohydrate ketogenic diet. (ATP—adenosine triphosphate.)

Figure 3. Fuel utilization for a low-carbohydrate ketogenic diet[5]

Insulin and Glucagon

The hormones insulin and glucagon are responsible for keeping blood glucose levels stable. When blood glucose levels are high, particularly after a meal, the alpha cells of the pancreas release insulin to facilitate the shuttling of glucose to target tissues. In response to insulin, red blood cells, fat cells, and muscle cells all take in glucose, lowering blood glucose levels. Conversely, beta cells of the pancreas release glucagon when blood glucose levels are low, as in fasting. This triggers the release of stored glucose from the liver to increase blood glucose levels.

Glycemic Index and Glycemic Load
Several diets are based on the concept of the glycemic index (GI), which measures the effect of dietary carbohydrate on blood glucose levels by comparing them to a reference carbohydrate (pure glucose). High GI foods raise blood sugar rapidly, while low GI foods raise blood sugar more slowly. Glycemic load (GL) is a similar measure of glycemic response to food, which uses the amount of carbohydrate in a serving of food as well as its glycemic index. Diets such as Paleo and South Beach specifically advocate eating low-GI/GL foods to normalize blood sugar levels along with insulin response, which ultimately controls weight and metabolism more effectively.

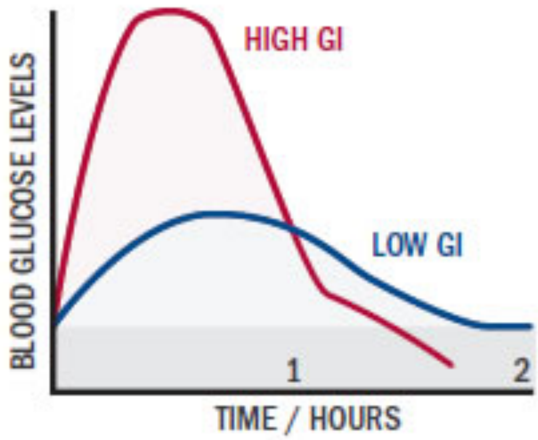


Figure 4. Glycemic effect of high GI and low GI foods[6]

Diets

Developing a definition for a "low carb diet" is one challenge in comparing and understanding variations on this concept. The Food and Drug Administration (FDA) currently does not have a definition for the term "low-carb".[7] This term is also not permitted in food labeling. From macronutrient ratios to specific foods, LC diets are quite variable (Figure 6). Traditional recommendations for carbohydrate intake advocate about 55% of calories from carbohydrates. According to Hite al[8], a reduced-carbohydrate diet can be defined as a diet deriving less than 130 g of carbohydrates per day. A low-carbohydrate diet allows 30-130g of carbohydrate per day. A very low-carbohydrateketogenic (VLCK) diet permits up to 30g of carbohydrate per day. For the purposes of this review, a "LC diet" will be defined as a diet comprised of no more than 40%of energy from carbohydrates.

The Atkins Diet - 1972
According to cardiologist and author of the Atkins diet, Robert Atkins, The Atkins approach is the most effective weight loss program in recent years, and it works

for a majority of those who try it—without counting calories. Additionally, he asserts that following this diet positively affects people with chronic diseases such as diabetes, hypertension, and heart disease, as well as people with gastrointestinal problems such as food intolerances and allergies.[9] Some athletes also follow this diet because of its promises that increased dietary fat may help improve physical endurance, as this effect has been shown in several studies of cyclists and runners mentioned by Atkins in his book, Dr. Atkins new diet revolution.

The diet is based on findings that suggest that adverse effects of eating too much carbohydrate include excessive insulin release, which leads to metabolic dysfunction called hyperinsulemia that is linked to obesity and diabetes. Atkins provides a “metabolic advantage” by causing the body to use fat instead of carbohydrates for energy (i.e. ketosis). The author believes that overweight people are more sensitive to carbohydrates than others, and for this reason, they should adopt a controlled carbohydrate diet. According to Atkins, the obesity and diabetes crises in America can be directly attributed to the promotion of the Food Guide Pyramid, which purportedly encouraged the intake of refined carbohydrates.[9]

Following this diet is advocated as a lifetime practice to keep excess weight off. Adopting the diet follows four phases: Induction, Ongoing Weight Loss, Pre-Maintenance, and Lifetime Maintenance. Induction is meant to result in ketosis. This phase allows up to 20 g of carbohydrate per day, with no fruit, bread, pasta, grains, starchy vegetables, dairy products, or legumes. Supplements are recommended during this phase, namely the formularies created by Atkins (including potassium, magnesium, and calcium) to combat nutrient deficiencies and side effects such as leg cramps. To test whether the body is in the required state of ketosis for Induction, ketone strips are used to test urine. This phase continues for a minimum of fourteen days, but can be extended indefinitely depending on weight loss goals. The Ongoing Weight Loss phase involves adding 5 g of carbohydrates to the diet per week, according to the carbohydrate ladder (table 1), until weight loss slows significantly. Regular exercisers (those who participate in vigorous exercise 5 days per week for at least 45 minutes) are advised to consume 60-90 g of carbohydrates per day. Pre-Maintenance can be initiated when the dieter is 5-10 pounds away from their goal weight. Slow weight loss at a rate of 1 pound per week over 2-3 months is advocated here. Carbohydrate intake is increased by no more than 10 g per week. Lifetime Maintenance involves sustaining the “Critical Carbohydrate Level for Maintenance” found during the Pre-Maintenance phase. Those with high metabolic resistance should take in 25-40 g of carbohydrate per day, whereas regular exercisers may need upwards of 90 g of carbohydrate daily.[9]

Table 1. Atkins Carbohydrate Ladder[9]

Rung 1	Foundation vegetables: leafy greens and other low-carb vegetables
Rung 2	Dairy foods high in fat and low in carbs: cream, sour cream, and most hard cheeses
Rung 3	Nuts and seeds (but not chestnuts)
Rung 4	Berries, cherries, and melon (but not watermelon)
Rung 5	Whole milk yogurt and fresh cheeses, such as cottage cheese and ricotta
Rung 6	Legumes, including chickpeas, lentils, and the like.
Rung 7	Tomato and vegetable juice "cocktail" (plus more lemon and lime juice)
Rung 8	Other fruits (but not fruit juices or dried fruits)
Rung 9	Higher-carb vegetables, such as winter squash, carrots, and peas
Rung 10	Whole grains

The South Beach Diet - 2003

The South Beach Diet was developed by cardiologist Arthur Agatson as a diet for weight loss, and can also be seen as a response to the Atkins diet. The diet promises sustainable weight loss and improved cardiovascular health. Agatson believes that the saturated fats promoted in the Atkins diet can contribute to cardiovascular disease, so South Beach is based on "good carbs" and "good fats." Vegetables and other low-GI foods are considered "good carbs" and unsaturated fats found in foods like olive oil, seafood, nuts, and seeds are considered "good fats." This diet is more plant-based than the Atkins diet, which is high in animal fats and proteins.

The diet follows three phases. Phase 1 lasts for two weeks only, and aims to resolve insulin resistance. Like Atkins, it is meant to induce ketosis. Only foods low on the glycemic index are allowed. No bread, rice, potatoes, pasta, baked goods, fruit, sugar, or alcohol are permitted. This stage should elicit 8-13 pounds of weight loss. Phase 2 allows the dieter to slowly add prohibited foods back according to the "carbohydrate ladder" inspired by the glycemic index. This ladder is very similar to the model featured in the Atkins Diet (Table 1). Weight loss should slow to 1-2 pounds per week for as long as desired. Phase 3 is seen as a lifelong diet, where all foods can be eaten in moderation.[10]

The Paleo Diet - 2002

The Paleo Diet is based on the rationale that humans are best adapted to eat foods resembling what ancient humans ate before modern agriculture. Meat, poultry, seafood, nuts, fruit, and vegetables are allowed while following this diet, as the authors maintain that these are the foods ate by Stone Age ancestors of dieters. Foods that are considered unacceptable using the Paleolithic diet model include dairy, grains, alcohol, salty foods, refined sugars, and processed foods.[11] This diet has become wildly popular in the past decade, with numerous people adopting the diet to receive the metabolic benefits, such as weight loss and decreased disease risk, that Paleo promises. Among these people are many athletes, which prompted the authors to publish a specialized book for these dieters:*The Paleo Diet for Athletes*. According to the authors, athletes have needs far greater than Stone Age humans, so the diet must be modified.

When following the Paleo diet, athletes training rigorously for more than 10 hours per week are advised to modify the Paleo diet by eating certain non-Paleo foods (commercially prepared foods that may contain dairy, wheat, and soy) before, during, and after workouts and competitions. Athletes following Paleo need to include more carbohydrates to keep muscle glycogen levels adequate.Two hours before exercise, the athlete should consume 200-300 calories of low-GI carbohydrates and protein (preferably with branched-chain amino acids (BCAAs)). During exercise, carbohydrates need to be replenished and BCAAs should be included while maintaining hydration status. Thirty minutes following exercise, 3 calories per pound of bodyweight of high-GI carbohydrates (such as dextrose or commercially-prepared recovery drinks) should be consumed. Additionally, drinking 16 oz of liquid for every pound lost during exercise and replacing electrolytes is advocated. BCAAs should be consumed in a carbohydrate-to-protein ratio of 4:1 or 5:1. After a period equal to the length of the training session, the focus is placed on solid foods once hunger returns. These solid foods should be high-GI, alkaline carbohydrate foods (starchy vegetables and grains are permitted) and animal proteins. For long-term recovery, it is recommended that the athlete consume low-GI, nutrient-dense foods.[11]

The Zone Diet - 1995

Biochemist Barry Sears developed the Zone Diet to help dieters achieve “SuperHealth” which is defined as a state that reduces inflammation and prevents the development of chronic disease. The diet’s promises include: an improvement of mental clarity and satiety, maintenance of stable blood glucose levels, improved physical performance, and loss of excess body fat.[12,13] Sears believes that the macronutrient composition of a diet matters as much as, if not more than, its calories.

“The Zone” refers to a controlled range of insulin that optimizes weight control, satiety, and metabolic function.The Zone diet contains 1,000 to 1,600 calories per day for most people, because it is intended to burn energy from stored body fat. According to its author, the Zone is “protein-adequate,” “moderate carbohydrate” and low in fat. Sears is an advocate of moderation of carbohydrates, not drastically reducing them. Because food forms of grains did not exist 10,000 years ago, Sears believes that many humans are not adapted to consume them. In turn, excessive carbohydrate intake can cause the body to overproduce insulin. On this diet, fats assist in weight loss and lipolysis because they do not stimulate insulin secretion, they decrease the glycemic effect of carbohydrates, and they stimulate cholecystokinin, which stimulates satiety.

Following this diet involves eating three meals and two snacks, with less than five hours between them. The foundation of the Zone diet is determining a "protein prescription". This is accomplished by calculating body fat percentage, lean body mass, and activity level. Individuals with more lean body mass will need more protein to maintain it. Macronutrients are divided into "blocks" for portion control. 1 block of protein contains 7 g of protein. Examples include 1 oz meat, 1.5 oz fish, 2 egg whites, ¼ cup cottage cheese, or 3 oz firm tofu. A typical male needs 3-4 blocks per meal and 1 block for snacks. A typical female needs 2-3 blocks per meal and 1 block for snacks. Protein balance is crucial meaning the "protein prescription" is spread evenly across the day. To add muscle mass, a dieter can add one protein block per day. Carbohydrate blocks are matched to protein blocks. It is advised that carbohydrates come mostly in the form of fruit and vegetables, with grains and starches in moderation (no more than ¼ of total carbohydrate blocks). One carbohydrate block contains 9 g of "insulin-promoting" or digestible carbohydrate. Fat blocks are matched to carbohydrate and protein blocks. The focus is placed on polyunsaturated fats (omega-3, specifically) and monounsaturated fats while limiting saturated fats. One block contains 1.5 g of fat. Examples include 1 macadamia nut and 1/3 teaspoon of olive oil. If needed, calories can be increased by increasing fat blocks. This modification is advised for athletes. Most elite athletes following the Zone diet eat 40-45% of their calories in the form of fat.[12,13]

Fig 5. The Zone Food Pyramid[13]

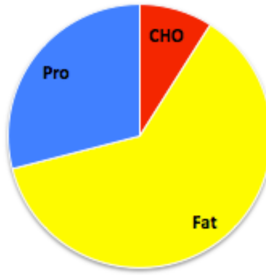
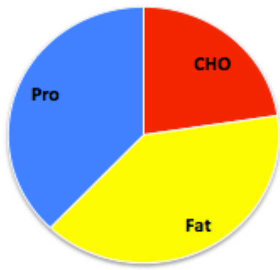
Atkins	**CHO:** 9% **Fat:** 62% **Pro:** 29%	
Paleo	**CHO:** 22.6% **Fat:** 39.5% **Pro:** 37.9%	
South Beach	**CHO:** 33% **Fat:** 40% **Pro:** 26%	
Zone	**CHO:** 37% **Fat:** 27% **Pro:** 35%	

Figure 6 Macronutrient distribution of LC diets[9-14]

Considerations

Understanding of the methodology and specifications of popular LC diets makes it easier to compare them and consider their implications for athletes. Two common characteristics exist between these diets: weight loss, and reduction in muscle glycogen availability. Additionally, LC diets are often tied to changes in hydration status, hormonal function, and risk factors for cardiovascular disease. All of these factors are relevant to athletic performance and require further exploration.

Weight loss and performance

For many sports, such as gymnastics, endurance events, and wrestling, athletes may seek ways to reduce excess body fat, improve endurance, and gain a competitive edge. LC diets are often sought out to accomplish this. Weight loss may be efficacious in athletes who truly can stand to lose excess body fat, but for athletes who are already quite lean (especially females) it may pose some dangers. Amenorrhea has been noted in studies of some studies of children following ketogenic diets.[15,16] Being in the catabolic, hypocaloric state necessary for weight loss raises some concerns as well. Athletes should seek to maintain or increase muscle mass, so it is crucial that any weight loss come from fat, and not the breakdown of protein. As fatigue is often associated with weight loss, this may also negatively impact performance.

A 30-day study of 9 male elite artistic gymnasts[4] tested the effect of a ketogenic diet on performance, specifically explosive strength. In the first part of the study, the gymnasts followed a modified ketogenic diet also known as a very low carbohydrate ketogenic diet (VLCKD), defined as 54.8% fat, 40.7% protein, and 4.5% carbohydrate. The second part of the study required the gymnasts to eat a more mixed diet, which was very similar to USDA recommendations (46.8% carbohydrate, 38.5% fat, and 14.7% protein). Before and after the dietary interventions, body composition was determined and various sport-specific strength tests (pull-ups, push-ups, and counter-movement jumps) were performed. No statistically significant changes were seen in athletic performance after dietary intervention. Body weight was significantly lower post-VLCKD, along with an increase in lean muscle mass. Respiratory quotients also decreased, confirming a metabolic shift towards utilizing more fatty acids.

It is important to note which of the popular LC diets are truly ketogenic. It is a common misconception that all low-carbohydrate diets are ketogenic, when in fact, most are considered too high in carbohydrates to allow for ketosis. A pair of studies featured in a review of LC diets[17] concerning the Atkins and South Beach diets confirmed that carbohydrates are strictly limited during induction to the point of ketosis. When followed correctly, the Zone and Paleo diets do not induce ketosis. Ketosis is confirmed by testing for urinary ketone excretion. Ketosis does elicit the weight loss promised by Atkins and South Beach, and may be primarily a result of water loss due to glycogen depletion and hyperventilation. The induction phase of such diets led to a 50% decrease in high-intensity exercise capacity, weight loss of about 3-4.5%, and elevated plasma ketone levels (200-300% of normal levels). The diminished exercise capacity as well as water and glycogen losses caused by initiating Atkins or South Beach should be considered by any serious exerciser wishing to follow these diets.

Beyond their effect on performance, one of the major debates concerning LC diets is the mechanism by which they cause weight loss. Is a calorie simply a calorie, or does its source determine its effect on metabolism? More often than not, low-carbohydrate diets are lower in calories than control diets. In the first 5 months of LC dieting, weight loss occurs more rapidly than with more traditional diet protocols, but after one year, weight loss is comparable between the two.[7] In a systematic review of low-carbohydrate diets[1], it was found that the participants who experienced the greatest amount of weight loss were those who ate the lowest calorie diets, followed the diet for the longest period of time, and had the greatest weight at baseline. Increased protein intake may also be a key factor in the satiating nature of low-carbohydrate diets.[7] Specifically, protein intakes of about 26% (rather than the usually recommended 15-18%) are effective for reducing appetite, which can contribute to improved weight control.

Reduced availability of muscle glycogen
Training with low levels of pre-exercise glycogen has been suggested as a method to enhance muscle glycogen stores and lessen reliance on carbohydrates during competition. Although promising in terms of training adaptations, this method has not been proven effective for performance enhancement, and may be deleterious to the health and performance of athletes involved in high-intensity activities.[18]

After a review of three randomized controlled trials (RCTs) and six randomized crossover trials, the Academy of Nutrition and Dietetics concluded that training with low carbohydrate availability can elicit some metabolic changes, but can negatively affect the intensity and duration of endurance training.[19] In an RCT by Hulston et al[20], low muscle glycogen availability caused increased fat oxidation in endurance athletes, but decreased training intensity. Camera et al[21] used a RCT to test the effect of glycogen depletion on anabolic signaling following resistance exercise, and found that depletion does not affect anabolism. By comparing glycogen-depleted runners after they ate either a high or low carbohydrate diet, Bartlett et alobserved a marked decrease in muscle glycogen stores in the low carbohydrate group.[22] A randomized crossover trial by Howarth[23] concluded that active male subjects on a low carbohydrate diet had a higher level of body protein breakdown after exercise than did athletes on a higher carbohydrate diet.

Hydration Status
Water loss is also a significant factor in the rapid weight loss seen in LC diets. For each g of glycogen the body stores, the body also stores 2.6 g of water. As water is normally stored with glycogen, a decrease in glycogen stores while following a LC diet would cause an increase in water loss. This is supported by studies that cite decreases in glycogen stores and elevated sodium excretion as a short-term effect of a LC diet. Losses of sodium and calcium are associated with water loss, and can lead to dehydration and bone demineralization.[24] Increased dehydration is an unfavorable outcome for athletes following a LC diet. Dehydration exacerbates thermal and cardiovascular exhaustion.[25] During

exercise, every 1% decrease in bodyweight due to fluid loss increases heart rate by three to five beats per minute.[26] In addition to physiologic changes, dehydration increases an athlete's rate of perceived exertion and decreases time to exhaustion.[26-28] Several studies show that a dehydration of 3-4% decreases muscular endurance performance[29-33] and aerobic power decreases at 3% dehydration.[33] Although the extent of dehydration in athletes following a LC diet is not yet well documented, this issue may be an important area for athletes to consider, as well as for researchers to explore further.

Hormonal function

Selecting low-glycemic foods is thought to attenuate insulin secretion and contribute to improvements in satiety and hormonal function. In theory, this may be an area worthy of further exploration, but in practice, GI and GL have not been shown to affect insulin response to meals in people with healthy BMIs.[7,35-37] In fact, insulin response may not contribute to weight gain, as many theories assert. Normally, a meal should be accompanied by an increase in insulin secretion. When insulin secretion is abnormally low, this metabolic dysfunction can be a predictor of weight gain.[7,38] When comparing dieters following low-carbohydrate to those following high-carbohydrate diets, there are no significant difference in fasting serum glucose or insulin levels.[1]

Additionally, high protein diets (30-40% of calories, as in Paleo and Zone) may result in an increase in cortisol, a hormone linked to stress. Little research is available on the stress response elicited by these types of diets when followed by athletes. This may be a crucial piece of information for understanding how high-protein, and subsequently low-carbohydrate diets affect athletic performance. The author of a study conducted on master endurance athletes following a two-week isocaloric Zone diet noted no changes in performance, but a significant number of participants reported they lacked energy and experienced more strain and fatigue after following this diet.[39] The same author conducted a more detailed study of master athletes following a four-week isocaloric Zone diet. The diet did not affect performance or insulin-to-glucagon ratio as claimed by Sears, but it did induce a reduction in body mass and an increase in resting cortisol concentrations.[40]

GI and GL are closely related to the methodology of LC diets, but the validity of these measures as they relate to hormonal function is questionable. At a 2005 workshop sponsored by the International Life Sciences Institute (ILSI) Technical Committee on Carbohydrates concerning low-carbohydrate diets, philosophies concerning the glycemic index were thoroughly discussed. It was concluded that measuring GI is extremely variable. When compared to glucose, foods themselves are variable, as is the body's glucose response in each individual. Based on current evidence, these limitations of the glycemic index and its derivatives, such as glycemic load, make this strategy unreliable.[7] The Academy of Nutrition and Dietetics also evaluated the claim that the GI and/or GL of foods may have a positive effect on exercise performance and metabolic measures related to exercise[41]. After examining 16 studies of endurance athletes, GI and GL were found to have no effect on performance or metabolic function.

Cardiovascular disease risk

Often, LC diets are called into question because of the high amounts of fat and protein they contain. More traditional dietary recommendations include consuming plenty of whole grains and reducing fat to decrease the risk of cardiovascular disease (CVD). Based on the available research, the relationship between LC diets and CVD risk is still unclear. LC diets do not seem to have a negative effect on some biomarkers of CVD, such as lipids. When carbohydrates are exchanged for protein instead of fat, triglyceride levels can be improved.[7,42-45] In terms of specific LC diets, ketosis-inducing LC diets have been associated with high levels of LDL cholesterol, uric acid, and free fatty acids, but do not seem to change levels of HDL cholesterol[24], however, during a six-week randomized controlled trial of 20 normal-weight men, Kraemer et al[46] found that six-week ketogenic diet does not negatively impact CVD risk profile, and may in fact improve some factors associated with dyslipidemia. Additionally, cholesterol levels often rise during the first few months of following the Atkins diet, but according to Atkins[9], they should level off after those two months.

Discussion

LC Diets are followed to elicit their proposed benefits, some of which are certainly reinforced by the current research. When followed correctly, LC diets are effective for short-term weight loss, mostly from fat. Reducing carbohydrate in the diet causes a decrease in glycogen availability, but this decrease is accompanied by an increase in fat oxidation. Weight loss, especially from fat, may be helpful for athletes who are overweight or can safely lose a small amount of weight. Studies of individuals following LC diets[1,4,7,17] report significant weight loss fairly consistently. Additionally, some of these studies did not report any decrease in athletic performance or post-exercise anabolic responses.

The findings on LC diets and their effect on biomarkers of CVD are very mixed. Some studies[7,42-45] report that LC diets can have a positive effect on blood lipids, while others[24,9] report negative changes. The subjects used in these studies may be one reason for the variance in results. As LC diets are primarily intended for weight loss, many studies have been conducted on their effect on participants that are overweight, obese, or have diabetes. It is reasonable to expect that the results of initiating a LC diet would be very different for a high-risk participant than a healthy participant. What can be drawn from these contradictory results is that more long-term studies need to be conducted with a variety of participants, including healthy people and athletes.

In addition to their benefits, LC diets come with their fair share of pitfalls. While fat loss may be advantageous for some athletes, athletes who are already very lean can be harmed by it. An important consideration for athletes is avoiding the female athlete triad (more recently referred to as Relative Energy Deficiency in Sport, which includes males).[47] This condition is evidenced by: amenorrhea, bone demineralization, and disordered eating (among other markers of dysfunction). These symptoms are all brought on by insufficient energy intake, and specifically, excessive fat loss. Before initiating a LC diet, athletes should consult with a physician or dietitian to discuss whether weight loss is appropriate for them. Additionally, rapid weight loss is associated with decreases in athletic performance parameters such as intensity, as well as increased fatigue. Athletes must consider whether they are able to afford diminishing their exercise capacity during training to achieve rapid weight loss.

Carbohydrate reduction causes glycogen stores to be diminished, which particularly affects athletes performing high intensity activities. Because muscle glycogen is the primary fuel for this type of exercise, LC diets that deplete glycogen stores, namely ketogenic diets, are inadvisable for people participating in weight lifting or sprinting activities.[48] Additionally, because of the decreased insulin levels brought on by ketogenic diets, muscle growth is curtailed while following them.[22] This means that ketogenic diets are appropriate for the maintenance of lean muscle mass, but not the building of it.[4] Ketogenic diets are sometimes advocated for use in endurance athletes as well as athletes where weight classes are a factor in competition (i.e. gymnasts, wrestlers). The proposed benefits of increased stamina and preservation of lean body mass with increased weight loss are appealing, but the potential drawbacks (possible fatigue, adherence, and efficacy of the intervention) are also worth exploring. Most studies[19,20,22] of athletic performance and LC diets have been conducted with endurance athletes. Research on strength and power athletes is very limited.

Glycogen depletion and decreases in weight caused by water loss lead to dehydration, which can negatively impact performance. High protein diets, which often coexist with LC dieting can increase cortisol concentrations, which have the potential to increase fatigue and slow recovery time. Overall, the stresses brought on by LC diets may make them inadvisable for athletes who do not truly need to lose weight.

Although LC diets can be discussed altogether, the benefits and drawbacks of specific LC diet models also merit discussion.The Atkins Diet is intended for significant, rapid weight loss, but it also allows the dieter to eat foods that feel decadent. Some studies cited by Atkins show that this diet may improve endurance performance. When followed correctly, this diet has the potential to be nutritionally sound, however, many dieters can misinterpret the diet. Following the diet correctly almost always involves supplements. If followed incorrectly, this diet may be extremely high in saturated fat and contribute to weight gain, plateaus, and unfavorable lipid profiles. Both the Atkins Diet and the South Beach Diet restrict carbohydrates to levels lower than many athletes need, namely during the initiation phase, which is severe. The diminished exercise capacity as well as water and glycogen losses caused by initiating Atkins or South Beach should be considered by any serious exerciser wishing to follow these diets. The South Beach Diet allows a greater variety of carbohydrates and nutrient-dense foods, and is lower in fat than Atkins, but will likely be too low in calories for athletes.

The Paleo Diet helps dieters eliminate nutrient-poor foods by not permitting the intake of processed and refined foods and emphasizing nutrient-dense foods instead. Despite this merit, this diet is extremely restrictive, cutting out large categories of foods otherwise seen as beneficial, which can result in significant nutrient deficiencies, such as calcium (provides an average of 69% of the RDA, according to *The Paleo Diet for Athletes*).[11] On average, the diet is even lower in carbohydrates than the South Beach Diet, which can cause diminished exercise capacity. If followed correctly, the diet has the potential to be nutritionally sound, but this requires significant planning and knowledge of nutrition to accomplish. As is mentioned in *The Paleo Diet for Athletes*, the training and competition today's elite athletes are involved in is far more intense than physical activities of prehistoric humans.[18,11] The "*Paleo for Athletes*" approach involves eating non-Paleo foods in conjunction with training and competition, so this calls into question whether the Paleo diet, unmodified, is truly the ideal diet for everyone to follow. If non-Paleo foods are acceptable for athletes to eat, why are they unacceptable for others?

The Zone diet results in restrictions and a caloric deficit for most dieters.[12,13] The close measurements involved in this diet help to safely control carbohydrate, fat, and protein intake, promoting moderation and balance. The measurement and planning involved in this diet may make it difficult for dieters to adhere to it. Generally, the diet meets AMDRs[14] and is effective for fat loss. Although the diet is more liberal than other LC diets, it restricts some nutrient-dense foods such as grains and dairy that may result in deficiencies. If not modified correctly to meet an athlete's needs, it may be too low in calories. If the diet is hypocaloric, the loss of body fat experienced may be excessive, especially for female athletes.

Conclusions

Low-carbohydrate diets have developed quite a following, and for some very sound reasons. Diets like Atkins, South Beach, Paleo, and Zone deliver on their promise of weight loss. By reducing carbohydrates, dieters can lose excess fat rapidly. Atkins, Paleo, and Zone also promise improved physical performance. The allure of being leaner and performing better is enticing to athletes, which is why many adopt LC diets. What many athletes do not realize is how reducing carbohydrates in their diet will affect their performance. Excessive weight loss may lead to dehydration, fatigue, slower recovery, and thus, decreased performance. Reduced carbohydrate intake leads to a decreased storage of glycogen in muscle tissue, which is essential for any athlete competing in an event requiring speed or power. This decreased muscle glycogen availability may not affect endurance athletes in the same way, as these efforts can be powered by lipolysis.

Specifically, the Atkins and South Beachdiets feature initiation phases that severely limit carbohydrates to an extent of ketosis that will not support an athlete’s normal training or competition needs. Dehydration often coincides with weight loss experienced following these diets, which can further impact performance. Dietary restrictions advocated by LC diets can often lead to energy and nutrient deficiencies. Of all of the LC diets discussed, the Zone diet is the most balanced, and provides the most carbohydrates to fuel the performance of athletes. Other diets may limit carbohydrates to the point of ketosis, which can be deleterious and even dangerous for the athlete if not closely monitored.

Before initiating a LC diet, an athlete must consider his or her priorities. Which is more important to being successful in their sport: weight loss, or performance?

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