CHAPTER 7

CELLULAR RESPIRATION

Like other heterotrophs, the giant panda, *Ailuropoda melanoleuca,* obtains organic compounds by consuming other organisms. Biochemical pathways within the panda's cells transfer energy from those compounds to ATP.

BIOLOGY INTERACTIVE TUTOR

Unit 3—Cellular Respiration
Topics 1–6

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GLYCOLYSIS AND FERMENTATION

Most foods contain usable energy, stored in complex organic compounds such as proteins, carbohydrates, and fats. All cells break down organic compounds into simpler molecules, a process that releases energy to power cellular activities.

SECTION 1

OBJECTIVES

- **Identify** the two major steps of cellular respiration.
- **Describe** the major events in glycolysis.
- **Compare** lactic acid fermentation with alcoholic fermentation.
- **Calculate** the efficiency of glycolysis.

VOCABULARY

cellular respiration
pyruvic acid
NADH
anaerobic
aerobic respiration
glycolysis
NAD^+
fermentation
lactic acid fermentation
alcoholic fermentation
kilocalorie

HARVESTING CHEMICAL ENERGY

Cellular respiration is the complex process in which cells make adenosine triphosphate (ATP) by breaking down organic compounds. Recall that autotrophs, such as plants, use photosynthesis to convert light energy from the sun into chemical energy, which is stored in organic compounds. Both autotrophs and heterotrophs undergo cellular respiration to break these organic compounds into simpler molecules and thus release energy. Some of the energy is used to make ATP. The energy in ATP is then used by cells to do work.

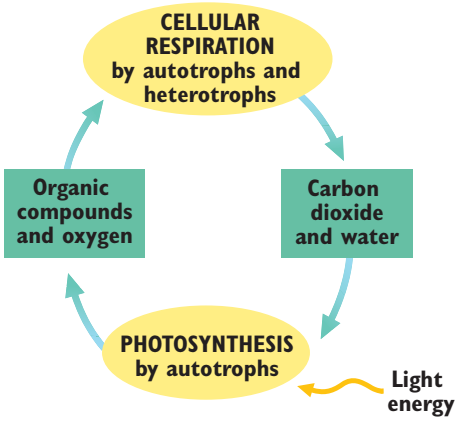
Overview of Cellular Respiration

Figure 7-1 shows that autotrophs and heterotrophs use cellular respiration to make carbon dioxide (CO_2) and water from organic compounds and oxygen (O_2). ATP is also produced during cellular respiration. Autotrophs then use the CO_2 and water to produce O_2 and organic compounds. Thus, the products of cellular respiration are reactants in photosynthesis. Conversely, the products of photosynthesis are reactants in cellular respiration. Cellular respiration can be divided into two stages:

1. **Glycolysis** Organic compounds are converted into three-carbon molecules of **pyruvic** (pie-ROO-vik) **acid,** producing a small amount of ATP and **NADH** (an electron carrier molecule). Glycolysis is an **anaerobic** (AN-uhr-oh-bik) process because it does not require the presence of oxygen.
2. **Aerobic Respiration** If oxygen is present in the cell's environment, pyruvic acid is broken down and NADH is used to make a large amount of ATP through the process known as **aerobic** (uhr-OH-bik) **respiration** (covered later).

Pyruvic acid can enter other pathways if there is no oxygen present in the cell's environment. The combination of glycolysis and these anaerobic pathways is called *fermentation*.

FIGURE 7-1
Both autotrophs and heterotrophs produce carbon dioxide and water through cellular respiration. Many autotrophs produce organic compounds and oxygen through photosynthesis.



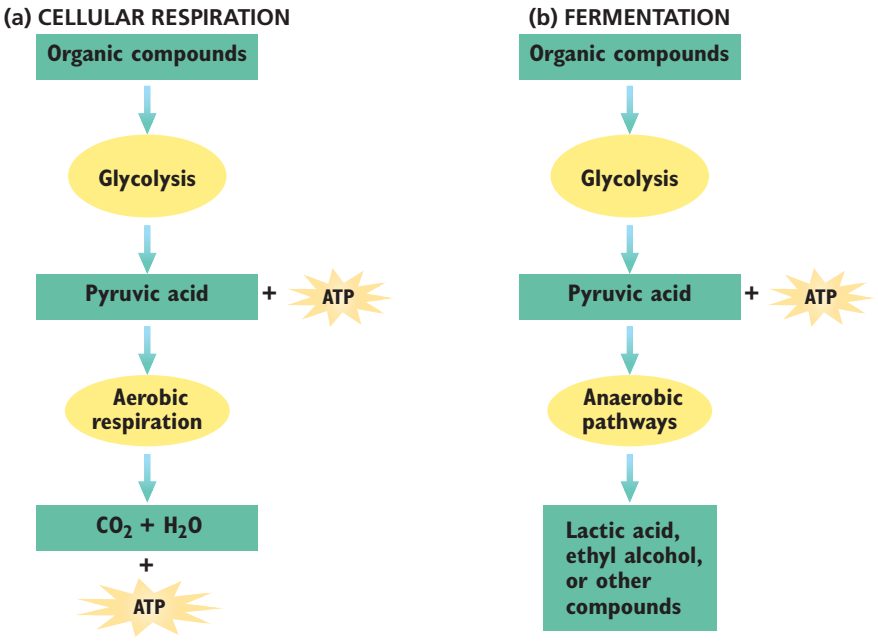


FIGURE 7-2

Organisms use cellular respiration to harness energy from organic compounds in food. (a) Glycolysis, the first stage of cellular respiration, produces a small amount of ATP. Most of the ATP produced in cellular respiration results from aerobic respiration, which is the second stage of cellular respiration. (b) In some cells, glycolysis may result in fermentation if oxygen is not present.

Many of the reactions in cellular respiration are redox reactions. Recall that in a *redox reaction,* one reactant is oxidized (loses electrons) while another is reduced (gains electrons). Although many kinds of organic compounds can be oxidized in cellular respiration, it is customary to focus on the simple sugar called *glucose* ($C_6H_{12}O_6$). The following equation summarizes cellular respiration:

$$C_6H_{12}O_6 + 6O_2 \xrightarrow{\text{enzymes}} 6CO_2 + 6H_2O + \text{energy (ATP)}$$

This equation, however, does not explain how cellular respiration occurs. It is useful to examine each of the two stages, summarized in Figure 7-2a. (Figure 7-2b illustrates the differences between cellular respiration and fermentation.) The first stage of cellular respiration is glycolysis.

GLYCOLYSIS

Glycolysis is a biochemical pathway in which one six-carbon molecule of glucose is oxidized to produce two three-carbon molecules of pyruvic acid. Like other biochemical pathways, glycolysis is a series of chemical reactions catalyzed by specific enzymes. All of the reactions of glycolysis take place in the cytosol and occur in four main steps, as illustrated in Figure 7-3 on the next page.

In step 1, two phosphate groups are attached to one molecule of glucose, forming a new six-carbon compound that has two phosphate groups. The phosphate groups are supplied by two molecules of ATP, which are converted into two molecules of ADP in the process.

In step 2, the six-carbon compound formed in step 1 is split into two three-carbon molecules of glyceraldehyde 3-phosphate (G3P). Recall that G3P is also produced by the Calvin cycle in photosynthesis.

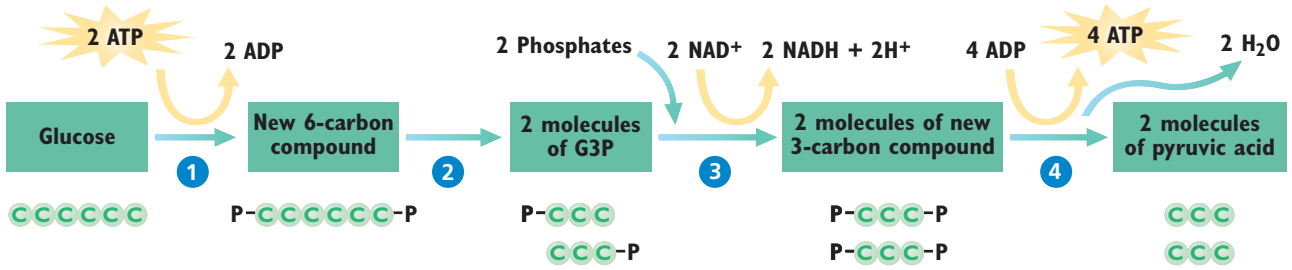


FIGURE 7-3

Glycolysis takes place in the cytosol of cells and involves four main steps. A net yield of two ATP molecules is produced for every molecule of glucose that undergoes glycolysis.

In step 3, the two G3P molecules are oxidized, and each receives a phosphate group. The product of this step is two molecules of a new three-carbon compound. As shown in Figure 7-3, the oxidation of G3P is accompanied by the reduction of two molecules of nicotinamide adenine dinucleotide (**NAD^+**) to NADH. NAD^+ is similar to $NADP^+$, a compound involved in the light reactions of photosynthesis. Like $NADP^+$, NAD^+ is an organic molecule that accepts electrons during redox reactions.

In step 4, the phosphate groups added in step 1 and step 3 are removed from the three-carbon compounds formed in step 3. This reaction produces two molecules of pyruvic acid. Each phosphate group is combined with a molecule of ADP to make a molecule of ATP. Because a total of four phosphate groups were added in step 1 and step 3, four molecules of ATP are produced.

Notice that two ATP molecules were used in step 1, but four were produced in step 4. Therefore, glycolysis has a net yield of two ATP molecules for every molecule of glucose that is converted into pyruvic acid. What happens to the pyruvic acid depends on the type of cell and on whether oxygen is present.

FERMENTATION

When oxygen is present, cellular respiration continues as pyruvic acid enters the pathways of aerobic respiration. (Aerobic respiration is covered in detail in the next section.) In anaerobic conditions (when oxygen is absent), however, some cells can convert pyruvic acid into other compounds through additional biochemical pathways that occur in the cytosol. The combination of glycolysis and these additional pathways, which regenerate NAD^+, is known as **fermentation.** The additional fermentation pathways do not produce ATP. However, if there were not a cellular process that recycled NAD^+ from NADH, glycolysis would quickly use up all the NAD^+ in the cell. Glycolysis would then stop. ATP production through glycolysis would therefore also stop. The fermentation pathways thus allow for the continued production of ATP.

There are many fermentation pathways, and they differ in terms of the enzymes that are used and the compounds that are made from pyruvic acid. Two common fermentation pathways result in the production of lactic acid and ethyl alcohol.

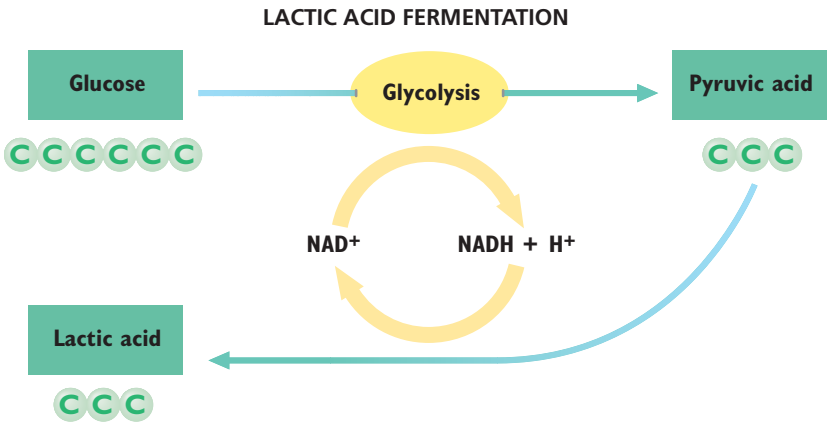
Word Roots and Origins

fermentation

from the Latin *fermentum,* meaning "leaven" or anything that causes baked goods to rise, such as yeast

FIGURE 7-4

Some cells engage in lactic acid fermentation when oxygen is absent. In this process, pyruvic acid is reduced to lactic acid and NADH is oxidized to NAD^+.



Lactic Acid Fermentation

In **lactic acid fermentation,** an enzyme converts pyruvic acid made during glycolysis into another three-carbon compound, called lactic acid. As Figure 7-4 shows, lactic acid fermentation involves the transfer of one hydrogen atom from NADH and the addition of one free proton (H^+) to pyruvic acid. In the process, NADH is oxidized to form NAD^+. The resulting NAD^+ is used in glycolysis, where it is again reduced to NADH. Thus, the regeneration of NAD^+ in lactic acid fermentation helps to keep glycolysis operating.

Lactic acid fermentation by microorganisms plays an essential role in the manufacture of many dairy products, as illustrated in Figure 7-5. Milk will ferment naturally if not refrigerated properly or consumed in a timely manner. Such fermentation of milk is considered "spoiling." But ever since scientists discovered the microorganisms that cause this process, fermentation has been used in a controlled manner to produce cheese, buttermilk, yogurt, sour cream, and other cultured dairy products. Only harmless, active microorganisms are used in the fermentation of dairy products.

FIGURE 7-5

In cheese making, fungi or bacteria are added to large vats of milk. The microorganisms carry out lactic acid fermentation, converting some of the sugar in the milk to lactic acid.

Lactic acid fermentation also occurs in your muscle cells during very strenuous exercise, such as sprinting. During this kind of exercise, muscle cells use up oxygen more rapidly than it can be delivered to them. As oxygen becomes depleted, the muscle cells begin to switch from cellular respiration to lactic acid fermentation. Lactic acid accumulates in the muscle cells, making the cells' cytosol more acidic. The increased acidity may reduce the capacity of the cells to contract, resulting in muscle fatigue, pain, and even cramps. Eventually, the lactic acid diffuses into the blood and is transported to the liver, where it can be converted back into pyruvic acid.

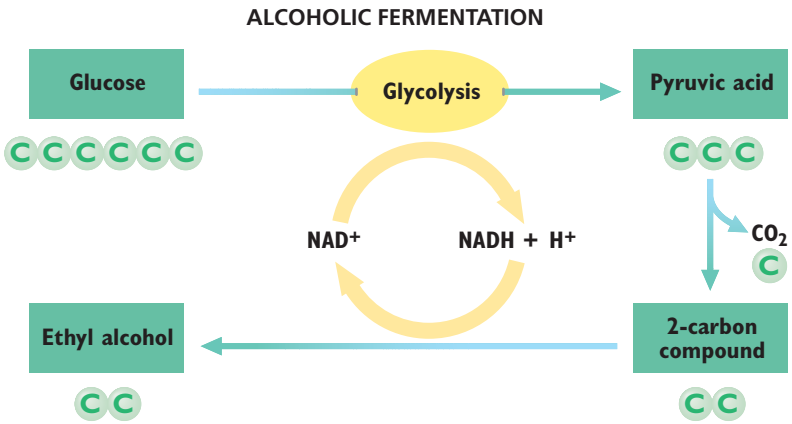


FIGURE 7-6

Some cells engage in alcoholic fermentation, converting pyruvic acid into ethyl alcohol. Again, NADH is oxidized to NAD^+.

Alcoholic Fermentation

Some plant cells and unicellular organisms, such as yeast, use a process called **alcoholic fermentation** to convert pyruvic acid into ethyl alcohol. After glycolysis, this pathway requires two steps, which are shown in Figure 7-6. In the first step, a CO_2 molecule is removed from pyruvic acid, leaving a two-carbon compound. In the second step, two hydrogen atoms are added to the two-carbon compound to form ethyl alcohol. As in lactic acid fermentation, these hydrogen atoms come from NADH and H^+, regenerating NAD^+ for use in glycolysis.

Alcoholic fermentation by yeast cells such as those in Figure 7-7 is the basis of the wine and beer industry. Yeasts are a type of fungi. These microorganisms cannot produce their own food. But supplied with food sources that contain sugar (such as fruits and grains), yeast cells will perform the reactions of fermentation, releasing ethyl alcohol and carbon dioxide in the process. The ethyl alcohol is the 'alcohol' in alcoholic beverages. To make table wines, the CO_2 that is generated in the first step of fermentation is allowed to escape. To make sparkling wines, such as champagne, CO_2 is retained within the mixture, "carbonating" the beverage.

Bread making also depends on alcoholic fermentation performed by yeast cells. In this case, the CO_2 that is produced by fermentation makes the bread rise by forming bubbles inside the dough, and the ethyl alcohol evaporates during baking.

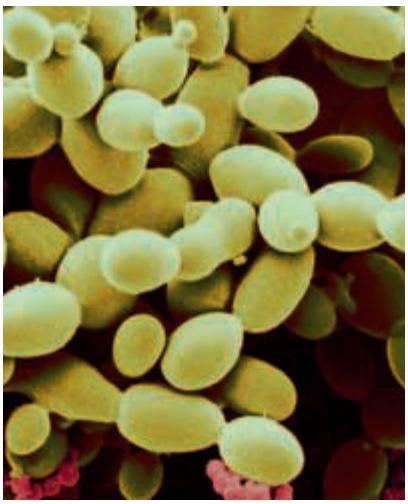


FIGURE 7-7

The yeast *Saccharomyces cerevisiae* is used in alcohol production and bread making.

EFFICIENCY OF GLYCOLYSIS

How efficient is glycolysis in obtaining energy from glucose and using it to make ATP from ADP? To answer this question, one must compare the amount of energy available in glucose with the amount of energy contained in the ATP that is produced by glycolysis. In such comparisons, energy is often measured in units of **kilocalories** (kcal). One kilocalorie equals 1,000 calories (cal).

Word Roots and Origins

kilocalorie

from the Greek *chilioi,* meaning "thousand," and the Latin *calor,* meaning "heat"

Scientists have calculated that the complete oxidation of a standard amount of glucose releases 686 kcal. The production of a standard amount of ATP from ADP absorbs a minimum of about 7 kcal, depending on the conditions inside the cell. Recall that two ATP molecules are produced from every glucose molecule that is broken down by glycolysis.

$$\text{Efficiency of glycolysis} = \frac{\text{Energy required to make ATP}}{\text{Energy released by oxidation of glucose}}$$

$$= \frac{2 \times 7 \text{ kcal}}{686 \text{ kcal}} \times 100\% = 2\%$$

You can see that the two ATP molecules produced during glycolysis receive only a small percentage of the energy that could be released by the complete oxidation of each molecule of glucose. Much of the energy originally contained in glucose is still held in pyruvic acid. Even if pyruvic acid is converted into lactic acid or ethyl alcohol, no additional ATP is synthesized. It's clear that glycolysis alone or as part of fermentation is not very efficient in transferring energy from glucose to ATP.

Organisms probably evolved to use glycolysis very early in the history of life on Earth. The first organisms were bacteria, and they produced all of their ATP through glycolysis. It took more than a billion years for the first photosynthetic organisms to appear. The oxygen they released as a byproduct of photosynthesis may have stimulated the evolution of organisms that make most of their ATP through aerobic respiration.

By themselves, the anaerobic pathways provide enough energy for many present-day organisms. However, most of these organisms are unicellular, and those that are multicellular are very small. All of them have limited energy requirements. Larger organisms have much greater energy requirements that cannot be satisfied by glycolysis alone. These larger organisms meet their energy requirements with the more efficient pathways of aerobic respiration.

SECTION 1 REVIEW

1. Explain the role of organic compounds in cellular respiration.
2. For each six-carbon molecule that begins glycolysis, identify how many molecules of ATP are used and how many molecules of ATP are produced.
3. Distinguish between the products of the two types of fermentation discussed in this section.
4. Calculate the efficiency of glycolysis if 12 kcal of energy are required to transfer energy from glucose to ATP.

CRITICAL THINKNG

5. **Applying Information** A large amount of ATP in a cell inhibits the enzymes that drive the first steps of glycolysis. How will this inhibition of enzymes eventually affect the amount of ATP in the cell?
6. **Predicting Results** How might the efficiency of glycolysis change if this process occurred in only one step? Explain your answer.
7. **Relating Concepts** In what kind of environment would you expect to find organisms that carry out fermentation?

AEROBIC RESPIRATION

In most cells, glycolysis does not result in fermentation. Instead, when oxygen is available, pyruvic acid undergoes aerobic respiration, the pathway of cellular respiration that requires oxygen. Aerobic respiration produces nearly 20 times as much ATP as is produced by glycolysis alone.

SECTION 2

OBJECTIVES

- **Relate** aerobic respiration to the structure of a mitochondrion.
- **Summarize** the events of the Krebs cycle.
- **Summarize** the events of the electron transport chain and chemiosmosis.
- **Calculate** the efficiency of aerobic respiration.
- **Contrast** the roles of glycolysis and aerobic respiration in cellular respiration.

VOCABULARY

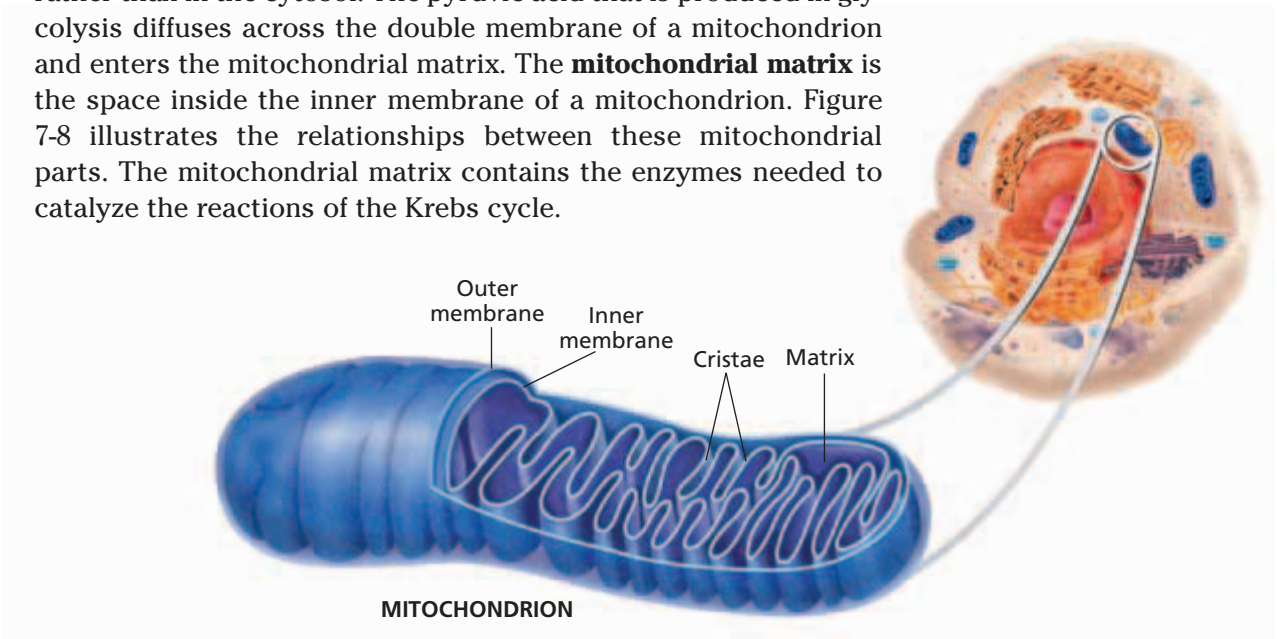
mitochondrial matrix
acetyl CoA
Krebs cycle
oxaloacetic acid
citric acid
FAD

OVERVIEW OF AEROBIC RESPIRATION

Aerobic respiration has two major stages: the Krebs cycle and the electron transport chain, which is associated with chemiosmosis (using the energy released as protons move across a membrane to make ATP). In the Krebs cycle, the oxidation of glucose that began with glycolysis is completed. As glucose is oxidized, NAD^+ is reduced to NADH. In the electron transport chain, NADH is used to make ATP. Although the Krebs cycle also produces a small amount of ATP, most of the ATP produced during aerobic respiration is made through the activities of the electron transport chain and chemiosmosis. The reactions of the Krebs cycle, the electron transport chain, and chemiosmosis occur only if oxygen is present in the cell.

In prokaryotes, the reactions of the Krebs cycle and the electron transport chain take place in the cytosol of the cell. In eukaryotic cells, however, these reactions take place inside mitochondria rather than in the cytosol. The pyruvic acid that is produced in glycolysis diffuses across the double membrane of a mitochondrion and enters the mitochondrial matrix. The **mitochondrial matrix** is the space inside the inner membrane of a mitochondrion. Figure 7-8 illustrates the relationships between these mitochondrial parts. The mitochondrial matrix contains the enzymes needed to catalyze the reactions of the Krebs cycle.

FIGURE 7-8
In eukaryotic cells, the reactions of aerobic respiration occur inside mitochondria. The Krebs cycle takes place in the mitochondrial matrix, and the electron transport chain is located in the inner membrane.



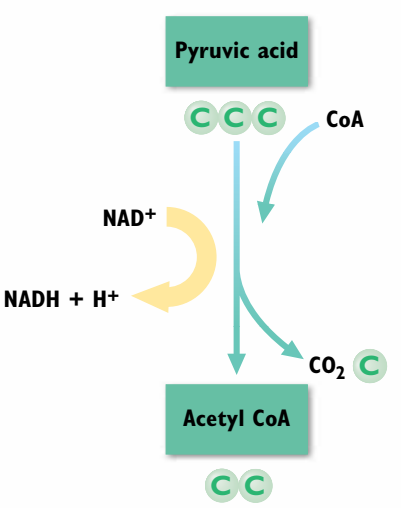


FIGURE 7-9

Glycolysis yields two molecules of pyruvic acid. In aerobic respiration, each molecule of pyruvic acid reacts with coenzyme A (CoA) to form a molecule of acetyl CoA. Notice that CO_2, NADH, and H^+ are also produced in this reaction.

When pyruvic acid enters the mitochondrial matrix, it reacts with a molecule called coenzyme A to form acetyl (uh-SEET-uhl) coenzyme A, abbreviated **acetyl CoA** (uh-SEET-uhl KOH-AY). This reaction is illustrated in Figure 7-9. The acetyl part of acetyl CoA contains two carbon atoms, but as you learned earlier, pyruvic acid is a three-carbon compound. The carbon atom that is lost in the conversion of pyruvic acid to acetyl CoA is released in a molecule of CO_2. This reaction reduces a molecule of NAD^+ to NADH.

THE KREBS CYCLE

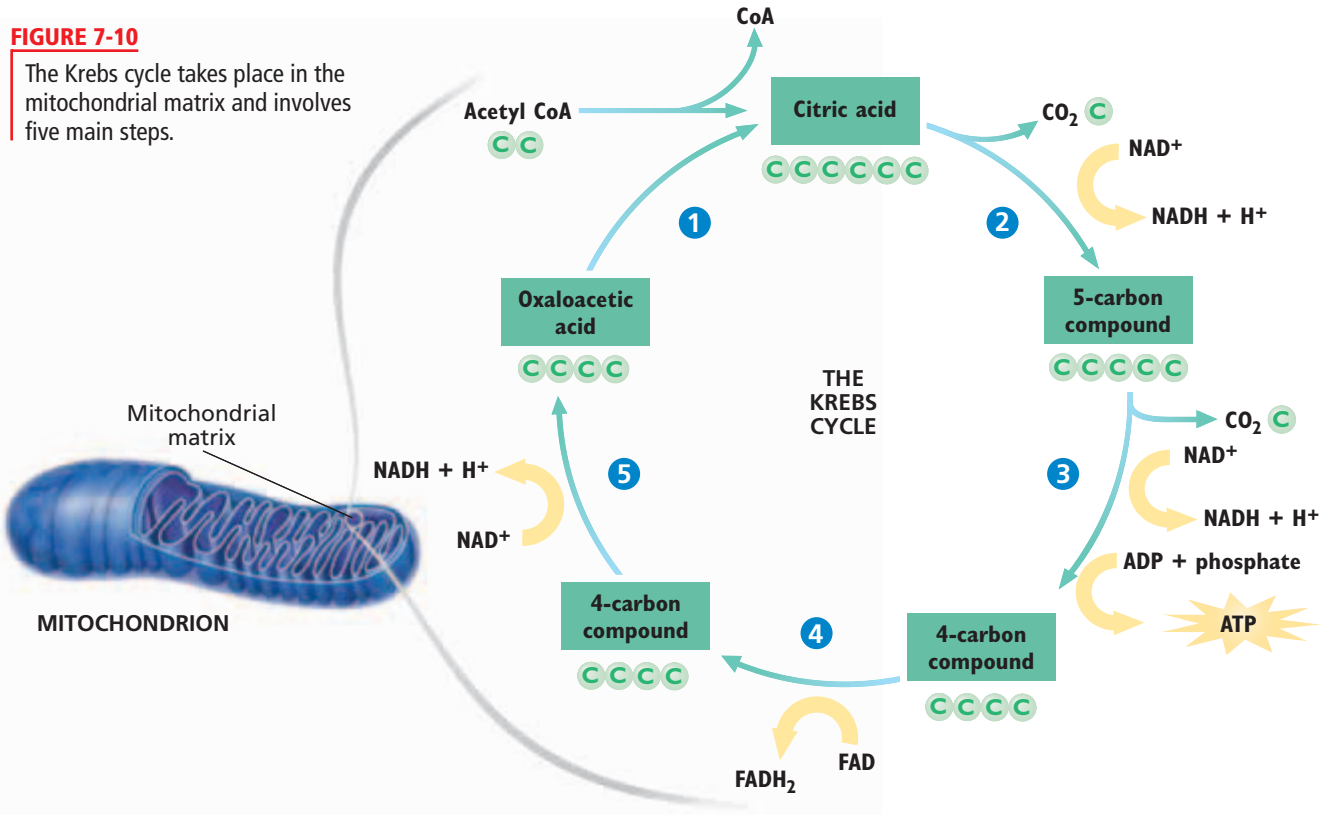
The **Krebs cycle** is a biochemical pathway that breaks down acetyl CoA, producing CO_2, hydrogen atoms, and ATP. The reactions that make up the cycle were identified by Hans Krebs (1900–1981), a German biochemist. The Krebs cycle has five main steps. In eukaryotic cells, all five steps occur in the mitochondrial matrix. Examine Figure 7-10 as you read about the steps in the Krebs cycle.

In step 1, a two-carbon molecule of acetyl CoA combines with a four-carbon compound, **oxaloacetic** (AHKS-uh-loh-uh-SEET-ik) **acid,** to produce a six-carbon compound, **citric** (SI-trik) **acid.** Notice that this reaction regenerates coenzyme A.

In step 2, citric acid releases a CO_2 molecule and a hydrogen atom to form a five-carbon compound. By losing a hydrogen atom with its electron, citric acid is oxidized. The electron in the hydrogen atom is transferred to NAD^+, reducing it to NADH.

FIGURE 7-10

The Krebs cycle takes place in the mitochondrial matrix and involves five main steps.



In step 3, the five-carbon compound formed in step 2 also releases a CO_2 molecule and a hydrogen atom, forming a four-carbon compound. Again, NAD^+ is reduced to NADH. Notice that in this step a molecule of ATP is also synthesized from ADP.

In step 4, the four-carbon compound formed in step 3 releases a hydrogen atom to form another four-carbon compound. This time, the hydrogen atom is used to reduce FAD to $FADH_2$. **FAD,** or flavin adenine dinucleotide, is a molecule very similar to NAD^+. Like NAD^+, FAD accepts electrons during redox reactions.

In step 5, the four-carbon compound formed in step 4 releases a hydrogen atom to regenerate oxaloacetic acid, which keeps the Krebs cycle operating. The electron in the hydrogen atom reduces NAD^+ to NADH.

Recall that in glycolysis one glucose molecule produces two pyruvic acid molecules, which can then form two molecules of acetyl CoA. Thus, one glucose molecule is completely broken down in two turns of the Krebs cycle. These two turns produce four CO_2 molecules, two ATP molecules, and hydrogen atoms that are used to make six NADH and two $FADH_2$ molecules. The CO_2 diffuses out of the cells and is given off as waste. The ATP can be used for energy. But note that each glucose molecule yields only two molecules of ATP through the Krebs cycle—the same number as in glycolysis.

The bulk of the energy released by the oxidation of glucose still has not been transferred to ATP. Glycolysis of one glucose molecule produces two NADH molecules, and the conversion of the two resulting molecules of pyruvic acid to acetyl CoA produces two more. Adding the six NADH molecules from the Krebs cycle gives a total of 10 NADH molecules for every glucose molecule that is oxidized. These 10 NADH molecules and the two $FADH_2$ molecules from the Krebs cycle drive the next stage of aerobic respiration. That is where most of the energy transfer from glucose to ATP actually occurs.

Quick Lab

Comparing CO_2 Production

Materials disposable gloves, lab apron, safety goggles, 250 mL flask, 100 mL graduated cylinder, phenolphthalein solution, pipet, drinking straw, water, clock, sodium hydroxide solution

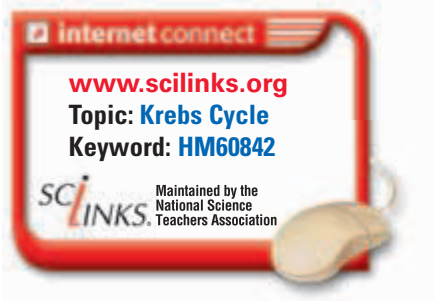
Procedure

1. Put on your disposable gloves, lab apron, and safety goggles.
2. Add 50 mL of water and four drops of phenolphthalein to the flask.
3. Use the straw to gently blow into the solution for 1 minute. Add the sodium hydroxide one drop at a time, and gently swirl the flask. Record the number of drops you use.
4. When the liquid turns pink, stop adding drops.
5. Empty and rinse your flask as your teacher directs, and repeat step 2. Walk vigorously for 2 minutes, and repeat steps 3 and 4.

Analysis Which trial produced the most carbon dioxide? Which trial used the most energy?

ELECTRON TRANSPORT CHAIN AND CHEMIOSMOSIS

The electron transport chain, linked with chemiosmosis, constitutes the second stage of aerobic respiration. Recall that the *electron transport chain* is a series of molecules in a membrane that transfer electrons from one molecule to another. In eukaryotic cells, the electron transport chain and the enzyme ATP synthase are embedded in the inner membrane of the mitochondrion in folds called *cristae.* In prokaryotes, the electron transport chain is in the cell membrane. ATP is produced by the electron transport chain when NADH and $FADH_2$ release hydrogen atoms, regenerating NAD^+ and FAD. To understand how ATP is produced, you must follow what happens to the electrons and protons that make up these hydrogen atoms.



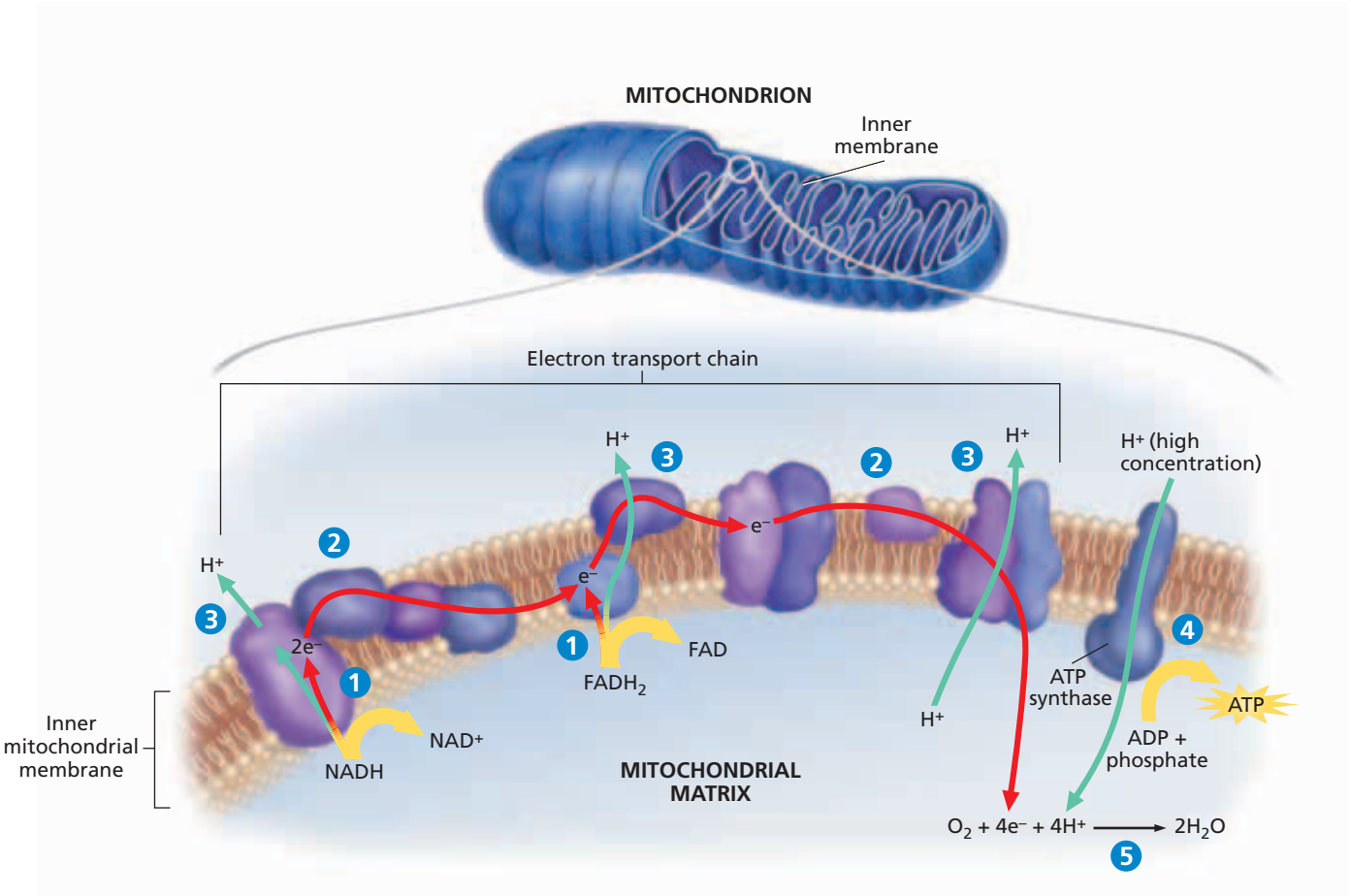


FIGURE 7-11

Electron transport and chemiosmosis take place along the inner mitochondrial membrane and involve five steps.

The electrons in the hydrogen atoms from NADH and $FADH_2$ are at a high energy level. In the electron transport chain, these electrons are passed along a series of molecules embedded in the inner mitochondrial membrane, as shown in Figure 7-11. In step 1, NADH and $FADH_2$ give up electrons to the electron transport chain. NADH donates electrons at the beginning, and $FADH_2$ donates them farther down the chain. These molecules also give up protons (hydrogen ions, H^+). In step 2, the electrons are passed down the chain. As they move from molecule to molecule, they lose energy. In step 3, the energy lost from the electrons is used to pump protons from the matrix, building a high concentration of protons between the inner and outer membranes. Thus, a concentration gradient of protons is created across the inner membrane. An electrical gradient is also created, as the protons carry a positive charge.

In step 4, the concentration and electrical gradients of protons drive the synthesis of ATP by chemiosmosis, the same process that generates ATP in photosynthesis. ATP synthase molecules are embedded in the inner membrane, near the electron transport chain molecules. As protons move through ATP synthase and down their concentration and electrical gradients, ATP is made from ADP and phosphate. In step 5, oxygen is the final acceptor of electrons that have passed down the chain. Oxygen also accepts protons that were part of the hydrogen atoms supplied by NADH and $FADH_2$. The protons, electrons, and oxygen all combine to form water, as shown by the equation in step 5.

MITOCHONDRIA: Many Roles in Disease

Every cell contains very small organelles that are known as *mitochondria*. Mitochondria generate almost all of the ATP that fuels the activity in living organisms. Scientists have known for years that certain diseases are directly caused by mitochondrial dysfunction. However, new research shows that mitochondria may play roles in the symptoms of aging and may contribute to the development of Alzheimer's disease and cancer.

Mitochondrial Diseases

Mitochondria are very unusual organelles, because they have their own DNA. Mutations in mitochondrial DNA are responsible for several rare but serious disorders. Examples include *Leigh's syndrome,* a potentially deadly childhood disease that causes loss of motor and verbal skills, and *Pearson's syndrome,* which causes childhood bone marrow dysfunction and pancreatic failure.

Mitochondria in Aging

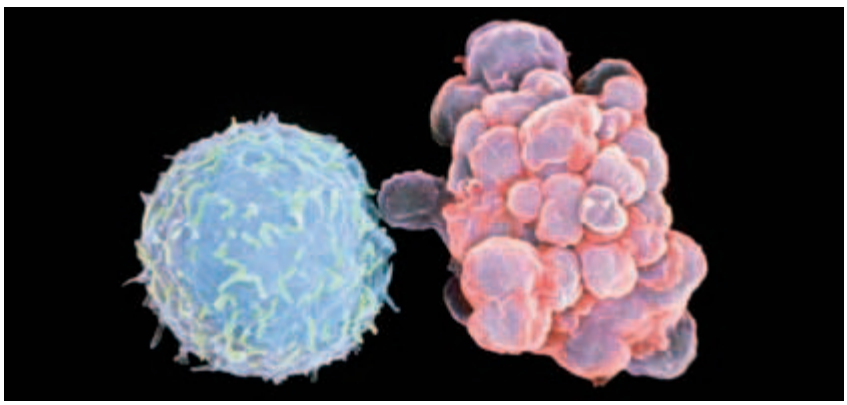
Mitochondria may play a role in causing some problems associated with aging. Chemical reactions of the Krebs cycle and electron transport chain sometimes release stray electrons that "leak out" of mitochondria into the cell. These electrons can combine with oxygen to form free radicals. Free radicals are especially reactive atoms or groups of atoms with one or more unpaired electrons. Free radicals quickly react with other molecules, such as DNA and protein; these reactions may disrupt cell activity. Biologists think that many characteristics of human aging, from wrinkles to mental decline, may be brought on partly by the damage caused by free radicals.

Mitochondria in Other Diseases

Recent research also shows that mitochondria may be important in diseases related to *apoptosis,* or programmed cell death. Scientists have shown that signals from the mitochondria are instrumental in starting and/or continuing the apoptosis process. Yet sometimes, mitochondria mistakenly push or fail to push the "self-destruct button" in cells. In cases of stroke and Alzheimer's disease, for example, mitochondria may cause too many cells to die, which may lead to mental lapses and other symptoms. In the case of cancer, mitochondria may fail to initiate apoptosis. This failure could allow tumor cells to grow and invade healthy tissues.

Promise of New Treatments

Researchers are now investigating mitochondria as targets for drug treatments to prevent or treat a variety of conditions. Conversely, researchers are also studying how certain conditions impair mitochondrial function. One day, scientists may use knowledge about mitochondria to help ease the symptoms of aging and to cure or prevent many diseases.



Mitochondria may play a role in programmed cell death, or apoptosis. A white blood cell undergoing apoptosis (right) looks very different from a normal white blood cell (left). (SEM 2,600×)

REVIEW

1. How do mitochondria contribute to free radical formation?
2. How could research on mitochondria be helpful to society?
3. **Critical Thinking** Evaluate the following statement: Mitochondria—we can't live with them; we can't live without them.

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The Importance of Oxygen

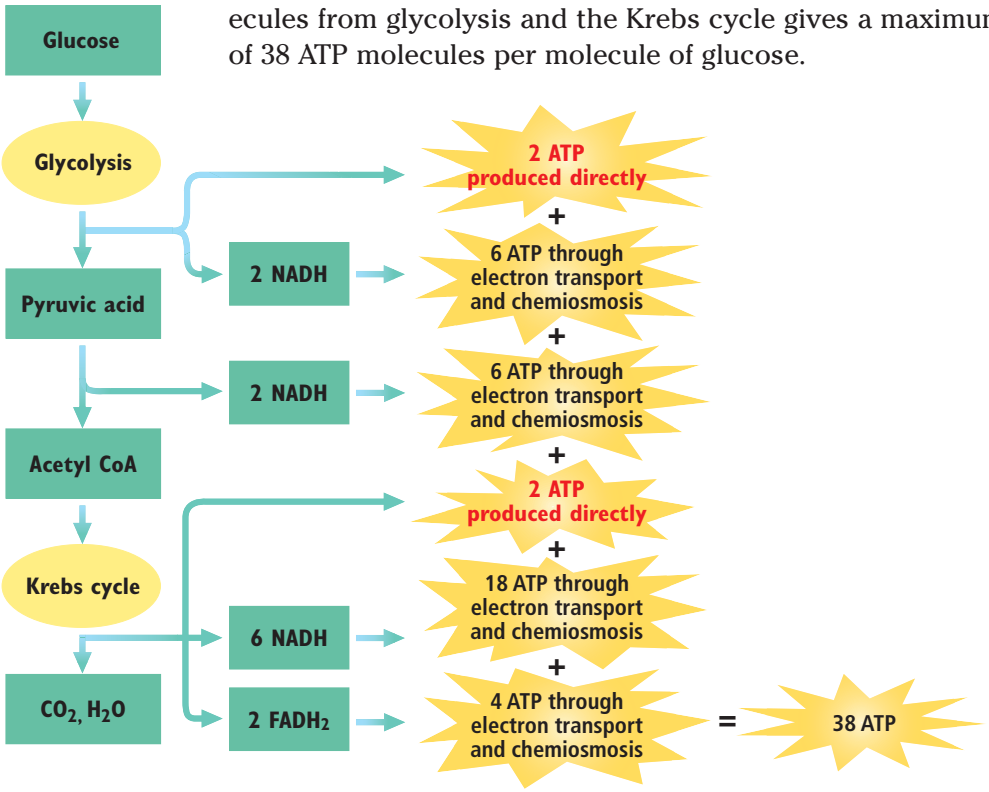
ATP can be synthesized by chemiosmosis only if electrons continue to move from molecule to molecule in the electron transport chain. The last molecule in the electron transport chain must pass electrons on to a final electron acceptor. Otherwise, the electron transport chain would come to a halt. Consider what would happen if cars kept entering a dead-end, one-way street. At some point, no more cars could enter the street. Similarly, if the last molecule could not "unload" the electrons it accepts, then no more electrons could enter the electron transport chain and ATP synthesis would stop. By accepting electrons from the last molecule in the electron transport chain, oxygen allows additional electrons to pass along the chain. As a result, ATP can continue to be made through chemiosmosis.

EFFICIENCY OF CELLULAR RESPIRATION

How many ATP molecules are made in cellular respiration? Refer to Figure 7-12 as you calculate the total. Recall that glycolysis and the Krebs cycle each produce two ATP molecules directly for every glucose molecule that is oxidized. Furthermore, each NADH molecule that supplies the electron transport chain can generate three ATP molecules, and each $FADH_2$ molecule can generate two ATP molecules. Thus, the 10 NADH and two $FADH_2$ molecules made through glycolysis, conversion of pyruvic acid to acetyl CoA, and the Krebs cycle can produce up to 34 ATP molecules by the electron transport chain and chemiosmosis. Adding the four ATP molecules from glycolysis and the Krebs cycle gives a maximum yield of 38 ATP molecules per molecule of glucose.

FIGURE 7-12

Follow each pathway to see how one glucose molecule can generate up to 38 ATP molecules in cellular respiration when oxygen is present.



The actual number of ATP molecules generated through cellular respiration varies from cell to cell. In most eukaryotic cells, the NADH that is made in the cytosol during glycolysis cannot diffuse through the inner membrane of the mitochondrion. Instead, it must be actively transported into the mitochondrial matrix. The active transport of NADH consumes ATP. As a result, most eukaryotic cells produce only about 36 ATP molecules per glucose molecule.

FIGURE 7-13
Through cellular respiration, cells are more efficient at generating energy than many machines—including cars.

The efficiency of cellular respiration can vary depending on conditions in the cell. In general, the efficiency when 38 ATP molecules are generated can be estimated as shown below:

$$\text{Efficiency of cellular respiration} = \frac{\text{Energy required to make ATP}}{\text{Energy released by oxidation of glucose}}$$

$$= \frac{38 \times 7 \text{ kcal}}{686 \text{ kcal}} \times 100\% = 39\%$$

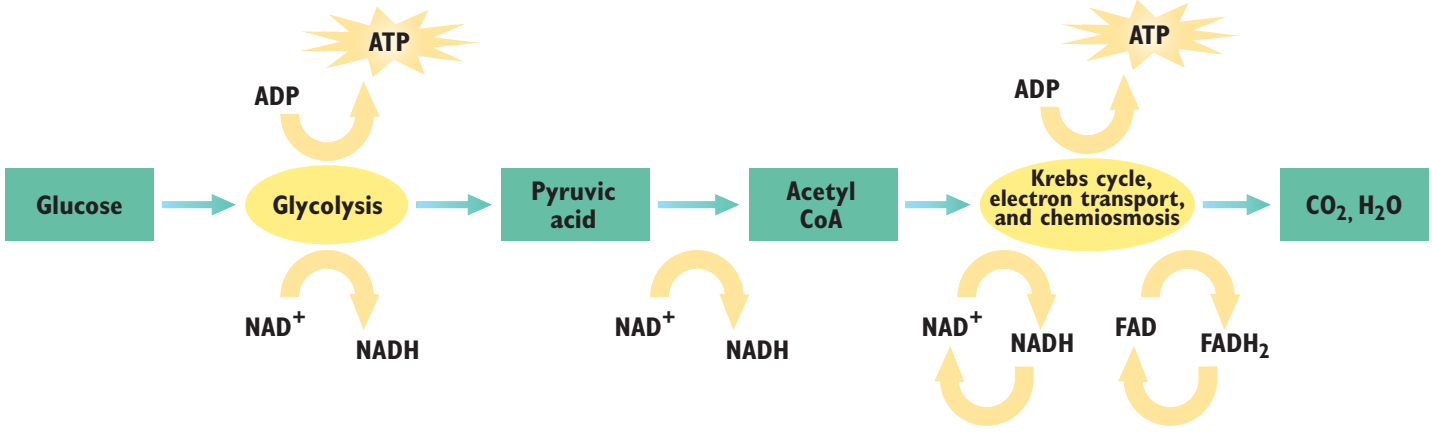
Thus, cellular respiration is nearly 20 times more efficient than glycolysis alone. In fact, the efficiency of cellular respiration is quite impressive compared with the efficiency of machines that humans have designed, such as the car shown in Figure 7-13. An automobile engine, for example, is only about 25 percent efficient in extracting energy from gasoline to move a car. Most of the remaining energy released from gasoline is lost as heat.

A SUMMARY OF CELLULAR RESPIRATION

Cellular respiration occurs in two stages, as listed below and shown in Figure 7-14:

1. Glycolysis—Glucose is converted into pyruvic acid, producing a small amount of ATP and NADH.
2. Aerobic respiration—Pyruvic acid is converted into CO_2 and water in the presence of oxygen, producing a large amount of ATP.

FIGURE 7-14
Cellular respiration occurs in two stages: glycolysis and aerobic respiration (which includes the conversion of pyruvic acid to acetyl CoA, the Krebs cycle, the electron transport chain, and chemiosmosis).



The following equation summarizes the complete oxidation of glucose in cellular respiration:

$$C_6H_{12}O_6 + 6O_2 \longrightarrow 6CO_2 + 6H_2O + \text{energy (ATP)}$$

In addition to glucose, many other compounds can be used as fuel in cellular respiration. Molecules derived from the breakdown of fats, proteins, and carbohydrates can enter glycolysis or the Krebs cycle at various points in order to yield more energy to an organism.

The equation above can be considered the opposite of the overall equation for photosynthesis, if glucose is considered to be a product of photosynthesis:

$$6CO_2 + 6H_2O \xrightarrow{\text{light energy}} C_6H_{12}O_6 + 6O_2$$

That is, the products of photosynthesis are reactants in celluar respiration, and the products of cellular respiration are reactants in photosynthesis. However, cellular respiration is not the reverse of photosynthesis. These two processes involve different biochemical pathways and occur at different sites inside cells.

Another Role of Cellular Respiration

Cellular respiration provides the ATP that all cells need to support the activities of life. But providing cells with ATP is not the only important function of cellular respiration. Cells also need specific organic compounds from which to build the macromolecules that compose their own structures. Some of these specific compounds may not be contained in the food that a heterotroph consumes.

The molecules formed at different steps in glycolysis and the Krebs cycle are often used by cells to make the compounds that are missing in food. Compounds formed during glycolysis and the Krebs cycle can be diverted into other biochemical pathways in which the cell makes the molecules it requires. For example, approximately 10 of the amino acids needed by the human body can be made with compounds diverted from the Krebs cycle.

SECTION 2 REVIEW

1. In what part of a mitochondrion does the Krebs cycle occur?
2. In what part of a mitochondrion is the electron transport chain located?
3. What four-carbon compound is regenerated at the end of the Krebs cycle?
4. What molecule does oxygen become a part of at the end of the electron transport chain?
5. Is cellular respiration more or less efficient than fermentation?
6. List the two processes that together result in cellular respiration.

CRITICAL THINKING

7. **Predicting Results** Sometimes protons leak out of a cell or are used for purposes other than ATP production. How would this loss of protons affect the production of ATP in aerobic respiration?
8. **Inferring Relationships** How does the arrangement of the cristae in the inner membrane of mitochondria affect the rate of aerobic respiration? Explain your answer.
9. **Making Calculations** Calculate the efficiency of cellular respiration if a cell generates 32 ATP molecules per molecule of glucose.

CHAPTER HIGHLIGHTS

SECTION 1 Glycolysis and Fermentation

- Cellular respiration is the process by which cells break down organic compounds to produce ATP.
- Cellular respiration begins with glycolysis, which takes place in the cytosol of cells. During glycolysis, one glucose molecule is oxidized to form two pyruvic acid molecules. Glycolysis results in a net production of two ATP molecules and two NADH molecules.
- If oxygen is not present, glycolysis may lead to anaerobic pathways in which pyruvic acid is converted into other organic molecules in the cytosol. Glycolysis combined with these anaerobic pathways is called *fermentation.* Fermentation does not produce ATP, but it does regenerate NAD^+, which helps keep glycolysis operating.
- In lactic acid fermentation, an enzyme converts pyruvic acid into lactic acid.
- In alcoholic fermentation, other enzymes convert pyruvic acid into ethyl alcohol and CO_2.
- Through glycolysis, only about 2 percent of the energy available from the oxidation of glucose is captured as ATP.

Vocabulary

cellular respiration (p.131)
pyruvic acid (p. 131)
NADH (p. 131)
anaerobic (p. 131)
aerobic respiration (p. 131)
glycolysis (p. 132)
NAD^+ (p. 133)
fermentation (p. 133)
lactic acid fermentation (p. 134)
alcoholic fermentation (p. 135)
kilocalorie (p. 135)

SECTION 2 Aerobic Respiration

- In eukaryotic cells, the processes of aerobic respiration occur inside the mitochondria. The Krebs cycle occurs in the mitochondrial matrix. The electron transport chain is embedded in the inner mitochondrial membrane.
- In the mitochondrial matrix, pyruvic acid produced in glycolysis is converted into acetyl CoA. Then, acetyl CoA enters the Krebs cycle. Each turn of the Krebs cycle generates three NADH, one $FADH_2$, one ATP, and two CO_2 molecules.
- NADH and $FADH_2$ donate electrons to the electron transport chain in the inner mitochondrial membrane. These electrons are passed from molecule to molecule in the transport chain.
- As electrons pass along the electron transport chain, protons donated by NADH and $FADH_2$ are pumped into the space between the inner and outer mitochondrial membranes. This pumping creates a concentration gradient of protons and a charge gradient across the inner mitochondrial membrane. As protons move through ATP synthase, down their concentration and charge gradients, and back into the mitochondrial matrix, ATP is produced.
- During aerobic respiration, oxygen accepts both protons and electrons from the electron transport chain. As a result, oxygen is converted to water.
- Cellular respiration can produce up to 38 ATP molecules from the oxidation of a single molecule of glucose. Thus, up to 39 percent of the energy released by the oxidation of glucose can be transferred to ATP. However, most eukaryotic cells produce only about 36 ATP molecules per molecule of glucose.
- Cellular respiration uses the processes of glycolysis and aerobic respiration to obtain energy from organic compounds.

Vocabulary

mitochondrial matrix (p. 137)
acetyl CoA (p. 138)
Krebs cycle (p. 138)
oxaloacetic acid (p. 138)
citric acid (p. 138)
FAD (p. 139)

CHAPTER REVIEW

USING VOCABULARY

1. For each pair of terms, explain the relationship between the terms.
   a. *alcoholic fermentation* and *lactic acid fermentation*
   b. *glycolysis* and *pyruvic acid*
   c. *mitochondrial matrix* and *Krebs cycle*
2. Use the following terms in the same sentence: *acetyl CoA, citric acid,* and *oxaloacetic acid*.
3. Explain the difference between the terms *fermentation* and *cellular respiration*.
4. **Word Roots and Origins** The word *glycolysis* is derived from the Greek words *glykys,* which means "sweet," and *lysis,* which means "loosening." Using this information, explain why the term *glycolysis* is a good name for the biological process it describes.

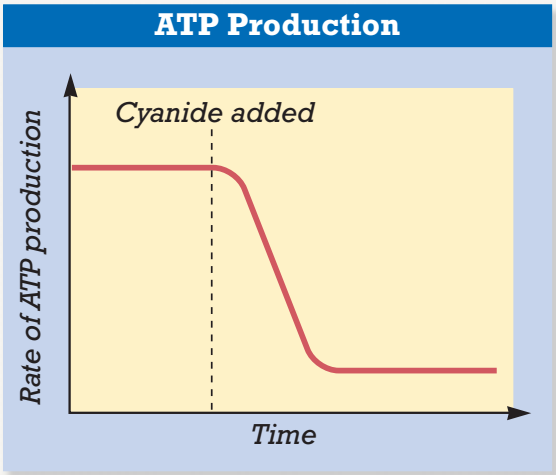
UNDERSTANDING KEY CONCEPTS

5. **Compare** the two stages of cellular respiration.
6. **Explain** why the net yield of ATP molecules in glycolysis is two, even though four ATP molecules are produced.
7. **Describe** what causes your muscles to become fatigued and sometimes develop cramps when you exercise too strenuously.
8. **Calculate** the efficiency of glycolysis if the number of ATP molecules produced during glycolysis were 5 times greater.
9. **Name** the two areas of the mitochondrion where the major stages of aerobic respiration occur.
10. **Explain** the importance of the cyclical nature of the Krebs cycle.
11. **Define** the specific role that oxygen plays in the electron transport chain.
12. **Summarize** the process of electron transport and chemiosmosis, including where the electron transport chain is located, what structures make up the electron transport chain, where the electrons come from and their characteristics, what happens to them as they move along the electron transport chain and as they reach the end of the chain, and what is accomplished by this process.
13. **Explain** why most eukaryotic cells produce fewer than 38—the maximum number possible—ATP molecules for every glucose molecule that is oxidized by cellular respiration.
14. **Compare** the efficiency of glycolysis alone with the efficiency of cellular respiration.
15. **Unit 3—Cellular Respiration**
    

    Write a report summarizing how exercise physiologists regulate the diets and training of athletes. Find out how diets vary according to the needs of each athlete. Research the relationship between exercise and metabolism.
16. 
    CONCEPT MAPPING Use the following terms to create a concept map that shows the activities of fermentation: *alcoholic fermentation, anaerobic pathway, fermentation, glycolysis, lactic acid fermentation,* and *pyruvic acid*.

CRITICAL THINKING

17. **Evaluating Results** Some yeast can use fermentation or cellular respiration. If oxygen is present, these yeast cells consume glucose much more slowly than if oxygen is absent. Explain this observation.
18. **Inferring Relationships** How does cellular respiration ultimately depend on photosynthesis?
19. **Predicting Results** Some eukaryotic cells must use ATP to move NADH into the mitochondrial matrix. Would you expect cellular respiration to be more or less efficient in prokaryotic cells than in eukaryotic cells? Explain your answer.
20. **Interpreting Graphics** The graph below shows the rate of ATP production by a culture of yeast cells over time. At the time indicated by the dashed line, cyanide was added to the culture. Cyanide blocks the flow of electrons to O_2 from the electron transport chain in mitochondria. Explain why adding cyanide affects ATP production in the way indicated by the graph.



Standardized Test Preparation

DIRECTIONS: Choose the letter of the answer choice that best answers the question.

1. Which of the following must pyruvic acid be converted into before the Krebs cycle can proceed?
   A. NADH
   B. glucose
   C. citric acid
   D. acetyl CoA

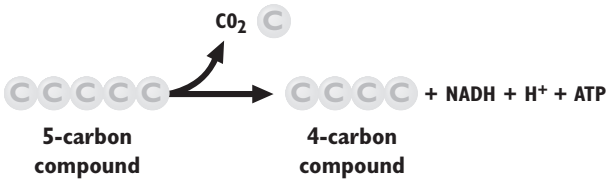
2. Which of the following occurs in lactic acid fermentation?
   F. Oxygen is consumed.
   G. Lactic acid is converted into pyruvic acid.
   H. NAD^+ is regenerated for use in glycolysis.
   J. Electrons pass through the electron transport chain.

3. Which of the following is not a product of the Krebs cycle?
   A. CO_2
   B. ATP
   C. $FADH_2$
   D. ethyl alcohol

4. In which way is cellular respiration similar to photosynthesis?
   F. They both make G3P.
   G. They both involve ATP.
   H. They both involve chemiosmosis.
   J. all of the above

5. ATP is synthesized in chemiosmosis when which of the following moves across the inner mitochondrial membrane?
   A. NADH
   B. oxygen
   C. protons
   D. citric acid

INTERPRETING GRAPHICS: The illustration shows part of a biochemical pathway. Use the illustration to answer the question that follows.

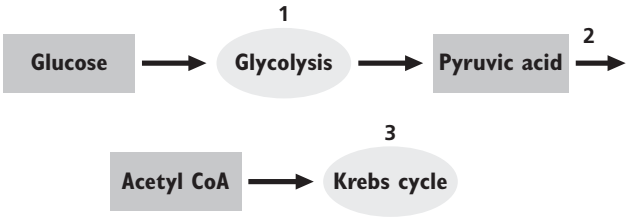


6. This reaction occurs during which of the following processes?
   F. Krebs cycle
   G. acetyl CoA formation
   H. alcoholic fermentation
   J. lactic acid fermentation

DIRECTIONS: Complete the following analogy.

7. glycolysis : pyruvic acid :: Krebs cycle :
   A. O_2
   B. ATP
   C. lactic acid
   D. acetyl CoA

INTERPRETING GRAPHICS: The illustration below shows some stages and reactants of cellular respiration. Use the illustration to answer the question that follows.



8. At which of the points is ATP, the main energy currency of the cell, produced?
   F. 1 only
   G. 2 only
   H. 1 and 3
   J. 1, 2, and 3

SHORT RESPONSE

The inner membrane of a mitochondrion is folded; these folds are called *cristae*.

How might cellular respiration be different if the inner mitochondrial membrane were not folded?

EXTENDED RESPONSE

Oxygen is produced during the reactions of photosynthesis, and it is used in the reactions of cellular respiration.

Part A How does oxygen get into or out of chloroplasts and mitochondria?

Part B What are the roles of oxygen in the processes of photosynthesis and cellular respiration, and how are the roles similar?

Test TIP Make sure you get plenty of rest the night before the test. Eat a healthy breakfast the day of the test and wear comfortable clothing.

Observing Cellular Respiration

OBJECTIVES

- Measure the rate of cellular respiration in germinating seeds.
- Compare cellular respiration rates in germinating and nongerminating seeds.

PROCESS SKILLS

- experimenting
- collecting data
- analyzing data

MATERIALS

- volumeter jar and screw-on lid
- tap water at room temperature
- ring stand with support ring
- 8.5 in. × 11 in. piece of cardboard
- 8.5 in. × 11 in. sheet of white paper
- cellophane tape
- 40 germinating corn or pea seeds
- 40 nongerminating corn or pea seeds
- 100 mL graduated cylinder
- glass or plastic beads
- 3 plastic or paper cups
- 3 volumeters
- cotton
- 3 soda-lime packets
- forceps
- Pasteur pipet
- colored water
- ruler with millimeter markings

Background

1. When glucose is oxidized in cellular respiration, what other substance is consumed and what substances are produced?
2. Write the balanced equation for the complete oxidation of glucose in cellular respiration.

PART A Setting Up the Apparatus

1. Pour water into the volumeter jar until the jar is about two-thirds full. Screw on the lid.
2. Place the cardboard on top of the ring stand support ring, and tape a sheet of white paper to the cardboard. Adjust the support ring so that the cardboard is level, as shown in the illustration below.
3. **CAUTION Put on a lab apron, safety goggles, and protective gloves. Keep the seeds, which may have been treated with a fungicide, away from your skin.** Place 40 germinating seeds in a graduated cylinder and measure their volume. Do the same for the 40 nongerminating seeds.
4. Add beads to the seeds that have the smaller volume until the combined volume is the same as the volume of the other group of seeds. Then transfer both groups to separate cups. To a third cup, add a volume of beads equal to the volume of each of the other two cups.
5. Remove the stopper assemblies from three volumeter tubes and transfer the contents of the three cups to separate tubes. Place a 2 cm plug of dry cotton into each tube, leaving a gap of about 1 cm between the cotton and the seeds or beads.
6. **CAUTION Soda lime is corrosive. Do not touch it. If it gets on your skin or clothing, wash it off at the sink. If it gets in your eyes, immediately flush it out at the eyewash station while calling to your teacher.** Using forceps, place a packet of soda lime wrapped in gauze on top of the cotton plug in each tube. Soda lime absorbs the CO_2 that is produced as a result of respiration.
7. Gently but firmly press the stopper assembly into each volumeter tube. Insert the tubes into the volumeter jar through the large holes in the lid.

8. Use a Pasteur pipet to place a small drop of colored water into the three capillary tubes. Tilt two of the tubes slightly until the drops are lined up with the outermost calibration mark. Carefully attach these tubes to the latex tubing on the two volumeter tubes containing seeds. Position the drop in the third capillary tube near the middle of the tube. Attach this tube to the volumeter tube that contains only beads. This volumeter is the control volumeter. Tape all three capillary tubes to the paper on the ring stand.
9. Wait 5 min for the temperature to become uniform throughout the volumeter jar. While you wait, make a data table like the one shown below. Then return the drops in the capillary tubes to their original positions by using the syringes to inject air into or withdraw air from the volumeter tubes, if necessary.

PART B Measuring Respiration Rates

10. On the paper beneath the capillary tubes, mark the position of one end of each drop of colored water. Note the time. Repeat this procedure every 5 min for 20 min. If respiration is rapid, you may have to reposition the drops as you did in Step 9. In which direction would you expect a drop to move if respiration in the volumeter tube were causing it to move?
11. Remove the paper from the ring stand and use a ruler to measure the distance moved by the drops during each time interval. If you repositioned any drops in Step 10, be sure to add this adjustment when you measure the distances. Enter the measurements in the "Uncorrected" columns in your data table.
12.  Clean up your materials and wash your hands before leaving the lab.

Analysis and Conclusions

1. No respiration should have occurred in the control volumeter, which contained only beads. Therefore, any movement of the drop in the control volumeter must have been caused by changes in the temperature of the volumeter jar or the air pressure in the classroom. Since these changes would have affected all three volumeters to the same extent, you must subtract the distance you measured for the control volumeter from the distances you measured for the other two volumeters. Do this calculation for each time interval, and enter the results in the "Corrected" columns in your data table.
2. Each capillary tube has a capacity of 0.063 mL between each 1 cm mark on the tube. Use this information to calculate the volume of O_2 consumed by the germinating and nongerminating seeds during each time interval. Enter these results in your data table.
3. Prepare a graph to show the volume of O_2 consumed versus time; use different symbols or colors to distinguish the points for the germinating seeds from those for the nongerminating seeds. Make sure each point represents the cumulative volume of O_2 consumed. For example, the point plotted for the 15–20 min interval should represent the volume consumed during that interval plus the volume consumed during all of the preceding intervals. Draw the best-fit line through the points for each group of seeds. From the slope of this line, calculate the average rate of respiration in milliliters of O_2 per minute for both groups of seeds.
4. Which group of seeds had the higher average rate of respiration? What is the significance of this difference in terms of a seed's ability to survive for long periods?

MEASUREMENTS OF CELLULAR RESPIRATION

Time interval (min)	Distance moved by drops in volumeters (mm)					Volume of O_2 consumed (mL)	
	Control	Germinating seeds		Nongerminating seeds			
		Uncorrected	Corrected	Uncorrected	Corrected	Germinating	Nongerminating
0–5							
5–10							
10–15							
15–20							