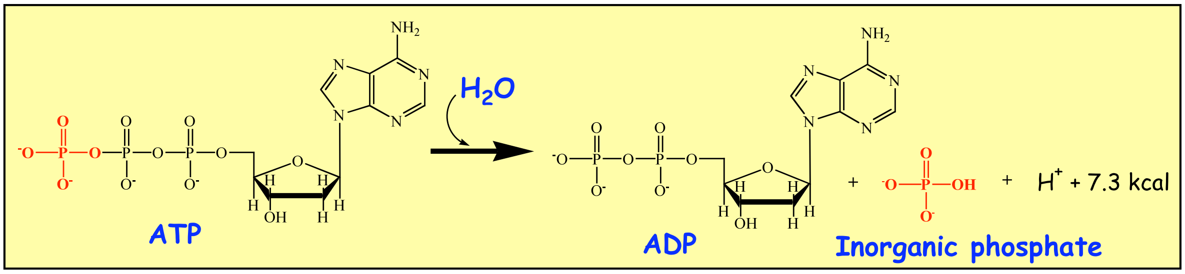
Chapter 3

Energy Production

The reason that we eat, besides the fact that food can be so delicious, is for energy and building blocks. Although energy cannot be created or destroyed, its form can change. During metabolism, our bodies break down fuel molecules and trap the energy released within the molecule adenosine triphosphate (ATP). In this chapter, we examine the energy transformations that occur during metabolism.

ATP, the Cell's Energy Currency

During exercise, muscles are constantly contracting to power motion, a process that requires energy. The brain is also using energy to maintain ion gradients essential for nerve activity. The source of the chemical energy for these and other life processes is the molecule **ATP**. ATP contains potential energy that is released during its hydrolysis, or reaction with water. In this reaction, the bond linking the terminal phosphate group (shown below in red) is broken, ATP is converted to *ADP* (adenosine diphosphate), and 7.3 Cal (kcal) of energy is released. This energy can be used to power the cell's activities, like muscle contraction.



The energy requirements of an individual vary widely with the activity being performed (Table 1). During periods of heavy exertion, energy demands increase dramatically, particularly by muscles. However, the muscle's supply of ATP is sufficient to power vigorous activity for only a second or two.

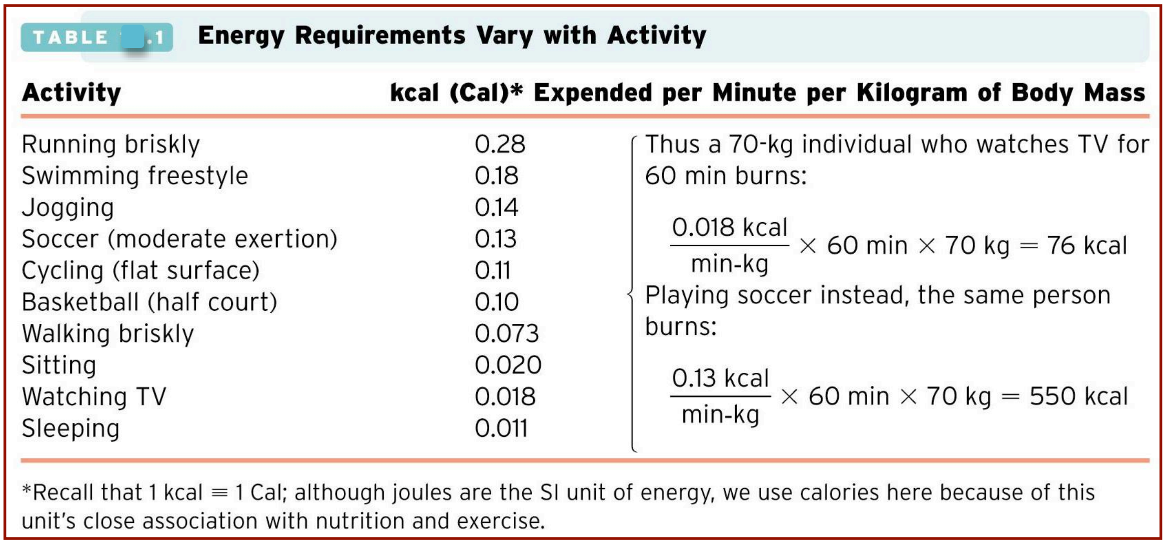


TABLE [redacted].1 Energy Requirements Vary with Activity

Activity	**kcal (Cal)* Expended per Minute per Kilogram of Body Mass**
Running briskly	0.28
Swimming freestyle	0.18
Jogging	0.14
Soccer (moderate exertion)	0.13
Cycling (flat surface)	0.11
Basketball (half court)	0.10
Walking briskly	0.073
Sitting	0.020
Watching TV	0.018
Sleeping	0.011

Thus a 70-kg individual who watches TV for 60 min burns:

$$\frac{0.018\ \text{kcal}}{\text{min-kg}} \times 60\ \text{min} \times 70\ \text{kg} = 76\ \text{kcal}$$

Playing soccer instead, the same person burns:

$$\frac{0.13\ \text{kcal}}{\text{min-kg}} \times 60\ \text{min} \times 70\ \text{kg} = 550\ \text{kcal}$$

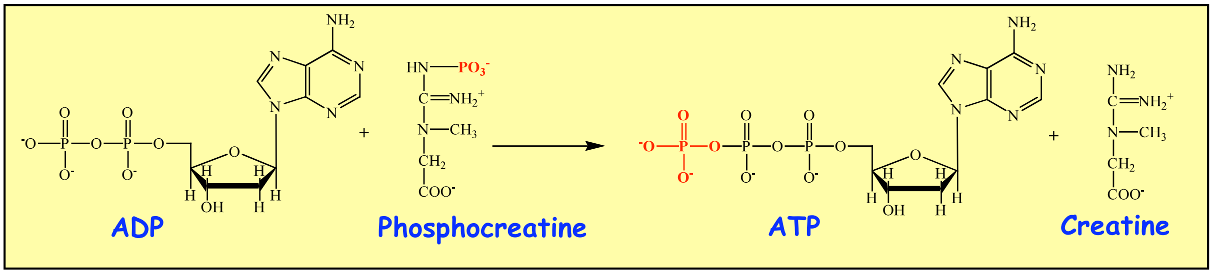
*Recall that 1 kcal ≡ 1 Cal; although joules are the SI unit of energy, we use calories here because of this unit's close association with nutrition and exercise.

When the muscle's supply of ATP is exhausted, it can be resynthesized from ADP in three ways:

1. via phosphorylation by phosphocreatine
2. via anaerobic metabolism
3. via aerobic metabolism

Phosphocreatine

Phosphocreatine is a secondary reserve of energy that can quickly generate more ATP from ADP as follows:



In this reaction, a phosphate group (in red) is transferred from phosphocreatine to ADP to form ATP very rapidly, allowing muscle contraction to continue for about 10 seconds. When phosphocreatine is depleted, the muscles must turn to metabolism of fuel molecules to produce more ATP to power physical activity.

Aerobic versus Anaerobic Activity

Exercise can take many forms, from yard work to a leisurely afternoon walk to a punishing regime in the weight room. At the molecular level, we can divide all exercise into two general categories: **aerobic** and **anaerobic** exercise. Aerobic activity, which involves sustained effort such as distance running and walking, occurs when the body has sufficient oxygen available to oxidize fuel molecules for energy. Anaerobic activity, which involves quick bursts of effort like weightlifting and sprinting, occurs in the absence of sufficient oxygen for the aerobic pathway. The types of fuels that can be used differ, depending on the type of exercise that we're doing.

Fuels that Power Exercise

In addition to the fuels that we consume in the form of food on a regular basis, our bodies also have reserves of energy that are called upon during exercise. Recall that chemical energy is stored primarily as lipids, commonly called fats, and carbohydrates. We also eat proteins, although we do not have expendable protein stores in our body. Let's briefly review the major classes of food molecules (Figure 1).

Carbohydrates

Animals store carbohydrates as *glycogen*, a polysaccharide consisting of thousands of glucose units covalently linked together. Glycogen reserves, which represent the body's "quick" form of energy, are found in the muscles and the liver. They are first broken down to glucose before undergoing further metabolism. Glucose can then be further processed to release energy under both anaerobic and aerobic conditions.

Fats

Fats are stored as *triglycerides*, molecules that contain a single glycerol unit linked to three fatty acid units. Most of our fat stores are found in adipose tissue, but other organs, including muscles, also have small reserves to fuel their ongoing needs. Triglycerides, which account for about 84% of the total energy stores in the average individual, are degraded to fatty acids (and glycerol) before being further metabolized. Fatty acids can undergo only aerobic metabolism.

Proteins

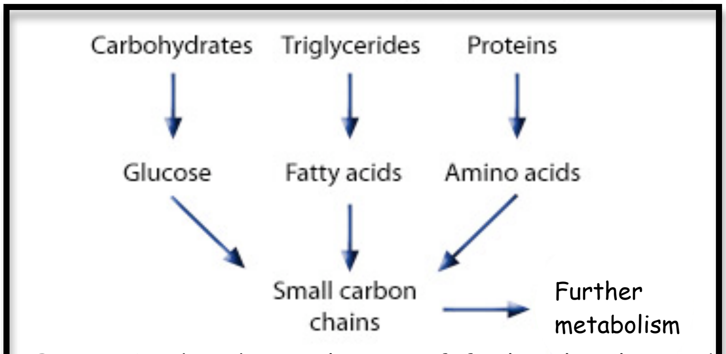


Figure 1. The three classes of fuel molecules and how they are broken down during metabolism.

While dietary protein can also be degraded for energy, we have very little expendable protein reserves. In dire circumstances, such as a precipitous drop in blood sugar levels, skeletal muscle will actually be broken down despite potentially disastrous consequences. This occurs primarily to fuel the brain, which needs a constant source of energy in the form of glucose. Animals lack a metabolic pathway that can make glucose from fats, but most amino acids can undergo conversion to glucose. Thus, skeletal muscle may be sacrificed when glycogen stores are depleted.

Energy Content

Glucose and triglycerides are normally broken down to release energy through *oxidation* to carbon dioxide, with oxygen undergoing *reduction* to water in the process. Recall that redox reactions involve the transfer of electrons from one substance to another. **In reactions involving electron transfer there cannot be an oxidation without a reduction.**

During aerobic metabolism, animals obtain energy for essential life processes through the oxidation of carbon-containing nutrients such as glucose ($C_6H_{12}O_6$):

$$C_6H_{12}O_6 + 6\ O_2 \rightarrow 6\ CO_2 + 6\ H_2O$$

This reaction illustrates that there are several ways to think about redox reactions. We can think about oxidation as loss of electrons, as gain of oxygen (hence the name), or as loss of hydrogen. Reduction is just the opposite: gain of electrons, loss of oxygen, or gain of hydrogen. $C_6H_{12}O_6$ (glucose) is *oxidized* in the last reaction because carbon gains bonds to oxygen and loses bonds to hydrogen in its conversion to CO_2. If glucose is oxidized, then O_2 (oxygen) must be *reduced* as it is the only other reactant, and oxidation is always paired with reduction. Indeed, oxygen gains hydrogen atoms during the conversion to H_2O, meeting the third criterion for reduction.

If we examine the structure of a representative carbohydrate, like glucose, in comparison to a representative fat, like lauric acid ($C_{12}H_{24}O_2$), we can account for the different energy contents of these fuels. Many of the carbon atoms in glucose are bonded to oxygen, meaning that they are initially more oxidized than the carbons in fat (Figure 2). Therefore, only 4 kcal of energy per gram are released upon oxidizing carbohydrates versus 9 kcal per gram for fats. That is, fats represent a more efficient means of storing energy because they are more highly reduced, thereby releasing more energy upon oxidation.

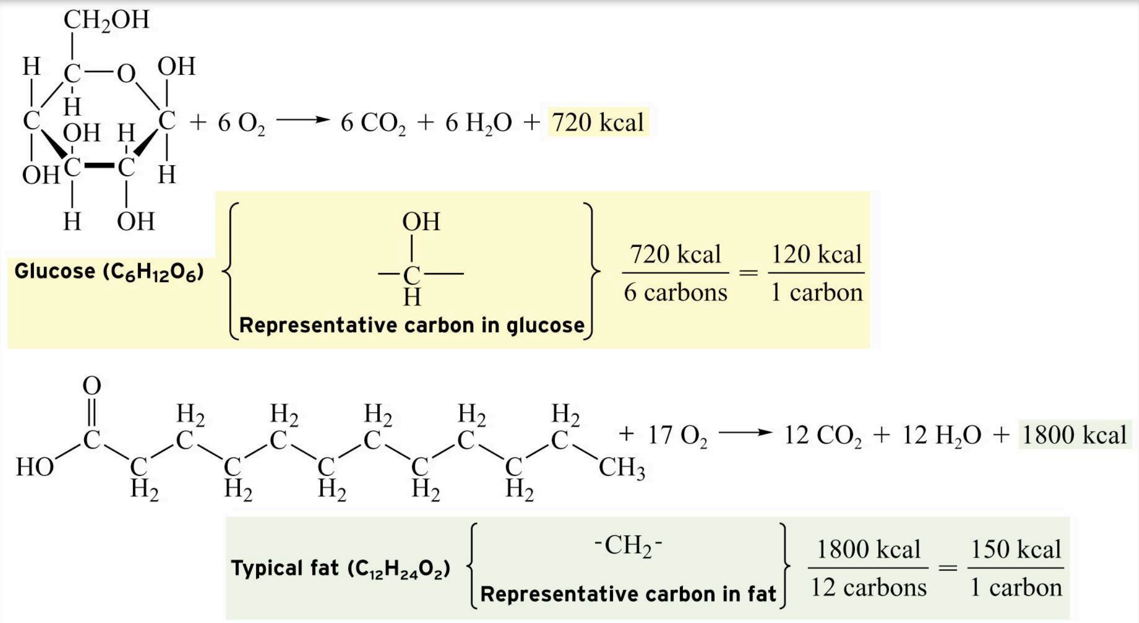


Figure 2. Energy is released through oxidation of fuels during aerobic metabolism. Carbohydrates start out with the carbons already partially oxidized, so they release less energy during metabolism than fats.

Mobilization of Fuels

When muscles exhaust their stores of readily available ATP and phosphocreatine, the next fuel of choice is glucose, either from blood sugar or the muscle's own glycogen. Glucose is quickly mobilized to produce ATP to power the muscles and allow activity to continue. The ultimate product of glucose degradation and the amount of energy captured as ATP depends on the type of exercise underway, aerobic or anaerobic activity.

First Stage of Glucose Metabolism: Glycolysis

The first stage in the breakdown of glucose to produce ATP is **glycolysis** (from the Greek words *glykys*, meaning "sweet" and *lysis* meaning "splitting"). In this metabolic pathway, the six-carbon glucose molecule undergoes a series of transformations, each catalyzed by a different enzyme. Along the way, glucose is cleaved into two pieces that each end up as the three-carbon molecule pyruvate (Figure 3). The energy from hydrolysis of two molecules of ATP is needed to drive this pathway, but four molecules of ATP are eventually formed, for a net gain of 2 ATP.

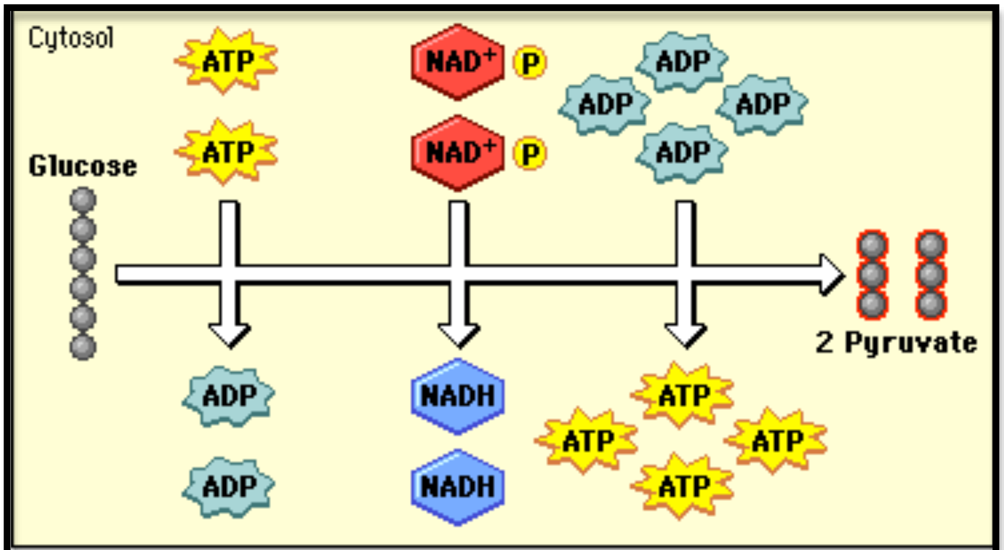


Figure 3. During glycolysis, glucose ends up as two molecules of pyruvate. Partial oxidation of glucose produces energy in the form of ATP (a net gain of 2 ATP) and two molecules of NADH, a cellular coenzyme used during metabolism.

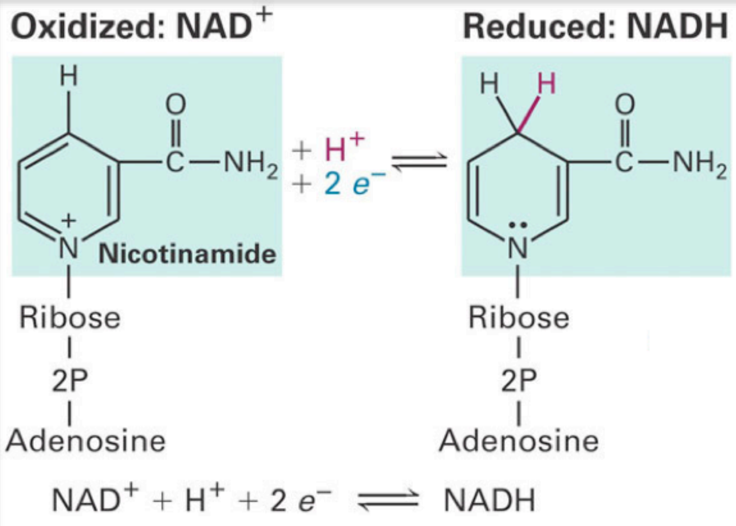


Figure 4. The molecule NAD^+ can accept two electrons (and a hydrogen ion) to become NADH. NADH is one of the most important electron carriers in metabolism.

During glycolysis, electrons produced during the oxidation of glucose end up captured in two molecules of NADH, which is made from Vitamin B3 (niacin). NADH is one of two primary electron carriers in metabolism (Figure 4), and it exists as an oxidized form (NAD^+) and a reduced form (NADH). This molecule is like a taxi for electrons, picking them up from glucose and dropping them off to other pathways of metabolism.

The two molecules of pyruvate produced during glycolysis still contain a great deal of the original chemical energy of glucose. Pyruvate can therefore undergo further degradation to produce more ATP. Its fate in the muscle during exercise, however, depends on the availability of oxygen.

Aerobic Metabolism: Cellular Respiration

If the muscles contain plenty of available oxygen, pyruvate can undergo complete oxidation to carbon dioxide and water during **cellular respiration** (Figure 5). Respiration, which consists of three phases, occurs in the mitochondria, the cell's "powerhouses." This metabolic pathway traps the maximum amount of stored chemical energy within a molecule of glucose, generating a total of 30 molecules of ATP in conjunction with glycolysis. We've already discussed Stage 1 of respiration, glycolysis. Let's take a look at Stages 2 and 3.

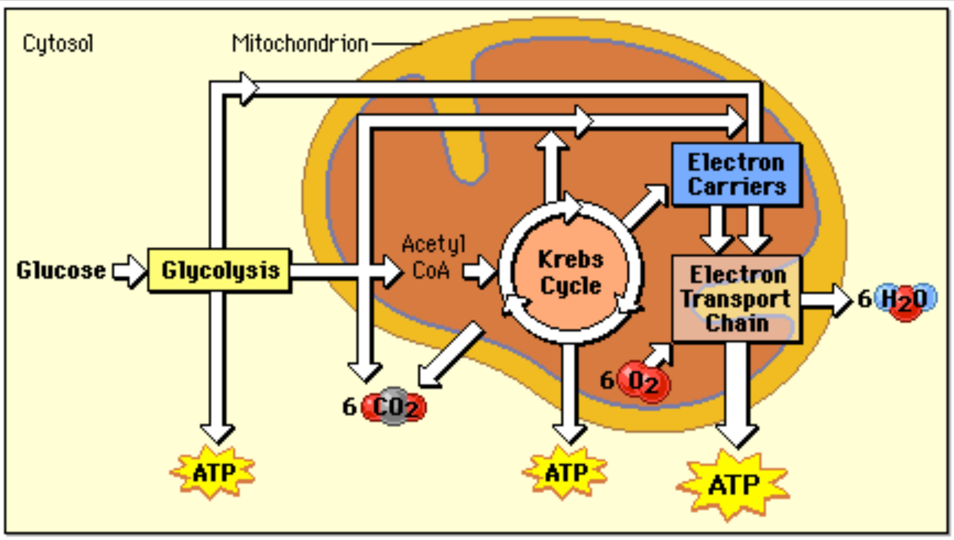


Figure 5. Cellular respiration consists of three metabolic phases: glycolysis, the Krebs cycle, and the electron transport chain. Glycolysis occurs in the cytosol, but the Krebs cycle and electron transport chain occur inside the mitochondria. Electron carriers such as NADH produced during glycolysis and the Krebs cycle pass their electrons to the electron transport chain, which results in synthesis of a lot of ATP.

The Krebs Cycle

The Krebs cycle (aka "the citric acid cycle"; Figure 6) occurs inside the mitochondria and generates a pool of chemical energy (ATP, NADH, and $FADH_2$, another electron carrier) from the oxidation of pyruvate, the end product of glycolysis. Pyruvate is transported into the mitochondria and loses carbon dioxide to form acetyl-CoA, a 2-carbon molecule attached to a carrier (coenzyme A). When acetyl-CoA is oxidized to carbon dioxide in the Krebs cycle, chemical energy is released and captured in the form of 3 molecules of NADH, 1 molecule of $FADH_2$, and 1 molecule of ATP. The cycle starts and ends with oxaloacetate.

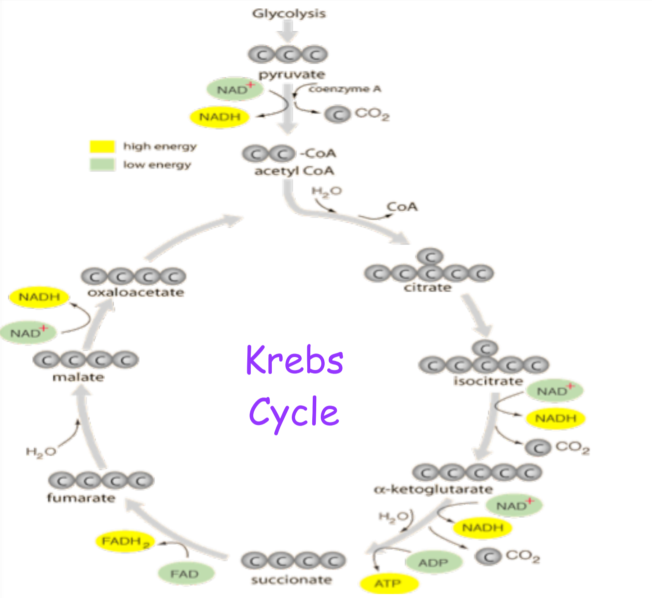


Figure 6. Pyruvate from glycolysis loses CO_2 to become a two-carbon fragment, acetate, before entering Stage 2 of respiration. Acetate is linked to coenzyme A to become acetyl-CoA, which enters the Krebs cycle. The Krebs cycle begins and ends with the same four-carbon molecule, oxaloacetate. Acetate is completely oxidized to CO_2 along the way.

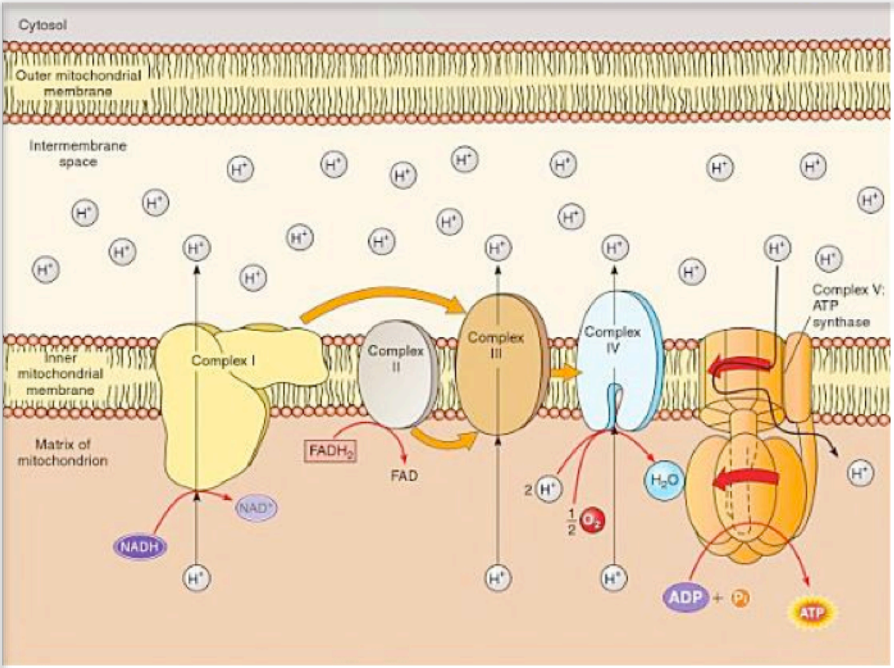


Figure 7. Electrons from NADH and $FADH_2$ enter the ETC at complex I and II, respectively. Electrons take the path indicated by the orange arrows, causing pumping of H^+ where shown, making the inside of the mitochondria less acidic. The resulting gradient can be used to make ATP when H^+ comes back inside through the ATP synthase.

The Electron Transport Chain

The NADH and $FADH_2$ produced during the Krebs cycle pass their electrons to the electron transport chain (ETC), the final stage of respiration (Figure 7). The electron transport chain consists of various proteins embedded in the mitochondrial membrane (complexes I –IV), as well as some mobile electron carriers (ubiquinone and cytochrome c). Electrons are passed through the carriers, eventually ending up reducing O_2 to form water. The energy released as the electrons flow through the chain is used to transport H^+ (hydrogen ions [aka protons]) out of the mitochondria. The end result is that it is more acidic outside the mitochondria, with a higher concentration of H^+. As the hydrogen ions flow back inside the mitochondria through another membrane protein, the ATP synthase, energy is released that is used to make ATP.

Notice that the electron transport chain is the part of aerobic metabolism that requires oxygen. Neither the Krebs cycle nor glycolysis use oxygen directly, but if NADH cannot be reoxidized to NAD^+ by the ETC, then the feeder pathways cannot continue. Another significant fact about the ETC is that the ATP synthase is the largest producer of ATP in the cell, with 2.5 ATPs made from each NADH and 1.5 ATP from each $FADH_2$ sent from glycolysis and the Krebs cycle. Adding the number of ATP molecules produced from glycolysis (2) and the number produced in the citric acid cycle (1) with the number produced in the ETC (27) yields a grand total of 30 molecules of ATP per molecule of glucose.

Anaerobic Metabolism: Fermentation

In the absence of oxygen, which is necessary to accept electrons from the ETC, NADH builds up in the cell. Unless it can be oxidized, pathways of metabolism that require removal of electrons (i.e., virtually all pathways that degrade fuel molecules) must stop. However, most cells can continue glycolysis, at least for a short time, because they have the ability to oxidize NADH through an alternative pathway that does not require oxygen: fermentation.

Fermentation complements glycolysis and makes it possible for the production of ATP to occur in the absence of oxygen. By oxidizing the NADH produced in glycolysis, fermentation regenerates NAD^+, which can take part in glycolysis once again to produce more ATP. The muscle regenerates NAD^+ from NADH, an *oxidation* reaction, by *reduction* of pyruvate. The fermentation pathway produces the NAD^+ necessary to accept electrons from glucose, allowing glycolysis to continue (Figure 8). The product of pyruvate reduction varies with organism. In yeast, pyruvate undergoes conversion to ethanol, a reaction used by winemakers for thousands of years. In humans, the product is the bane of many athletes, lactic acid.

The production of lactic acid during exercise is perceived as pain and muscle fatigue by the athlete. Lactic acid limits the duration of anaerobic activity because the resulting drop in pH inhibits one of the key enzymes in glycolysis. Therefore, anaerobic metabolism cannot be sustained for more than a minute or two before

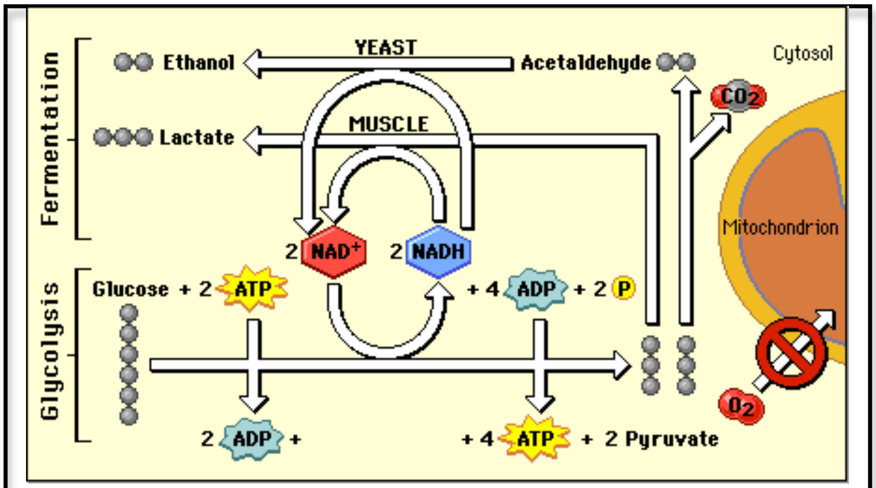


Figure 8. Glycolysis cannot continue without NAD^+. If the ETC chain isn't running because there is insufficient O_2, fermentation provides an alternate way to oxidize NADH back to NAD^+.

glycolysis shuts down.

Lactic acid produced in the muscle generally travels in the bloodstream to the liver, where it is converted back to glucose during the recovery period after exercise. This energy-requiring recycling process is called the *Cori cycle* after its discoverers Carl and Gerty Cori (Figure 9). The oxygen required for aerobic metabolism to produce the ATP necessary to power the Cori cycle is called "the oxygen debt", which corresponds to the period of heavy breathing following a burst of anaerobic activity.

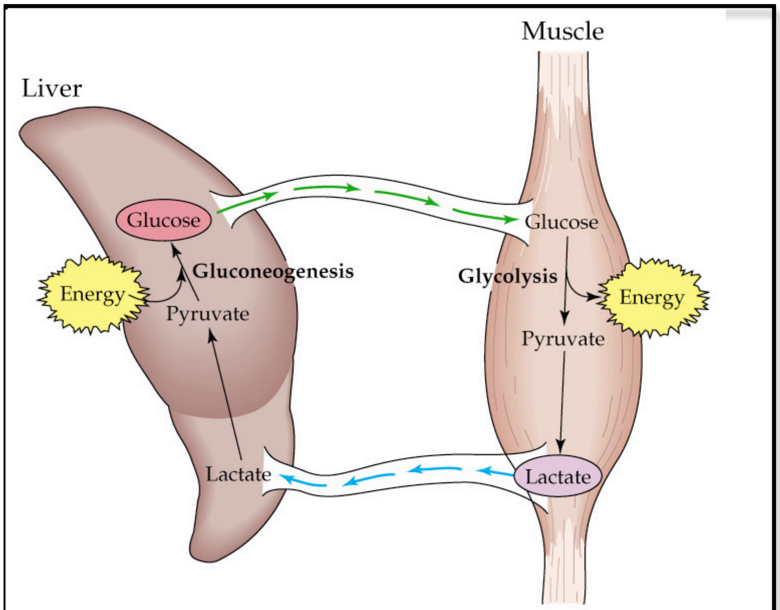


Figure 9. During anaerobic metabolism, lactic acid (aka lactate) is produced from glucose. Lactate is sent through the bloodstream to the liver, which recycles it back to glucose in an energy-requiring pathway called *gluconeogenesis*.

An alternative fate of lactic acid is oxidation back to pyruvate, which can then be completely oxidized during cellular respiration if sufficient oxygen is available. This is the chemical rationale behind the traditional "cool down" period after a heavy workout. A slow jog can burn up the lactic acid, clearing it from the muscles to prevent soreness after a strenuous workout. The heart is particularly good at using lactic acid, helping to clear it from the bloodstream and muscles.

Fat Metabolism

The average individual has enough stored fat to last for about two months without eating. Recall that fats are stored primarily in fat cells (adipocytes). These cells send out fatty acids when they receive a hormonal signal that either the body's blood sugar has dropped (the hormone glucagon) or that the body needs energy for fight or flight (the hormone adrenaline).

During exercise, it takes about 20 minutes for fats to be sent out from adipocytes and reach the skeletal muscle and heart. Once the fatty acids reach their target cells, they must enter the mitochondria to be broken down for energy. A specific transport system, called the carnitine shuttle, carries fatty acids into the mitochondria, where they broken up into two-carbon fragments and attached to coenzyme A to form acetyl-CoA (Figure 10). Acetyl-CoA can then enter the Krebs cycle and undergo complete oxidation. Because the Krebs cycle is dependent on the ETC to oxidize NADH and $FADH_2$, fats cannot be metabolized for energy unless the ETC is operating. In other words, there must be sufficient oxygen for fats to be used as fuels; they cannot be metabolized anaerobically.

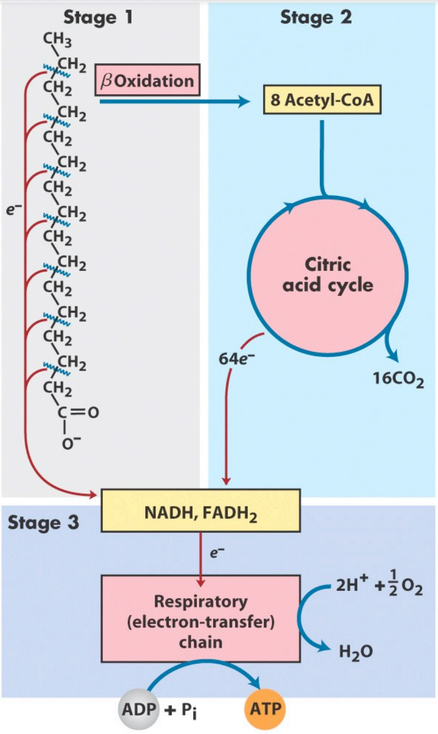


Figure 10. Inside the mitochondria, fats are broken down into acetyl-CoA, trapping electrons in NADH and $FADH_2$. Acetyl-CoA then enters the citric acid cycle, producing even more NADH and $FADH_2$. During electron transfer, large amounts of ATP are made.

Protein Metabolism

Although we do not have stores of proteins, proteins are present in many food sources. After they are broken down to their constituent amino acids, our muscles and liver can use them as fuels under some circumstances. Amino acids are broken down either into intermediates of the Krebs cycle or into acetyl-CoA, which then enters the Krebs cycle (Figure 11). Like fats, amino acids depend on the citric acid cycle to be oxidized completely, so they can only be metabolized under aerobic conditions.

Before any amino acid can enter the citric acid cycle to be used a fuel, the amino group ($-NH_3$) must be removed. This happens in the

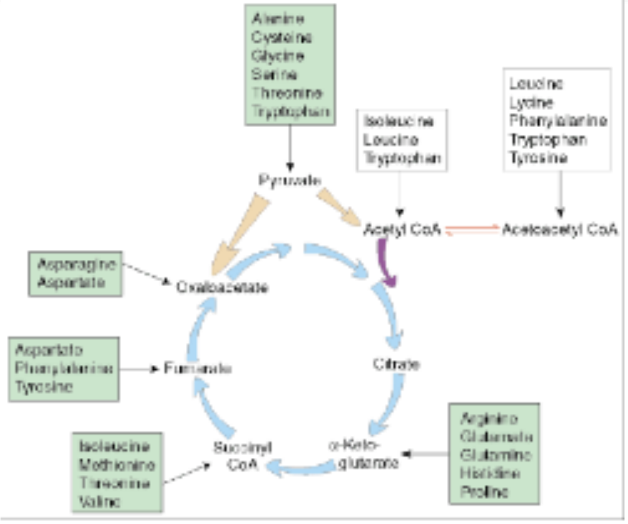


Figure 11. All amino acids are metabolized to products that eventually enter the citric acid cycle.

liver, which converts the NH_3 to the molecule urea (CH_4N_2O) for excretion because ammonia itself is toxic.

Interestingly, the liver lacks the appropriate enzyme to break down one family of amino acids, the branched-chain amino acids (leucine, isoleucine, and valine). On the other hand, not only can muscles use these amino acids for energy, but there is also some evidence that suggests that the branched-chain amino acids, particularly leucine, reduce muscle breakdown during exercise.

Summary of Energy Sources

To recap, ATP and phosphocreatine are the first energy sources to fuel the muscles during physical activity but are depleted very rapidly (Figure 12). Glucose then follows, degraded by glycolysis and then either fermentation (anaerobic metabolism) or the Krebs cycle/ETC (aerobic metabolism). Finally, under conditions of sustained aerobic activity, the abundant fats are mobilized. Amino acids from proteins are also metabolized aerobically but make only a modest contribution to the energy demands of exercise.

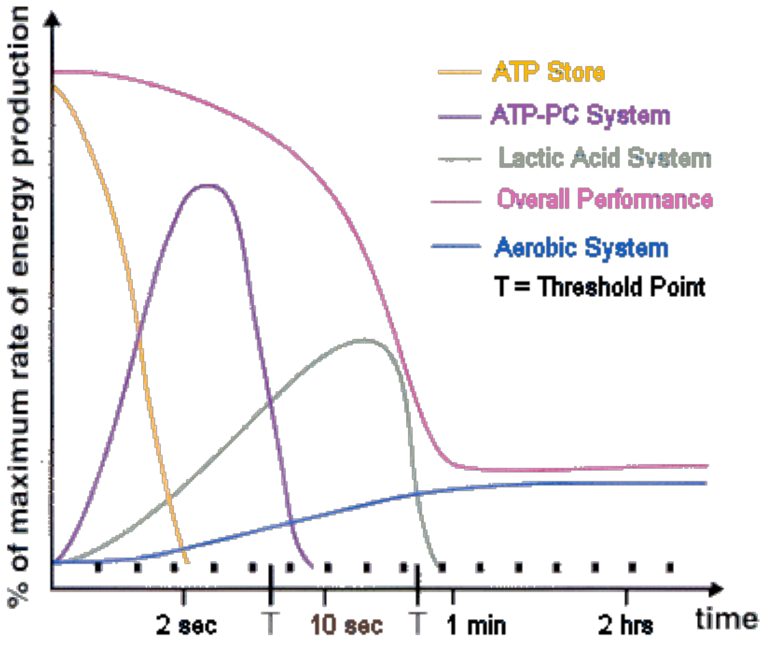


Figure 12. Muscles have small amounts of ATP that are used up in a couple of seconds. Phosphocreatine (PC) rapidly forms more ATP but is used up in about 10 seconds. Anaerobic metabolism of glucose (the lactic acid system) operates quickly but is shut down in a minute or two because of acidification of the muscle. Aerobic metabolism of glucose, fats, and amino acids is slower but can be sustained for hours.

Relative Advantages of Anaerobic versus Aerobic Metabolism

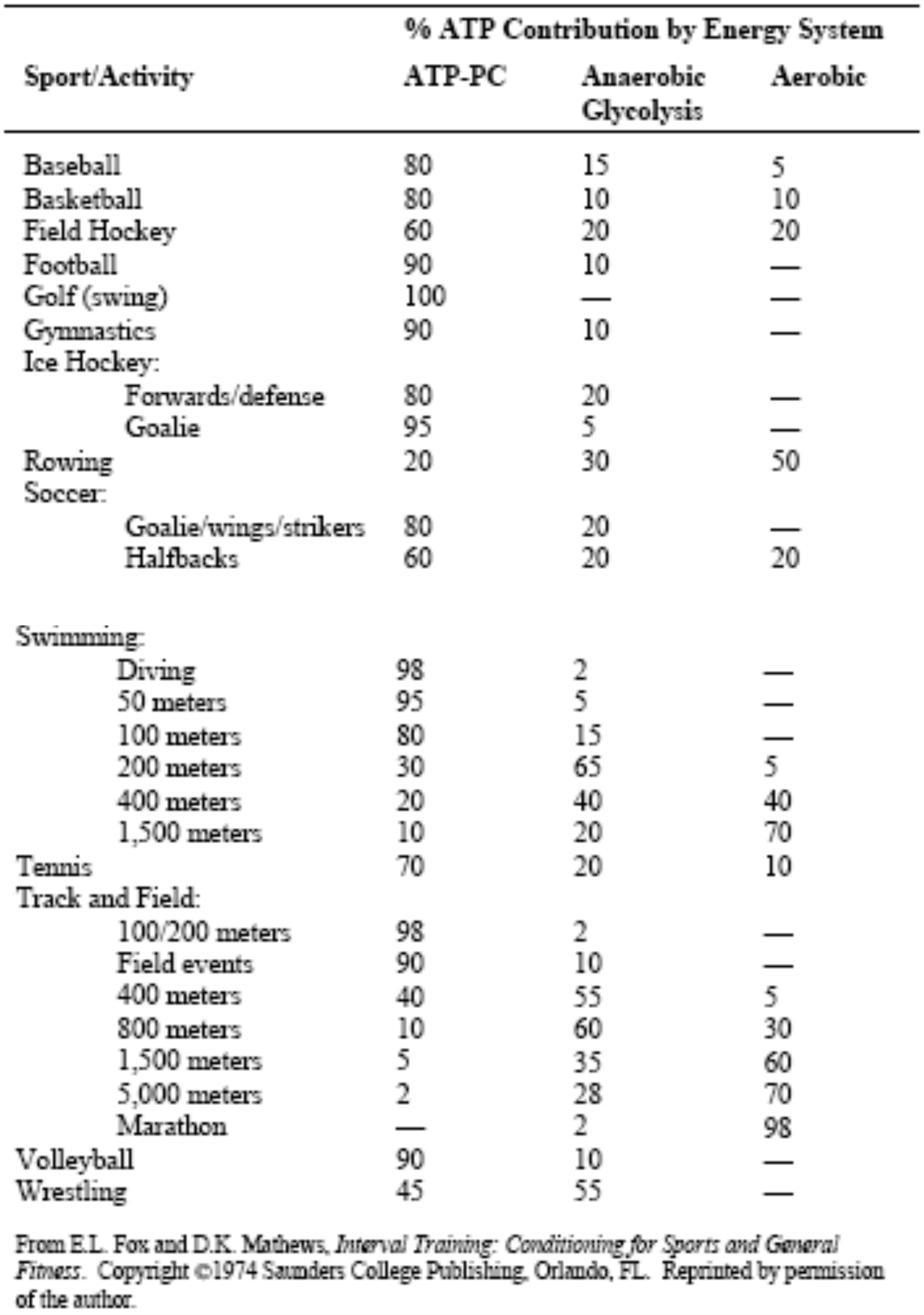
Anaerobic metabolism of a molecule of glucose produces significantly less ATP (**2 molecules**) than aerobic metabolism (**30 molecules total**). While anaerobic metabolism may seem to be an inefficient pathway in terms of energy production, each pathway has its own merits.

- Anaerobic metabolism has the distinct advantage of proceeding very quickly in the absence of oxygen. For sprinters, throwers, and other power athletes, this is the pathway that provides the energy needed to power their muscles. During such short bursts of intense muscle activity, oxygen cannot be carried fast enough to the tissues to oxidize all of the pyruvate produced and regenerate the NAD^+ necessary for glycolysis to continue. When NAD^+ is depleted, fermentation switches on, converting NADH to NAD^+ and pyruvate to lactic acid. However, because lactic acid inhibits glycolysis, anaerobic activity cannot be sustained for very long. Within a minute or two, the muscle is unable to produce any more ATP, reaching a state of fatigue.

- Aerobic metabolism oxidizes glucose completely to obtain the maximum amount of energy possible. For endurance athletes, this is the pathway that provides the necessary ATP until fat mobilization begins to supplement energy production. Thus, aerobic metabolism is highly efficient and can run on both glucose and fats. However, sufficient oxygen must be delivered to the muscles for them to perform aerobic metabolism.

Athletes in different events rely on the different energy-producing pathways to a varying degree (Table 1). Sports involving very quick bursts of activity rely on the phosphocreatine and anaerobic energy systems, while those involving more sustained activity have an increasing reliance on aerobic pathways.

Table 1. The Predominant Energy Systems for Selected Sports



Sport/Activity	% ATP Contribution by Energy System ATP-PC	 Anaerobic Glycolysis	 Aerobic
Baseball	80	15	5
Basketball	80	10	10
Field Hockey	60	20	20
Football	90	10	—
Golf (swing)	100	—	—
Gymnastics	90	10	—
Ice Hockey:			
Forwards/defense	80	20	—
Goalie	95	5	—
Rowing	20	30	50
Soccer:			
Goalie/wings/strikers	80	20	—
Halfbacks	60	20	20
Swimming:			
Diving	98	2	—
50 meters	95	5	—
100 meters	80	15	—
200 meters	30	65	5
400 meters	20	40	40
1,500 meters	10	20	70
Tennis	70	20	10
Track and Field:			
100/200 meters	98	2	—
Field events	90	10	—
400 meters	40	55	5
800 meters	10	60	30
1,500 meters	5	35	60
5,000 meters	2	28	70
Marathon	—	2	98
Volleyball	90	10	—
Wrestling	45	55	—

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Maximum Oxygen Uptake

Figure 13. Nordic skiing legend Bjorn Daehlie of Norway, winner of 12 medals in the Olympic games (8 gold and 4 silver) and 9 world championships, has the highest VO_2 max value ever recorded (96 mL/min/kg). Values for VO_2 max typically range from 20 to 85 mL/min/kg. Elite marathoner Joan Benoit Samuelson has one of the highest recorded VO_2 max values for a woman (78.6 mL/min/kg).

An important factor in dictating the rate at which aerobic metabolism can proceed is the **VO_2 max**, or the maximum rate of oxygen uptake by the muscles. Individuals with a greater ability to use oxygen to oxidize fuels such as glucose to carbon dioxide can sustain a higher level of effort without relying on the less efficient anaerobic pathway. Oxygen uptake is one of the physiological limits to performance that improves with training.

VO_2 max, measured in milliliters of oxygen per minute per kilogram of body mass, is an important indicator of the ability for sustained exercise (Figure 13). For events that are performed under aerobic conditions, the rate at which oxygen can be provided to the muscles for metabolism is a key factor limiting the pace. Because oxygen is carried to the tissues by the protein hemoglobin within red blood cells, determinants of VO_2 max include the **hematocrit** (the percentage of red cells in a volume of blood), the number of capillaries surrounding the muscle cells, and the volume of blood pumped by the heart. Additionally, the number of mitochondria, where cellular respiration occurs, also dictates how efficiently a muscle uses oxygen to burn fuels. Generally, an increase in overall cardiovascular fitness through regular training leads to an increase in an individual's VO_2 max.

Lactate Threshold

Lactic acid is produced by working muscles and released into the bloodstream for transport to the liver. As exercise intensity increases, there is usually little increase in the lactic acid concentration of blood initially because other tissues can burn it for energy, like the heart, or reprocess it, like the liver. Once the intensity reaches a certain level,

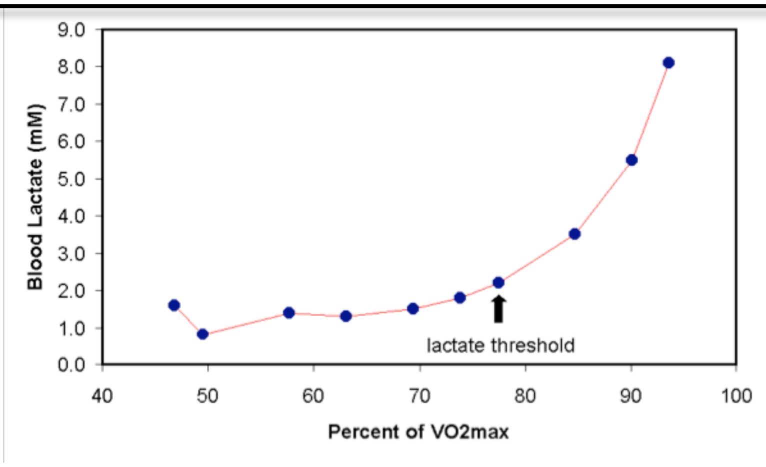
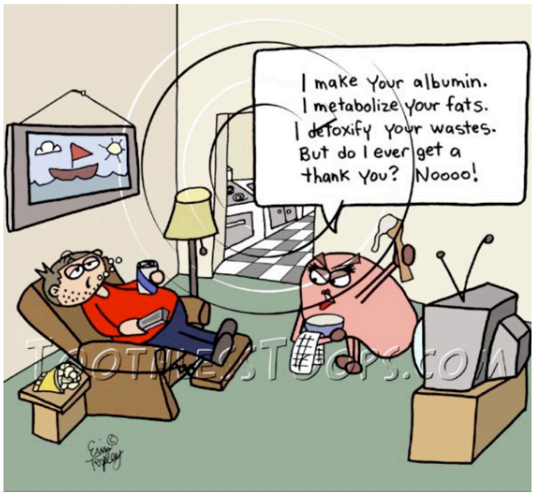


Figure 14. At relatively low intensities of exercise, lactate is effectively cleared from the blood so its concentration remains low. However, at about 80% of VO_2max, lactate is produced too fast, so its concentration increases, resulting in fatigue.

however, the amount of lactic acid in the blood increases dramatically. The point of sudden increase is called the Lactate Threshold, also known as the Anaerobic Threshold (Figure 14), and represents the point at which exercising muscles are releasing lactic acid more rapidly than other tissues can clear it. Typically, this occurs at an intensity corresponding to about 80% of VO_2max. The significance of the lactate threshold is that it correlates to the exercise intensity that can be sustained for long periods. Going any harder than this results in rapid fatigue because of acidification of the muscles, leading to the shutdown of glycolysis and the lack of energy production.

Central Role of the Liver in Metabolism

The liver plays an essential role in metabolism, especially for athletes. Two of the many functions of the liver are the synthesis of essential molecules used elsewhere to support homeostasis (the process by which the body maintains a state of balance) and the processing of waste products. Damage to the liver, which can be caused by injury, chemicals such as alcohol and drugs, or disease, can be catastrophic. Let's highlight some of the major functions of the body's unsung hero.



Maintaining Blood Sugar

It is critical for all animals to maintain concentrations of glucose in blood within a narrow, normal range (about 4 to 5 millimolar, or 80 to 110 mg/dL, in humans). Maintenance of normal blood sugar levels over both short (hours) and long (days to weeks) periods of time is a major function of the liver. Excess glucose entering the blood after a meal is rapidly taken up by the liver and sequestered as the polymer glycogen. Later, when blood sugar begins to decline, the liver breaks down glycogen and sends glucose back into the blood for transport to all other tissues. When liver glycogen reserves become exhausted, after several hours of fasting or a couple hours of exercise, the liver makes glucose out of amino acids in a process called gluconeogenesis. Gluconeogenesis also contributes to the clearance of lactic acid through the Cori Cycle mentioned earlier in this chapter. Thus, despite the starve-feed cycle, the liver is normally able to buffer blood sugar within a fairly narrow range by absorbing glucose after feeding and sending glucose back into the bloodstream during fasting.

Fat Metabolism

Many aspects of lipid metabolism are also carried out in the liver. The liver actively oxidizes triglycerides to meet its own energy demands. In fact, the liver breaks down many more fats than it needs, producing and exporting water-soluble derivatives of fats called ketone bodies that can be used by other tissues for energy. The liver is also the major site for converting excess carbohydrates and proteins into triglycerides, which are then exported and stored in adipose tissue.

Protein Metabolism

Several critical aspects of protein metabolism also occur in the liver, including processing of most ingested amino acids, followed by conversion of the non-nitrogenous part of those molecules to glucose or lipids. The liver also processes nitrogenous waste from proteins, helping to remove ammonia from the body through the synthesis of urea. Ammonia is very toxic and can affect the brain with a range of symptoms from mild confusion to possible brain damage, coma, and death. The liver also makes many proteins found in the bloodstream, including albumin, which escorts fats from adipose tissue to muscle cells during exercise.

With all the beneficial chemistry that the liver is performing, it’s no wonder that many athletes choose to go dry during their seasons. Your liver is busy enough without making it metabolize a bunch of alcohol!