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Carbohydrate Requirements for Exercise

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Think of carbohydrate as the body's gasoline supply — easily converted to motion in whatever amount is required. To satisfy the demand, as long as it lasts, there must be fuel in the tank. With low-carb diets currently being promoted for weight loss, food and beverage manufacturers are pushing the idea of fewer calories from carbohydrates as a good thing. The problem is, athletes — and even regular exercisers — can run out of gas.

Adequate carbohydrate stores are critical for optimum athletic performance. Carbohydrate is stored in three ways: muscle and liver glycogen, and blood glucose. Consuming adequate carbohydrate on a daily basis is necessary to replenish muscle and liver glycogen between daily training sessions and competitive events.

In this module, we'll discuss how carbohydrate is stored, made available and used, leading to recommendations for dietary carbohydrate consumption by exercisers and especially by athletes seeking optimum performance.

Carbohydrate availability

Muscle glycogen represents the major source of carbohydrate in the body (300 to 400 gm, or 1200 to 1600 kcal), followed by liver glycogen (75 to 100 gm or 300 to 400 kcal) and, lastly, blood glucose (25 gm or 100 kcal). These amounts vary widely between individuals, depending on factors such as dietary intake and state of training.

Untrained individuals have muscle glycogen stores that are roughly 80 to 90 mmol/kg of wet muscle weight. Endurance athletes have muscle glycogen stores of 130 to 135 mmol/kg of wet muscle weight. Carbohydrate-loading increases muscle glycogen stores to 210 to 230 mmol/kg of wet muscle weight (Jacobs and Sherman, 1999).

The energy demands of exercise dictate that carbohydrate is the preferred fuel for exercise intensities above 65 percent of VO_2max —the levels at which most athletes train and compete. Fat oxidation cannot supply adenosine triphosphate (ATP) rapidly enough to support such high-intensity exercise.

Muscle glycogen and blood glucose provide about half of the energy for moderate intensity exercise (65 percent of VO_2max) and two-thirds of the energy for high-intensity exercise (85 percent of VO_2max). It is impossible to meet the ATP requirements for high-intensity, high-power output exercise when these carbohydrate fuels are depleted (Coyle, 1995). The utilization of muscle glycogen is most rapid during the early stages of exercise and is exponentially related to exercise intensity (Hargreaves, 2006; Jacobs and Sherman, 1999).

There is a strong relationship between the pre-exercise muscle glycogen content and the length of time that exercise can be performed at 75 percent of $V0_2$max. The greater the athlete's pre-exercise glycogen content, the greater the endurance potential (Burke, 2006). Bergstrom and associates compared the exercise time to exhaustion at 75 percent of VO_2max after three days of three diets varying in carbohydrate content (Bergstrom *et al.,* 1967). A mixed diet (50 percent calories from carbohydrate) produced a muscle glycogen content of 106 mmol/kg and enabled the subjects to exercise 115 minutes. A low-carbohydrate diet (less than 5 percent of calories from carbohydrate) produced a muscle glycogen content of 38 mmol/kg and supported only one hour of exercise. However, a high-carbohydrate diet (more than 82 percent of calories from carbohydrate) provided 204 mmol/kg of muscle glycogen and enabled the subjects to exercise for 170 minutes.

Liver glycogen stores maintain blood glucose levels both at rest and during exercise. At rest, the brain and central nervous system (CNS) utilize most of the blood glucose and the muscle accounts for less than 20 percent of blood glucose utilization. During exercise, however, muscle glucose uptake can increase thirty-fold, depending on exercise intensity and duration. Initially, the majority of hepatic glucose output comes from glycogenolysis, however, as the exercise duration increases and liver glycogen declines, the contribution of glucose from gluconeogenesis increases (Jacobs and Sherman, 1999).

At the beginning of exercise, hepatic glucose output matches the increased muscle glucose uptake so that blood glucose levels remain near resting levels. Although muscle glycogen is the primary source of carbohydrate during exercise intensities between 65 and 75 percent of $V0_2$max, blood glucose becomes an increasingly important source of carbohydrate as muscle glycogen stores decline. When hepatic glucose output can no longer keep up with muscle glucose uptake during prolonged exercise, the blood glucose drops. Hypoglycemia occurs when the hepatic glucose output can no longer keep up with muscle glucose uptake during prolonged exercise (Hargreaves, 2006).

Liver glycogen stores can be emptied by a 15-hour fast and can fall from a typical level of 490 mmol on a mixed diet to 60 mmol on a low-carbohydrate diet. A high carbohydrate diet can increase liver glycogen content to about 900 mmol (Jacobs and Sherman, 1999).

Daily carbohydrate recommendations

Consuming adequate carbohydrate on a daily basis is necessary to meet the energy (calorie) requirements of the athlete's training program as well as replenish muscle and liver glycogen between training sessions and competitive events.

Costill and associates found a direct and positive relationship between the quantity of carbohydrate consumed (188 to 648 gm carbohydrate/day) and the amount of muscle glycogen synthesized during 24 hours of recovery from glycogen-depleting exercise. A diet providing 525 to 648 gm of carbohydrate (7 to 10 gm of carbohydrate/kg) promoted glycogen synthesis of 70 to 80 mmol/kg and provided near maximal repletion of muscle glycogen within 24 hours (Costill, *et al.,* 1981).

When adequate carbohydrate is not consumed on a daily basis between training sessions, however, the pre-exercise muscle glycogen content gradually declines and training or competitive performance may be impaired. Costill and colleagues evaluated glycogen synthesis on a 45 percent carbohydrate diet during three successive days of running 16.1 kg at 80 percent of VO_2max (Costill, *et al.,* 1971). Pre-exercise muscle glycogen levels started at 110 mmol/kg and fell to 88 mmol/kg on day two and 66 mmol/kg on day three.

The relationship between muscle glycogen depletion and exhaustion is strongest at moderate to high training intensities (65 to 85 percent of VO2max). A high carbohydrate diet is also necessary for optimal training adaptations and greater improvements in endurance performance in previously untrained individuals. Low blood glucose and low muscle and/or liver glycogen concentrations can contribute to fatigue during other types of exercise (Jacobs and Sherman, 1999).

It is apparent that a high carbohydrate intake acutely enhances recovery and improves endurance performance over 24 to 72 hours (Burke, 2006). Fallowfield and Williams reported that a high carbohydrate diet (8.8 gm/kg/day) restored endurance capacity within 22.5 hours of recovery between training sessions. An isocaloric diet containing less carbohydrate (5.8 gm/kg/day) was associated with decreased endurance (Fallowfield and Williams, 1993).

Although a high carbohydrate intake promotes greater recovery of muscle glycogen, only a handful of studies show chronic improvements in training outcomes over 11 to 28 days (Burke, 2006). Achten and colleagues (2004) found that a high carbohydrate diet (8.5 gm/kg/day) allowed better maintenance of physical performance and mood state during 11 days of intensified running training compared to a moderate carbohydrate diet (5.4 gm/kg/day). Simonsen and colleagues (1991) found that a diet containing 10 gm of carbohydrate/kg/day promoted greater muscle glycogen content and power output during training than a diet containing 5 gm of carbohydrate/kg/day over four weeks of intense twice-daily rowing training.

Until research shows otherwise, the evidence from studies of acute carbohydrate intake and performance remain the best estimate of the chronic carbohydrate needs of athletes. Overwhelming evidence indicates that carbohydrate supplementation before and during exercise improves performance. The use of short-term and training strategies to increase muscle glycogen stores (*e.g.* carbohydrate loading) also improves performance. Thus, a high carbohydrate diet is still the best recommendation for athletes (Burke, 2006; Jacobs and Sherman, 1999).

Carbohydrate recommendations for athletes range from 5 to 12 gm/kg/day. Athletes engaged in moderate during, low-intensity training should consume 5 to 7 gm of carbohydrate/kg/day). During moderate to heavy endurance training, athletes should consume 7 to 12 gm of carbohydrate/kg/day. Athletes participating in extreme endurance training for 4 to 6 hours/day should consume 10 to 12 gm of carbohydrate per day. These general recommendations should be fine-tuned with consideration to the athlete's total energy needs, specific training needs and feedback from their training performance (Burke, 2006; Burke, *et al.,* 2004).

Athletes should consume sufficient calories in addition to carbohydrate. Consumption of a reduced energy diet will impair endurance performance due to muscle and liver glycogen depletion. Costill and colleagues studied the effects of 10 days of increased training volume at a high intensity on muscle glycogen and swimming performance (Costill, *et al.,* 1988). Six swimmers self-selected a diet containing 4700 kcal/day and 8.2 gm of carbohydrate/kg/day, while four swimmers self-selected a diet containing only 3700 kcal/day and 5.3 gm of carbohydrate/kg/day. These four swimmers could not tolerate the heavier training demands and swam at significantly slower speeds, presumably due to a 20 percent decline in muscle glycogen.

Some athletes may need to significantly reduce fat intake to obtain 7 to 12 gm of carbohydrate/kg/day. Sugar intake may be increased to meet the increased carbohydrate requirement, but the majority of the carbohydrate should come from nutrient-dense carbohydrates (whole grain products, legumes, fruits, vegetables, and low-fat dairy products).

Adequate carbohydrate intake is also important for athletes in high-power activities such as wrestling, gymnastics, and dance (Walberg-Rankin, 1995). Athletes in high-power activities often want to lose weight and so consume low-energy diets. Inadequate energy intake can harm high-power performance due to impaired acid-based balance, reduced enzyme levels in the anaerobic pathway, selective atrophy of fast-twitch muscle fibers, and abnormal muscle contractile function. Adequate dietary carbohydrate may ameliorate some of these damaging effects of energy restriction on the muscle (Walberg-Rankin, 1995).

Athletes participating in ultra-endurance events (those lasting over 4 hours) have the highest carbohydrate requirements. Saris and colleagues studied food intake and energy expenditure during the Tour de France (Saris, *et al*., 1989). In this demanding 22-day, 2,400 mile race, the male cyclists consumed an average of 850 gm of carbohydrate per day or 12.3 gm/kg/day. High carbohydrate beverages (high carbohydrate energy drinks, sports drinks, sodas, and liquid meals) provided about 30 percent of the total carbohydrate consumed.

A study of Tour of Spain male cyclists by Garcia-Roves and colleagues (1998) found that the cyclists consumed an average of 842 gm of carbohydrate or 12.6 gm of carbohydrate/kg each day during the 21 day, 2250 mile race. The researchers noted that carbohydrate intake of the cyclists following competition (1.1 gm of carbohydrate/kg per hour for 6 hours), helped to promote muscle glycogen restoration.

Grams versus percentages

Nutrition guidelines for the public usually express goals for carbohydrate intakes as a percentage of total energy. For example, the Food and Nutrition Board of the Institute of Medicine established an Acceptable Macronutrient Distribution Range (AMDR) for carbohydrate at 45 to 65 percent of energy. While this general guideline may be appropriate for sedentary people, it is not always appropriate for athletes.

The absolute quantity of carbohydrate, rather than the percentage of energy from carbohydrate, is important for optimal glycogen synthesis and exercise performance (Burke, 2006). The recommendation to consume 5 to 10 gm of carbohydrate/kg/day is user-friendly and takes into consideration the athlete's body weight. It is relatively easy for an athlete to determine the carbohydrate content of meals and snacks to achieve a daily carbohydrate goal of 500 gm. It takes far more knowledge of nutrition to create a diet plan that provides 60 percent of energy from carbohydrate. It is also difficult for an athlete to visualize meals and snacks that meet this recommendation.

Another problem with using percentages is that the athlete's energy and carbohydrate requirements are not always matched. Athletes who have large muscle masses and heavy training regimens generally have very high energy requirements and can meet their carbohydrate needs with a lower percentage of energy from carbohydrate. When an athlete consumes 4000 to 5000 kcal/day, even a diet providing 50 percent of energy from carbohydrate will supply 500 to 600 gm of carbohydrate per day. This translates into 7 to 8 gm of carbohydrate/kg for a 70 kg athlete, which should be adequate to maintain muscle glycogen stores from day to day.

Conversely, when a 60 kg athlete consumes less than 2000 kcal per day, even a diet providing 60 percent of energy from carbohydrate (4 to 5 gm/kg/day) is unlikely to provide sufficient carbohydrate to maintain optimal carbohydrate stores for daily training. This situation is particularly common in female athletes who restrict energy intake to achieve or maintain a low body weight or percentage of body fat.

All in all, it is more reliable and practical to recommend that athletes consume an absolute quantity of carbohydrate (5 to 12 gm/kg/day) rather than a relative percent of energy from carbohydrate (45 to 65 percent). Attention must also be paid to achieving energy balance and to adequacy of protein and fat intake, especially over time.

Glycemic Index and Glycemic Load

A high-carbohydrate food may be classified by the type of carbohydrate (simple versus complex), by the form of carbohydrate (liquid versus solid), or by the glycemic index (GI) of the carbohydrate (low, moderate, or high).

The "simple" versus "complex" classification and "liquid" versus "solid" classifications do not indicate the effect of carbohydrate-rich foods and fluids on blood glucose and insulin levels. The GI classification, however, shows the effects of carbohydrate-rich foods and fluids on blood glucose and has an effect on insulin levels (Burke *et al*., 1998). Factors other than glycemic index also affect insulin levels.

The GI provides a way to rank carbohydrate-rich foods according to the blood glucose response following their intake. The GI is calculated by measuring the incremental area under the blood glucose curve following ingestion of a test food providing 50 gm of carbohydrate, compared with a reference food (glucose or white bread). All tests are conducted after an overnight fast (Burke, *et al.,* 1998).

Generally, foods are divided into those that have a high glycemic index (glucose, bread, potatoes, breakfast cereal, sports drinks), a moderate glycemic index (sucrose, soft drinks, oats, tropical fruits such as bananas and mangos), or a low glycemic index (fructose, milk, yogurt, lentils, pasta, nuts, cold climate fruits such as apples and oranges). Tables of the glycemic index of a large number of foods were published in the *American Journal of Clinical Nutrition* in 2002 (Foster-Powell *et al*., 2002).

The GI reflects the rate of digestion and absorption of a carbohydrate-rich food. Thus, the GI is influenced by the food form (including particle size, presence of intact grains, texture, and viscosity), the degree of food processing and cooking, the presence of fructose or lactose (both have a low glycemic index), the ratio of amylopectin and amylose in starch (amylose has a slower rate of digestion), starch-protein or starch-fat interactions, and the presence of antinutrients such as phytates and lectins (Burke *et al.,* 1998).

While the GI provides a reliable and consistent measure of relative blood glucose response to carbohydrate-rich foods and meals, the concept has practical limitations. The GI is based on equal grams of carbohydrate (50 gm), not average serving sizes, and the available numbers are largely based on tests using single foods. The blood glucose response to high GI foods may be blunted when combined with low GI foods in the meal (Burke, *et al.,* 1998). Although the GI can be applied to mixed meals by taking a weighted mean of the GI of the carbohydrate-rich foods that make up the meal, this is not very practical.

Some practitioners suggest that manipulating the GI of foods and meals may enhance carbohydrate availability and improve athletic performance. For example, low GI carbohydrate-rich foods may be recommended before exercise to promote sustained carbohydrate availability. Moderate to high GI carbohydrate-rich foods may be recommended during exercise to promote carbohydrate oxidation and after exercise to promote glycogen repletion. However, Burke and colleagues (1998) note that the total amount of carbohydrate consumed is the most important consideration for replenishing glycogen stores following daily training sessions and competitive events.

Perhaps more useful than glycemic index is the concept of glycemic load (GL) which considers both glycemic index and the amount of carbohydrate consumed (GL = GI (expressed as a decimal) times dietary carbohydrate content in grams). Since the carbohydrate content in an actual serving size is considered, the GL of a food is almost always lower than its corresponding GI. Although using the glycemic index to choose an individual food may be helpful in certain situations, glycemic load provides an overview of the daily diet and can be used to compare day-to-day intake (Foster-Powell *et al.,* 2002).

While the GI may be useful in sports by helping to find tune food choices, it should not be used exclusively to provide guidelines for carbohydrate and food intake before, during, and after exercise. Other features of foods such as nutritional content, palatability, portability, cost, gastrointestinal comfort, and ease of preparation are also important. Athletes should choose foods according to their nutritional goals and exercise situation (Burke, *et al.,* 1998).

Carbohydrate is fuel, and subject to pretty simple biochemical rules. Understanding these rules, concepts and calculations can help fitness professionals clear up the many misconceptions about carbohydrate being promulgated in the news and advertising.

Examples of high carbohydrate foods are shown in the chart on the following page.

Examples of High-Carbohydrate Foods

Food	Carbohydrate (gm)	Kcal
Apple	21	81
Apple juice (1 cup)	28	111
Applesauce (1/2 cup)	60	232
Bagel	31	165
Banana (medium)	27	105
Bread sticks (4)	30	154
Bread (whole wheat) (2 slices)	24	122
Cereal (cold ready to eat) (1 oz)	24	110
Cereal (oatmeal) (1 packet)	25	110
Corn (1/2 cup)	21	89
Carrot (1 medium)	8	31
English muffin	30	154
Fig bar (1)	10	50
Graham crackers (2 squares)	11	60
Granola Bar (low-fat, 1)	16	109
Milk (low-fat, 1 cup)	12	121
Oatmeal raisin cookie	9	62
Orange (1 medium)	16	65
Orange juice (1 cup)	26	112
Pancake (1)	9	61
Pear (1 medium)	19	75
Pizza (cheese, 1 slice)	39	290
Popcorn plain (1 cup, popped)	6	26
Potato (large)	32	139
Pretzels (1 oz)	21	106
Pudding (1/2 cup)	30	161
Raisins (2/3 cup)	79	302
Refried beans (1/2 cup)	23	135
Rice (1 cup)	50	223
Spaghetti (1 cup)	34	159
Strawberries (1 cup)	11	45
Tortilla (flour)	15	85
Waffle (2 waffles)	17	120
Yogurt (fruit, 1 cup)	42	225
Yogurt (frozen, low-fat, 1 cup)	34	220

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Examination for CRE10

1. __________ represents the major source of carbohydrate in the body:

A, Liver glycogen
B. Muscle glycogen
C. Blood glucose
D. Pyruvate
E. None of the above

2. Exercise above 65 percent of $V0_2$max is primarily fueled by:

A. Carbohydrate
B. Fat
C. Protein
D. Blood glucose
E. None of the above

3. Endurance athletes in heavy training should consume _________

A. 2 to 3 gm of carbohydrate/kg/day
B. 4 to 5 gm of carbohydrate/kg/day
C. 5 to 7 gm of carbohydrate/kg/day
D. 7 to 12 gm of carbohydrate/kg/day
E. None of the above

4. Ultraendurance cyclists in the Tour de France consumed about:

A. 6 gm of carbohydrate/kg/day
B. 8 gm of carbohydrate/kg/day
C. 10 gm of carbohydrate/kg/day
D. 12 gm of carbohydrate/kg/day
E. None of the above

5. Athletes, engaged in moderate duration, low-intensity training should consume a diet that provides:

A. 50 to 60 percent of kilocalories from carbohydrate
B. 60 to 70 percent of kilocalories from carbohydrate
C. 5 to 7 gm of carbohydrate/kg/day
D. 7 to 12 gm of carbohydrate/kg/day
E. 500 to 600 gm of carbohydrate per day

6. A 70 kg soccer player should consume *at least*:

   A. 350 gm of carbohydrate/day
   B. 490 gm of carbohydrate/day
   C. 50 to 60 percent of calories from carbohydrate
   D. 60 to 70 percent of calories from carbohydrate
   E. None of the above

7. A 70 kg marathon runner should consume *at least:*

   A. 350 gm of carbohydrate/kg/day
   B. 490 gm of carbohydrate/kg/day
   C. 50 to 60 percent of calories from carbohydrate
   D. 60 to 70 percent of calories from carbohydrate
   E. None of the above

8. Foods that have a high glycemic index:

   A. Fructose, milk, yogurt, lentils, pasta, nuts, apples and oranges
   B. Sucrose, soft drinks, oats, bananas and mangos
   C. Glucose, bread, potatoes, breakfast cereal, sports drinks
   D. B and C
   E. None of the above

9. Consumption of a reduced energy diet will impair endurance performance due to:

   A. Dehydration
   B. Muscle glycogen depletion
   C. Liver glycogen depletion
   D. A and B
   E. B and C

10. Negative energy balance can harm high-power performance due to:

   A. Impaired acid-base balance
   B. Reduced glycolytic enzyme levels
   C. Selective atrophy of Type II muscle fibers
   D. Abnormal sarcoplasmic reticulum function
   E. All of the above

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