Bioenergetics

IN THIS CHAPTER

Energy Value of Food
ATP
Creatine Phosphate
Glycolysis
Aerobic Metabolism
Energy Depletion
Energy
The first scientific law of thermodynamics states that energy cannot be created nor destroyed. Instead, it is transferred from one form to another. All biological functions require energy, and therefore, living matter requires energy to sustain life. For instance, plants use energy from sunlight, water, and CO2 to form carbohydrates, proteins, and fats using chlorophyll in the process of photosynthesis. The energy is stored in the bonds that connect the molecules. Carbohydrates can be manipulated to form proteins and fatty structures in plants and animals. When humans eat plants and animal products, the energy is transferred from one organism to another. The energy transferred in food is called a calorie. The calorie represents the quantity of heat necessary to raise the temperature of 1 g of water 1° Celsius. The calorie represents an extremely small measure of energy. If it were used as the unit for food energy on nutritional labels, the energy value per gram of a nutrient would be expressed in the thousands. For this reason the United States uses the kilocalorie. The kilocalorie (kcal) represents 1000 calories, or the measurement of heat required to raise 1 kg (1L) of water 1° Celsius. To avoid consumer confusion, the labels use the word calorie, but the value actually reflects kilocalorie units. The international unit of energy is the kilojoule, which is equal to 4.2 kilocalories.

Energy Value of Food
The energy value of food is determined by the respective heat of combustion yielded when it is burned. There are slight variations in the heat created between foods composed of similar energy substrates. For practical purposes, a food’s energy value is rounded to a whole number. For instance, fat values vary between animal lipids (mean = 9.5 kcal) and plant lipids (mean = 9.3 kcal). Food labels list fat as containing 9 kcal per gram. Likewise, the arrangement of atoms in carbohydrates determines the net value of the food. Glucose has a very simple molecular structure and therefore is valued at 3.74 kcal per gram, whereas complex carbohydrates such as glycogen and starch are valued at 4.2 kcal per gram. Protein variations in energy value are based on the type and nitrogen content of the particular protein. On average, protein yields 5.65 kcal of energy when burned.

The net energy yielded when foods are consumed by the body sometimes differs from the value identified through direct calorimetry (12). This is particularly true for foods containing nitrogen. Nitrogen yields energy when burned, but in the body, it is combined with hydrogen to form urea, which is excreted through urine. For this reason, proteins, which contain nitrogen, actually reflect a value of 4.6 kcal of body energy. Due to the fact that carbohydrates and fats do not contain nitrogen, their respective energy value is consistent between direct calorimetry and the consumed value. The net energy of food is also affected by the digestive and absorption process, referred to as the coefficient of digestibility. The coefficient of digestibility reflects the total energy the body has available from the food it consumes. Certain components of food are indigestible and pass through the body as excrement. Fibrous food reduces digestibility by as much as 5-10% in some foods (5). The fiber cannot be broken down and speeds transportation through the intestines, thereby reducing absorption time (37). Plant proteins seem to yield the lowest coefficient of digestibility, whereas animal products seem to yield the highest measured levels (13; 28). In general, 97% of carbohydrate, 95% of lipid and 92% of protein energy is absorbed by the body for fuel.

Atwater general factors represent the value food is assigned for nutritional purposes. The average net value for protein and carbohydrate is set at 4 kcal per gram and dietary fats are valued at 9 kcal per gram. Alcohol also contributes to energy intake when consumed. Pure alcohol is valued at 7 kcal per gram (ml). When the weight of each energy nutrient is
known, the calories can be determined for a select food or meal. Food labels attempt to clearly identify the energy value in foods and are expressed in both weight (g) and energy (kcal).

When food is consumed, the body breaks it down through the process of digestion. It then absorbs the energy substrates and either stores the energy in a state of potentiality (potential energy) or uses it to fuel biological activity (kinetic energy). The specific use of the energy is identified when changes in energy demands occur. Biological activity changes the form of energy based on its particular need. For instance, stored energy is released for mechanical work, while some is spared as chemical energy or released as heat energy. Recall, the first Law of Thermodynamics suggests the energy is not lost, it is just transferred as one reaction releases heat and energy (exothermic reaction) and another absorbs heat and energy (endothermic reaction).

**ATP**

The only form of energy that can be directly used for muscular contractions is Adenosine Triphosphate (ATP). The fuel for mechanical, chemical, and transport work all relies on the energy released from the high energy phosphate bonds within the ATP molecule. When the bonds are broken, energy is released into the system and cultivated for a particular action. ATP can be thought of as being “spring-loaded” with energy that can be released upon enzymatic hydrolysis of the bonds that connect the phosphate molecules. Enzymes serve as biological catalysts and are usually named for the functions they perform. ATPase is the enzyme responsible for the breakdown of the ATP molecule inside the cell. The suffix (–ase) identifies the substance as an enzyme.

When ATP is split for mechanical work, the action takes place deep within the muscle fiber at the level of the myofilaments. Myosin, the thick myofilament, holds the ATPase enzyme. In the presence of calcium, myosin binds with actin, forming crossbridges. When the crossbridges are formed, the catalyst reaction of the enzyme essentially cleaves off the end phosphate ion from the ATP molecule, leaving a by-product of ADP and an inorganic phosphate. The energy released causes the myosin to detach from the actin filament. This permits the movement of the myosin head, so it can expel the energy by-products and reattach to actin further along the filament. This process allows myofilaments...
within the sarcomeres of muscle fibers to lengthen and shorten to produce force. Thousands of muscle fibers contract within a whole muscle, causing joint action in response to the energy released from the phosphate bonds of ATP. Therefore, calories expended during exercise can serve as an indirect measurement of ATP molecules being split during muscular work and other metabolic processes.

ATP is derived from the metabolism of carbohydrate, fat, and protein fuel substrates. However, ATP for immediate work is stored in small quantities in the cell. This ATP is readily usable and therefore, is the primary source of energy for fast rate, powerful work. The energy potency of the molecule allows for high speed reactions. Maximal muscular work, lasting 1-3 seconds, will exploit stored ATP for energy. Examples of activities relying on stored ATP include a maximal vertical jump, pitching a fast ball, or swinging a driver on the golf course.

**Creatine Phosphate**

Due to the rapid depletion of stored ATP, the muscle maintains an additional pool of high energy phosphate storage in the form of intracellular creatine. Creatine is phosphorylated with an inorganic phosphate ion to form a high energy bond molecule called creatine phosphate (CP). When ATP becomes depleted, the first reaction to replenish the energy needed for continued muscular work is the splitting of CP by the enzyme creatine kinase (CK). CK breaks the high-energy creatine phosphate bond, which releases energy to re-phosphorylate intracellular ADP molecules. During the re-phosphorylation process, ADP binds with an inorganic phosphate molecule to resynthesize ATP for energy. After this occurs the newly formed ATP molecule is split, and energy to drive the cell continues. Creatine phosphate concentrations in the cell are 4-6x that of ATP, allowing for approximately 10-15 seconds of available high-power energy to drive burst activities, such as 3 maximal repetitions in weight lifting, a 40 yard dash, or a 100 meter sprint.

**CP Energy Sequence**

1) Creatine Phosphate is split by Creatine Kinase.
2) The liberated phosphate uses the released energy to bind ADP and P.
3) The new ATP molecule is split into ADP and P, and energy is released.

Phosphates are connected with very high energy bonds, and when they are connected in the form of ATP or CP, they are heavy molecules. This explains why the body does not maintain high levels of storage. Excessive storage would weigh down the body tissue. Instead, the body resynthesizes ATP after the bonds have been separated by ATPase. Thus, perpetual energy can be formed from lighter molecules rather than storing the weighty ATP in the cell. When exercise discontinues after a single maximal effort, it takes the body at least 90 seconds to fully refuel (64). It does so by rephosphorylating the ADP with the liberated phosphagen ions. When CP is required to fuel the mechanical work being performed, it too is depleted, and consequently, the high-power energy source runs out. CP replenishment can take between 2-5 minutes (63; 66). The phosphorylation periods required to re-establish ATP and CP stores in the muscle ultimately determine rest periods between heavy resistance training and sprinting activities. At maximal lifted loads or running speeds, the period of time between sets equals the time it takes to replenish the energy. Power exercises such as Olympic lifts and plyometrics, as well as heavy strength training, utilize low repetition numbers and longer rest periods to maximize the performance in the phosphagen energy system (65).

**Glycolysis**

ATP cannot be supplied through blood or other tissues, relying on other energy substrates to form its usable biological structure. It is easy to phosphorylate ATP from CP because the phosphagen is simply being mobilized from one molecule to another. But when phosphagen energy runs out and the body continues to demand ATP for work, the energy has to come from another source. Carbohydrates are the next fuel the body uses to create ATP. However, this energy must be derived from glucose, a 6-carbon sugar molecule, and this process takes several steps and numerous catalysts to accomplish. In fact, the energy derived from sugar requires 10 enzymatic reactions, whereas CP and ATP only use one enzyme. In the anaerobic process known as glycolysis (sugar-splitting), these ten controlled chemical reactions are required so that ATP can be synthesized and energy metabolites can be made available for ongoing work. Recall, CP can rapidly
donate a phosphate to ADP to form ATP; however due to the three-step process a level of power drop-off occurs. Thus, it makes sense that the ten-step process causes an even greater decline in maximal power output, and that the energy released from ATP produced from glycolytic means is less than the energy provided by immediate sources. This explains why a person is able to lift more weight for five repetitions than he or she can for ten repetitions. The energy system employed determines the maximal force output.

The breakdown of carbohydrates, like most reactions, uses water as an assistive catalyst with enzymes to fracture glucose into its respective parts outside of the mitochondria. Anaerobic glycolysis is unique in that glucose is the only carbon-fuel nutrient that can be used to yield energy without the use of oxygen. Fats and proteins cannot be used anaerobically. However, fat, protein, and glucose can all be used to produce energy via aerobic metabolism inside the mitochondria. Here, the hydrogen ions are essentially pulled off of the different carbon fuels and transferred to molecular oxygen to make water (H₂O). Since the anaerobic breakdown of glucose through glycolysis occurs without oxygen, water is not made and the liberated hydrogen ions remain free in solution, increasing the acidity of the surrounding environment.

Most of the energy generated through this exergonic reaction is not sufficient to form high-bond ATP and is lost to the body as heat. The products of glycolysis include two (2) molecules of ATP and two energy substrates, lactic acid or pyruvate. Although the efficiency of the process is only about 33%, significant energy can be derived from anaerobic glycolysis due to the high concentrations of glycolytic enzymes present in the muscle tissue and the speed of the associated reactions (11; 30). The ATP derived from this system is the major contributor to activities of maximal effort lasting up to 90 seconds (11; 16). Therefore, anaerobic glycolysis is the primary energy system to fuel the average weight lifting set.

When exercisers experience the onset of a burning sensation in active tissue, it is due to insufficient oxygen, not acid pain. Lactic acid is essentially the buffer for the hydrogen by-product of muscle that has become ischemic, receiving insufficient oxygen supply compared to the oxygen demand (48). Muscle ischemia causes pain, similar to the pain experienced if you placed a rubber band on the end of your finger to occlude blood flow. During moderate levels of activity, where the rate of energy utilization is matched by energy re-synthesis, the cellular pH stays in balance. However, during intense work, ischemia occurs, and the excess hydrogen builds up (59). This leads to a drop in pH which may inhibit enzymatic reactions, alter calcium handling, and lead to intrinsic muscular fatigue (60). The lactic acid that is produced can be transferred to a neighboring cell that is not ischemic and can be oxidized to yield additional energy (44). Lactic acid can also be transported in the blood to other skeletal muscles, the liver, or to the heart, where it can be metabolized (47). Although this can occur during exercise, lactic acid utilization is a marked component of the recovery phase.

It would seem that lactic acid is a consequentially detrimental byproduct of glycolysis, but this view would be short-sighted (7). Ongoing exercise requires large amounts of ATP from metabolic sources to sustain the work production. The body has contingency plans for all the substrate byproducts from metabolism. In this way, the body has potential energy stores ready to be converted to kinetic energy as dictated by exercise duration and intensity. Due to the fact that very little ATP is produced from glycolysis and that the

~Key Terms~

**Enzymes** - A protein that catalyzes a biochemical reaction or change.

**Creatine phosphate** - An organic compound found in muscle tissue and capable of storing and providing energy for muscular contraction.

**Creatine kinase** - An enzyme present in muscle and other tissues that catalyzes the reversible conversion of ADP and phosphocreatine into ATP and creatine.

**Re-phosphorylate** - The process of adding an inorganic phosphate back to a molecule such as ADP.

**Anaerobic** - The process of energy production in the body in the absence of freely available oxygen.

**Glycolysis** - A metabolic process that breaks down carbohydrates and sugars, through a series of reactions to either pyruvic acid or lactic acid, releasing energy for the body in the form of ATP.
carbohydrate substrates pyruvate and lactate are left over from the glycolytic process, the body can utilize the potential chemical energy by converting the carbon skeletons back to glucose in the liver (4). Lactate and pyruvate enter a biochemical process of gluconeogenesis called the Cori cycle. In this process the body can utilize the lactic acid from high-intensity activities to help preserve blood glucose levels which are crucial to physiological function, particularly in the brain, which, despite making up approximately 2% of the body’s mass, represents 50% of blood glucose utilization (3). The remanufactured glucose from exercise byproducts can also be used to replenish liver and muscle glycogen stores (51).

To improve exercise performance at high intensities and to reduce the reliance on the lactic acid system, exercisers should specifically train in the glycolytic pathways by recruiting larger and faster motor units. These motor units require near maximal efforts to be recruited and primarily use anaerobic glycolysis to produce ATP to fuel them. With more frequent recruitment, such as with interval training or more intense resistance training, these muscle fibers will have a greater tolerance to fatigue. This is often referred to as “lactic acid tolerance,” which seems somewhat paradoxical since the adaptation results in less lactic acid production at absolute exercise intensities. Analysis of training adaptations of glycolytic (anaerobic) muscle fibers reveals that recruitment of these fibers actually leads to improved aerobic adaptations, including oxygen delivery and utilization (27). Other adaptations include increased oxidation of lactic acid and more efficient lactate removal.

The body maintains ATP levels through metabolic processes that take place either in the cytosol of the cell or in the mitochondria. Anaerobic processes occur in the cytosol and use fuel from phosphocreatine, glucose, glycogen, glycerol (e.g. from triglyceride), and deaminated amino acids. The anaerobic processes can contribute to maximal biological work lasting approximately 3 minutes. For activities lasting beyond 3 minutes, ATP re-synthesis is achieved primarily by

~Quick Insight~

Lactic acid has been blamed for delayed onset muscle soreness (DOMS), cramping, and as an inhibitor to recovery from exercise. It is often considered to be a negative waste product from high intensity work. The reality is that none of these statements is true. Lactic acid is produced when glucose is metabolized. The breakdown leaves lactate and hydrogen ions as by-products. The hydrogen ions may build up under conditions of rapid metabolism and increase the acidity of the environment which may interfere with the electrical signals from motor neurons, slow enzymatic reactions, and impair muscle contractility. To the contrary, the lactate is a treasured fuel (7). It is rapidly produced and easily used by tissue. The heart, slow twitch muscle fibers, and postural muscles thrive on lactate because it is easily shuttled into the cell without insulin (40). Lactate rapidly moves across the cell membrane through a process called facilitated transport, enabling the body to use the lactate without the detrimental effects of insulin in the blood (46).

Lactate is produced in greater quantities when exercise intensity exceeds 50% of VO₂max. The production is linear with the rise in intensity as fast twitch fibers preferentially rely on carbohydrates as the fuel. As the lactate is produced, it is used by the muscle or transported to other tissues via general circulation. The increased blood flow with exercise effectively mobilizes the lactate for use by different tissues. Liver glycogen storage is maintained in part by the gluconeogenic activity to create glycogen for lactate. Equally important, lactate in the blood maintains available energy for working tissues (53). Unlike the liver, muscle tissue cannot free up glycogen stores to aid other working tissues due to a missing enzyme. Lactate can provide the needed assistance via circulatory delivery to muscles that need energy. The transport and use of lactate is often considered the “second wind” because more energy becomes available (49).

If the intensity of exercise becomes too elevated, the hydrogen ions produced inhibit muscle contractions. With quick recovery, the production removal balance is restored and training can continue. Training in the presence of lactic acid improves one’s performance through more efficient management of the lactate and removal of the hydrogen (7). Intense resistance conditioning, like plyometrics and sprints, intervals, and hill climbs produce large quantities of lactic acid and stimulate the body to produce enzymes that increase the rate of lactic acid utilization.

Blaming lactic acid for cramps, delayed onset muscle soreness (DOMS), and as an obstacle to recovery is simply ignorant. Cramps are not caused by a sugar metabolite, but more likely, the over-excitation of nerves from fatigue and intra/extracellular electrolyte imbalance. DOMS is an inflammatory response to cellular damage, ischemia, and tonic spasm, not from leftover lactic acid. Likewise, recovery is not inhibited by lactate (9). The body has already used the leftover lactic acid for fuel before the next bout of exercise has even occurred. Lactate is a friend of intensity. If there is a foe, it’s the hydrogen ion, and even that has been shown to be important for energy metabolism.
cellular oxidation via the **aerobic system**. This refers to the mitochondrial oxidation of fatty acids (fats), pyruvate from glucose (carbohydrates), and some deaminated amino acids (protein). Cellular oxidation is a process that is the reverse of photosynthesis, where plants take CO₂ and H₂O to produce O₂ and glucose, lipids, and protein.

At the onset of exercise, oxygen consumption undergoes a transitional phase in an attempt to meet the new demand. Physiological actions transpire to equalize the oxygen requirement of the activity and the available oxygen at the cell.

When the utilization of oxygen matches the demand, the body is said to reach metabolic **steady state**. During the transitional process, cells do not have the energy needed from oxygen sources and therefore, must borrow fuel from anaerobic sources in a phase referred to as **oxygen deficit**. This term quantitatively expresses the difference between the total oxygen consumed during an exercise bout and the actual amount of oxygen required. It is important to understand that exercise is not a product of switching on and off different energy systems, but rather a smooth blending and overlap of energy transfer from one pathway to another. With exercise training, the process of energy transfer among pathways becomes smoother, allowing trained individuals to reach steady-state sooner, consequently improving performance.

When exercise stops, the body is in a temporary state of disruption, compared to its normal resting state. **Recovery oxygen consumption** (also referred to as oxygen debt) persists after exercise and represents the excess oxygen consumption needed to recover from the physical activity and return the body to resting homeostasis. For example, after a vigorous set of squats a weight-lifter will be consuming greater levels of oxygen (notice greater ventilation rates following the lift) than those he or she was consuming prior to the set. During short aerobic bouts of exercise at a mild intensity, about 50% of the recovery oxygen will occur within 30 seconds after the exercise is completed. This is termed the “fast component” and is used primarily to re-synthesize high-energy phosphates and replenish oxygen in the body fluids and muscle stores (myoglobin). Intense exercise and exercise of long duration causes an additional, longer lasting phase of excess post-exercise oxygen consumption (EPOC; slow component) which can last up to 24 hours following exercise (33). It is attributed to: 1) the elevated body temperature persisting post-exercise; 2) ion-leakage across cell membranes, leading to greater reliance on active ionic transport across the membrane to preserve homeostasis; 3) mitochondrial calcium uptake during exercise, reducing aerobic efficiency; 4) increased levels of thermogenic hormones existing post-exercise; 5) the re-synthesis of glycogen in the liver from lactate; and 6) the oxidation of the lactate in the mitochondria. Even transient bouts of high intensity exercise, such as interval training and weight lifting can produce recovery oxygen periods lasting greater than an hour (18).

The work rate, oxygen availability, and enzymatic profile of the muscle cell determines the primary energy system relied on to perform an exercise. Practically, a trainer will be able to observe the effects of work rate (intensity) on energy system demand. If the intensity is too high, aerobic contributions will not be enough to sustain the reaction and the exercise will stop. This explains why heavier resistant loads can only be lifted for a short period of time and for a minimal number of repetitions. If activities are being performed beyond three minutes, the force, expressed as percentage of 1RM, will need to be relatively low. Energy will still be applied anaerobically by glucose, but aerobic activity will be the primary contributor. As the aerobic system contributions increase, the maximal force output will decline. This stems from the inhibitory actions of rising hydrogen ion concentration from the breakdown of glucose, as well as the decline in rapid energy metabolism from the anaerobic system. The number of enzymatic reactions necessary to produce ATP from energy substrates and oxygen slows the speed and degree of force production.
~Quick Insight~

A person rowing on an ergometer as fast as he or she can will travel through the energy pathways and decline in force output as the weaker energy systems are activated. The ATP-CP used in the first 10 seconds will correspond with the highest output. A decrease in force output begins to occur as lactic acid accumulates. If the intensity of force production is significantly above anaerobic threshold the activity speed will deteriorate because increasing aerobic contributions cannot produce adequate power to continue the activity. The decline in anaerobic energy availability is met by an equal increase in energy production from aerobic sources. The rate of movement declines linearly with the decreasing anaerobic energy due to consequential decreases in force outputs. As mentioned earlier, the greater the contribution from aerobic sources, the greater the decline in movement rate.

**AEROBIC METABOLISM**

The previous section identified that the body transitions very smoothly from one energy system to rising contributions from another. With the ongoing performance of activity, the transition from anaerobic metabolism to aerobic metabolism is initiated by the pyruvate left over from glycolysis as it is transferred to the mitochondria in the cell. We know that the mitochondria serve as manufacturing plants, housing enzymes and substrates used to make cellular fuel. When the pyruvate enters the mitochondria, it sparks the reaction called the **Citric Acid Cycle**, or **Krebs Cycle**. The Krebs cycle refers to the process in which ATP is formed using oxygen and energy substrates or **oxidative phosphorylation**. A simplified way to understand mitochondria would be to view them as blenders. Inside the organelle the body takes glucose, adds in some oxygen, then blends it through 11 reactions and spits out 36 molecules of ATP, water, carbon dioxide, and heat.

The mitochondrial density in the muscle cell directly relates to the amount of energy that can be produced through aerobic means. In aerobic exercise, the three largest determinants of efficiency are 1) the number of mitochondria, 2) the concentration of enzymes inside them, and 3) the amount of oxygen rich blood which can be delivered to the cell. These efficiency factors also represent the adaptations to muscle tissue when aerobic exercise is routinely employed. The metabolic pathway is characterized by the release of hydrogens and carbon dioxide as the carbohydrate and oxygen are transformed through the metabolic process.

~Key Terms~

**Mitochondria**- An intracellular organelle responsible for generating most of the ATP required for cellular operations.

**Exergonic reaction**- A chemical reaction where the variation of free energy is negative, identifying the direction that the reaction will follow.

**Lactic acid**- An energy substrate produced during the metabolic breakdown of glucose.

**Pyruvate**- An energy substrate deemed as the end product in glycolysis.

**Fatigue**- Physical or mental weariness resulting from exertion.

**Lactate**- The buffered form of lactic acid which can serve as an additional energy source.

**Gluconeogenesis**- The generation of glucose from other organic molecules like pyruvate, lactate, glycerol, and amino acids (primarily alanine and glutamine).

**Cori cycle**- Refers to the recycling of lactate or lactic acid produced by muscle during anaerobic metabolism. The lactate is converted to glucose by the liver.

**Oxygen deficit**- The difference between oxygen uptake of the body during early stages of exercise and during a similar duration in a steady state of exercise, sometimes considered as the formation of oxygen debt.

**Aerobic system**- The body’s ability to produce energy (ATP) in the presence of freely available oxygen.

**Recovery oxygen consumption**- The amount of extra oxygen required by muscle tissue during post-exercise recovery from vigorous activity.

The same process can be performed using lipids and proteins. When the body works at lower intensities, lipids are the primary source of energy in aerobic metabolism. For instance, when a person sits on the couch to watch TV or sits at their desk at work on a computer, approximately 70% of the aerobic energy comes from lipid metabolism. One might think this would cause people to lose weight. However, at rest, we burn very few calories per hour, so the contribution is minimal. During exercise, the system works the same way. Low level exercise (40-60% of maximal aerobic output) utilizes fat as the preferred fuel for energy (42). During low to moderate exercise, it takes approximately
10 minutes of continuous movement for lipids to significantly contribute to aerobic energy.

In order for fat to be used as a fuel, it must first be released into its individual parts. **Triglycerides** represent 90% of the fat stored in the body in adipose tissue. **Lipase** is the enzyme which, in the presence of water, splits triglycerides into a glycerol molecule and three **fatty acids** through a process called **lipolysis**. The fatty acids hold the predominance of energy to be used by the muscle cell. These fatty acids bind to plasma **albumin** to form **free fatty acids** (FFA) in the bloodstream where they can be transported to working tissue. Lipids can also be delivered by **lipoproteins** and freed to be used as fuel. The more blood flow to the tissue, the greater the propensity for fat to be burned for energy. Individuals who routinely engage in aerobic exercise enhance their ability to use lipids because they have more mitochondria and capillaries. These adaptations improve glucose sparing and increase exercise capacity. Additionally, exercise mediates lipid use through the adrenal hormones epinephrine and contributions from GH and glucagon. In Chapter 4, we learned that hormone augmentation was a factor in training adaptation. This further emphasizes the importance of participating in routine exercise for increased lipid metabolism (41).

When the lipids reach the cell, they have two pathways into oxidative phosphorylation. The glycerol molecule enters the same way glucose does by forming pyruvate. Remember, all these molecules are carbon chains of hydrogen and oxygen, so they can donate or accept ions to become something else. The triglycerides cannot enter as easily, they have to first enter a process called **beta oxidation** in the mitochondria. Fatty acid molecules must be reduced to smaller components before entering the Krebs cycle as **acetyl CoA**. Beta oxidation continues until the entire fatty acid molecule has been broken down and used. Through the process, a triglyceride molecule can yield 460 ATP, which is 10 times more energy than a glucose molecule can provide. The glycerol contributes to 19 ATP, while the three fatty acids provide 441 ATP. Clearly, lipids are a valuable source of energy for prolonged work.

**Key Terms**

**Citric acid cycle**- A series of enzymatic reactions in the mitochondria, involving oxidative metabolism of acetyl compounds, which produce high-energy phosphate compounds (ATP) that are the source of cellular energy.

**Oxidative phosphorylation**- The formation of ATP from the energy released by the oxidation of various substrates, especially the organic acids involved in the Krebs cycle.

**Triglycerides**- Consists of a glycerol and three fatty acids bound together in a single large molecule; an important energy source forming much of the fat stored by the body.
When the work rate increases, the body again shifts to a greater reliance on glucose metabolism through both anaerobic and aerobic pathways, which is faster, and can therefore provide a more efficient and powerful energy source. A person on a Stairmaster who performs high intensity intervals will notice the change as the muscles in the legs begin to burn and fatigue due to the increasing presence of hydrogen ions from glucose metabolism. For improvements in aerobic capacity, carbohydrates are a necessary fuel because they allow for training at higher intensity. Limited physiological adaptations occur at low intensities, and once they do occur, there will be no new improvements unless the demands of exercise increase.

When the demands of exercise are prolonged, the body can also elicit assistance from amino acids, freed from protein sources (15). Cortisol released during exercise will remove proteins from tissue, particularly the branched chain aminos (61). They are transported to the liver where they are deaminated into carbon skeletons. This ability also exists in the muscle itself, in a process called transamination. Enzymes, which break down amino acids in the cell, increase as an adaptation response with endurance training. Depending on the type of protein and subsequent amino acids released, the route to entry into the Krebs cycle can be through several mechanisms (62). Amino acids can be turned into pyruvate, acetyl CoA, or enter through hydrogen ion exchange called electron transport. During prolonged exercise, the preferred method is in the form of pyruvate. It should be noted that adequate carbohydrates are needed for protein to positively contribute to carbohydrate reserves. When proteins are deaminated, nitrogen is removed. Therefore, a byproduct of protein metabolism is urea. This increases the fluid intake requirements so urea can be mixed with water and passed from the body as urine.

**ENERGY DEPLETION**

When exercise intensity is low, it is sustained by lipid metabolism so that glycogen reserves may be spared. When the intensity is elevated to sustained, moderately-high performances or intermittent, high-intensity bouts, glycogen reserves become depleted with increasing exercise duration (16). The particular fiber depletion rate is specific to the intensity of the exercise. Shorter duration bouts, such as one minute sprints or heavy weight training deplete fast-twitch fibers. In contrast, the slow twitch fibers become depleted during continuous bouts of moderately high intensity. As it would be expected, depletion is a factor of recruitment. An interesting fact, related to cellular energy depletion, is that glycogen depletion is more rapid in trained individuals than untrained individuals in short all-out bouts of exercise. This is due to the faster conversion of glucose to lactic acid. Higher lactate levels signify higher power outputs. This emphasizes, again, the relative importance of energy specific training.

Fatigue sets in when the body experiences significant decline in glycogen stores. Even during aerobic exercise where adequate oxygen and fat is available, a lack of sugar in the system will lead to a fatigue condition and impaired performance. It is fairly obvious that during

~Key Terms~

**Lipase-** An enzyme capable of breaking down a lipid (fat) molecule.

**Fatty acids-** Form part of a lipid molecule and can be derived from fat by hydrolysis, often with a long aliphatic tail (long chains), either saturated or unsaturated.

**Lipolysis-** The breakdown of lipids.

**Albumin-** A blood protein produced in the liver that helps to regulate water distribution in the body.
anaerobic activities, glycogen depletion is related to direct use of the fuel. Since fats and proteins cannot support anaerobic exercise, when the sugars are gone, performance capabilities are lost. But this is also true of submaximal aerobic exercise. Even at levels where oxygen and lipids are adequate to meet the intensity demands of the work, the lack of carbohydrates in the body will cause significant fatigue (14). In endurance sports, this is referred to as hitting the wall. It is likely that the need for glucose to run the nervous system is a key component to the fatigue (19). It is also probable that the slow rate of lipid metabolism and the need for pyruvate to initiate oxidative phosphorylation causes inefficiency in the system (32). Insufficient carbohydrate intake leads to early decline in performance (23).

When inadequate carbohydrate consumption occurs for an extended period of time, the metabolic systems become dysfunctional (17). A lack of carbohydrate means a reduced quantity of pyruvate in the mitochondria (21). The lack of pyruvate means oxaloacetate (byproduct of pyruvate metabolism) is not available to bind with acetyl CoA to enter the Krebs cycle. Fatty acid metabolism will only occur when sufficient oxaloacetate is available for acetyl CoA in the process of betaoxidation (20). This presents two problems: 1) lipid metabolism yields only about half the power as that of carbohydrates and 2) when carbohydrates are not available, lipid metabolism is slowed. With a lack of carbohydrate availability, lipids are predominantly required for ATP formation aerobically. In this environment, central fatigue (neural) occurs, as does peripheral fatigue (muscular) (35). If this is an on-going occurrence due to a low carbohydrate diet or a diet insufficient in calories, it causes a back-up in the system. The delivery of free lipids has nowhere to go, and acetyl CoA does not have a binding partner due to insufficient oxaloacetate to enter the Krebs cycle. This causes the two compounds to build up in the tissue. In response to increasing concentrations, the liver responds by converting these compounds into ketone bodies. These ketones enter circulation and are either excreted in urine or build up and negatively affect the pH levels of body fluid. Extreme cases lead to acidosis.

Acute depletion of anaerobic sources is specific to the intensity and duration of the training as well as pre-exercise storage. Stored ATP and CP depletion is similar in untrained and trained individuals, but as stated earlier, the higher lactate tolerance in trained individuals accounts for the more rapid decline in peripheral glycogen reserves and higher power outputs. In acute peripheral fatigue, increased lactic acid formation creates an acidic environment (54). The increasing acidity negatively affects the cellular activity because enzymes function at specific pH levels (55). The low pH inactivates enzymes for energy metabolism and negatively effects contractility, causing the muscles’

~Quick Insight~

The body has natural buffers to counteract the shift in pH which occurs in glycolytic pathways during exercise performance. The declining pH levels adversely affect enzyme activity and likely serve an inhibitory response to contractility. In lower-intensity activities, lactic acid is buffered into its salt lactate and taken to the liver to reformulate glucose. When production of lactic acid is met by equal buffering mechanisms, a fairly static pH equilibrium exists and there are no metabolic consequences. With increasing intensities the tissue produces more lactic acid than can be buffered by normal means. If the body does not compensate, the acid levels in the blood can reach high levels, dropping pH down to 6.8 from its comfortable 7.4. This generally is the point of physical exhaustion. Individuals will suffer nausea, headaches, cramps, and even disorientation (52). At this point, the body shuts down to allow the acid to be buffered in a process to regain homeostasis.

To prevent this from occurring, the body will increase its buffering capabilities through chemical, renal, and ventilatory adjustments. Chemical buffering is enhanced by an increase in bicarbonate formation and phosphate buffers (45; 50). Renal buffering occurs by a shift in the rate of reabsorption of buffering agents with a concurrent increase in the number of hydrogen ions released into urine. Ventilation can also serve to buffer the blood by increasing the rate of carbon dioxide released by the body, consequently reducing carbonic acid concentrations, increasing fluid alkalinity (6; 22).

Some theorize that buffering adaptations may occur in response to near maximal or maximal training efforts lasting 1-2 minutes. This though, has not been clearly established. Additionally, the use of sodium bicarbonate and sodium citrate solutions prior to 1-2 minute all out exercise bouts has been tested in experiments, showing some benefits. More research is needed, but the solutions seem to have a positive effect on hydrogen efflux from the cells. No benefit has been shown in events lasting less than one minute, so it has little implication for traditional strength training.
force output to decline (10). The change in the enzymes’ surroundings is not an energy depletion-type of fatigue because a relatively short rest interval will remove the limiting factor. Peripheral fatigue associated with depletion of energy stores occurs relatively quickly during intense exercise because glucose (the primary fuel in intense exercise) is used up fairly rapidly. Performance decline is linear to glycogen decline in the muscle (34). When different muscles are used, as seen in resistance training, the rate of decline is inversely consistent with the amount of tissue used for work. Dispersing the work over many tissue areas avoids rapid depletion in individual muscle groups. Isolated muscle group activity, like repeated sprint training or lower body plyometrics, can only be performed at high intensity for short training bouts due to the localized depletion.

The body attempts to refuel depleted tissues by releasing sugar into the blood from the liver. Muscle stores of glycogen in unused tissues cannot be liberated in the presence of glucagons. Skeletal muscle cells do not contain the enzyme needed for glucose release into the blood (phosphatase), as it is only found in the liver. When excessive sugars are being used, the body will attempt to reserve some glucose for the central nervous system (56). Decline in performance mirrors both glycogen depletion and attempts to reserve glucose by reducing its availability through endocrine mediators and increasing fat substrates as a fuel. When glucose is not available to serve all the actions of exercise, peripheral fatigue will be joined with central fatigue (58). The lack of glucose affects the nervous system and communication signals decline in speed and strength (36). Without strong signals from the nervous system, exercise performance notably declines (57). Even though the body can produce glucose through gluconeogenesis in the liver, the by-products of fat metabolism cannot create sugar for the nervous system. Amino acids will support some level of glucose maintenance, but this most often occurs through catabolic means. Once this level has been reached, exercise is futile.

In attempts to maximize exercise performance, the most important component is the fuel available in the body. Although a high carbohydrate low fat meal consumed 3 hours before an event aids in available energy, to promote glycogen storage for subsequent events, it seems it is more important for exercisers to consume adequate energy post-exercise (1; 39). The physiological environment in the tissues causes a notable increase in energy substrate uptake immediately post-exercise. Scientists suggest that cellular permeability and heightened hormone sensitivity allows for increased storage capacity of glucose and protein in the three-hour period post exercise (38). Early literature in this area suggested that high amounts of carbohydrates (up to 500 g) should be consumed in 3-4 post-exercise meals (24; 26; 43). Higher glycemic foods were recommended to allow for glucose availability within the metabolic window following exercise.

The latest findings suggest that post-exercise muscle glycogen storage can be further enhanced with a carbohydrate/protein meal or supplement due to the interaction of the carbohydrate and protein on insulin secretion (2; 29; 70). Studies analyzing carbohydrate-protein recovery mixtures found increases in both carbohydrate and protein uptake occurred above that of the carbohydrate-only solutions (25; 68; 69). Additional research indicates that the rate of recovery is coupled with the rate of muscle glycogen replenishment and suggests that recovery supplements should be consumed to optimize muscle glycogen synthesis as well as fluid replacement post-exercise (31; 67). A key note to post-exercise replenishment is that the quantity of calories should reflect the intensity (8). Low to moderate efforts do not significantly deplete glycogen stores, so increasing post-exercise consumption of calories may not be warranted. In heavy resistance training and endurance bouts, energy and fluid replenishment is very important for subsequent bouts of training.

~Key Terms~

**Free fatty acids**- When fatty acids are not attached to other molecules, they are known as "free" fatty acids.

**Lipoproteins**- Compounds of protein that carry fats and fat-like substances, such as cholesterol in the blood.

**Beta oxidation**- is the process by which fats are broken down in the mitochondria to generate Acetyl-CoA, the entry molecule for the Citric Acid Cycle.
What Happens to Excess Macronutrients

Lipids
- Glycerol → Pyruvate → Acetyl-CoA → Fatty Acids → Fat Cells

Carbohydrates
- Glucose → Pyruvate → Acetyl-CoA → Fatty Acids → Fat Cells

Protein
- Amino Acids → NH₂ → Pyruvate → Acetyl-CoA → Glycerol
~Key Terms~

**Acetyl CoA** - A compound that functions as a co-enzyme in many biological acetylation reactions and is formed as an intermediate in the oxidation of carbohydrates, fats, and proteins.

**Amino acids** - Basic organic molecules consisting of hydrogen, carbon, oxygen, and nitrogen that combine to form proteins.

**Branched chain aminos** - Including leucine, isoleucine, glutamine, aspartic acid, and valine; used as fuel during long-term exercise bouts.

**Deaminate** - To break down a protein by removing an amino group.

**Transamination** - The transfer of an amino group from one molecule to another without the intermediate formation of ammonia.

**Electron transport** - A series of oxidation-reduction reactions during the aerobic production of ATP.

**Oxaloacetate** - The buffered form of oxaloacetic acid that binds with acetyl-CoA to enter the citric acid cycle.

**Acute peripheral fatigue** - Fatigue during physical work, caused by an inability of the body to supply sufficient energy to the contracting muscles to meet the increased energy demand. This causes contractile dysfunction that is manifested in the eventual reduction or lack of ability of a single muscle or local group of muscles to do work.

**Central fatigue** - The central component to fatigue generally described as a reduction in the neural drive or nerve-based motor command to working muscles that results in a decline in the force output.

---

**Chapter Five References**


Bioenergetics


56. Secher NH, Quistorff B and Dalsgaard MK. [The muscles work, but the brain gets tired]. Ugeskr Laeger 168: 4503-4506, 2006.

57. Secher NH, Quistorff B and Dalsgaard MK. [The muscles work, but the brain gets tired]. Ugeskr Laeger 168: 4503-4506, 2006.

58. Secher NH, Quistorff B and Dalsgaard MK. [The muscles work, but the brain gets tired]. Ugeskr Laeger 168: 4503-4506, 2006.


