4.5 Cellular Respiration in Detail

KEY CONCEPT Cellular respiration is an aerobic process with two main stages.

MAIN IDEAS

- Glycolysis is needed for cellular respiration.
- The Krebs cycle is the first main part of cellular respiration.
- The electron transport chain is the second main part of cellular respiration.

Review

glycolysis, Krebs cycle, electron transport chain, cellular respiration, aerobic respiration

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Connect If chloroplasts are like tiny factories that make products, mitochondria are like power plants that burn fuel to produce electricity. In a power plant, a processed fuel is burned in the presence of oxygen and energy is released as useful electricity. During cellular respiration, oxygen and digested molecules from food are used to produce useful energy in the form of ATP.

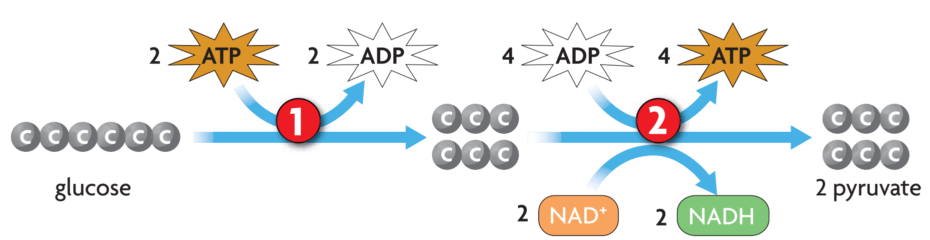
MAIN IDEA

Glycolysis is needed for cellular respiration.

In Section 4.4 you read a summary of how cellular respiration produces ATP molecules. But cellular respiration, like photosynthesis, is a very complex process. For example, glucose and oxygen do not react directly with one another, and many chemical reactions, such as glycolysis, must take place.

Glycolysis is an ongoing process in all cells, including yours. It takes place in the cytoplasm before cellular respiration, and it does not require oxygen. Glycolysis makes a small number of ATP molecules, but its other products are much more important. If oxygen is available, the products of glycolysis are used to produce many more ATP molecules through cellular respiration. The process of glycolysis can be summarized as follows.

1. Two ATP molecules are used to energize a glucose molecule. The glucose molecule is split into two three-carbon molecules. A series of enzymes and chemical reactions rearranges the three-carbon molecules.
2. Energized electrons from the three-carbon molecules are transferred to molecules of NAD^+. Molecules of NADH are formed. A series of reactions converts the three-carbon molecules to pyruvate (py-ROO-vayt), which enters cellular respiration. Four ATP molecules are made.



Connecting CONCEPTS

Fermentation When cells do not have a supply of oxygen for the aerobic processes of cellular respiration, the anaerobic processes of fermentation take place. You will learn about fermentation in Section 4.6.

Although glycolysis makes four ATP molecules, recall that two ATP molecules are used to first split the glucose molecule. So the breakdown of one glucose molecule by glycolysis gives a net gain of two ATP molecules. The pyruvate and NADH produced by glycolysis are used for cellular respiration when oxygen is present. NADH is an electron carrier like NADPH, the electron carrier in photosynthesis.

Summarize How does glycolysis result in a net gain of two ATP molecules?

MAIN IDEA

The Krebs cycle is the first main part of cellular respiration.

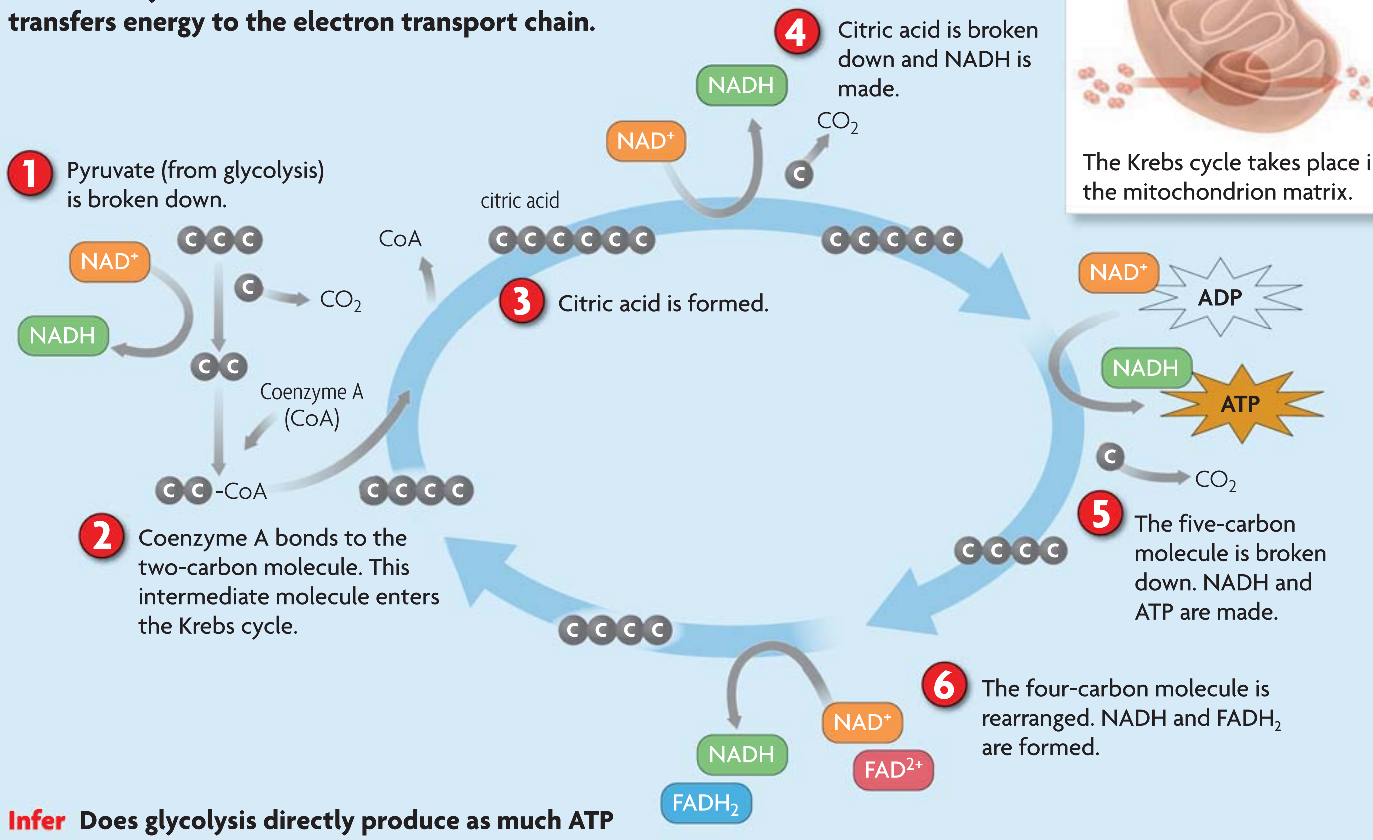
Cellular respiration makes many more ATP molecules than does glycolysis. It begins with the breakdown of pyruvate in steps 1 and 2 below. The process continues with the Krebs cycle, shown in **FIGURE 4.14**. Notice that steps 1, 4, and 5 below are very similar. In those steps, a carbon-based molecule is split, a molecule of carbon dioxide is formed, and energy-carrying NADH molecules are made. In fact, the main function of the Krebs cycle is to transfer high-energy electrons to molecules that carry them to the electron transport chain. The Krebs cycle is also sometimes called the citric acid cycle because citric acid is the first molecule formed, as you can see in step 3 below.

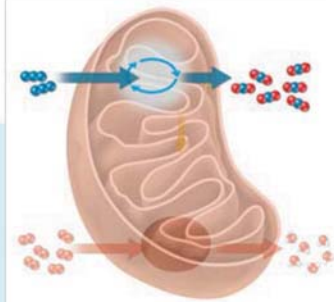
FIGURE 4.13 Gasoline engines burn carbon-based molecules in the presence of oxygen, and they release water, carbon dioxide, and energy. The overall process of cellular respiration is similar.

1. **Pyruvate broken down** A pyruvate molecule is split into a two-carbon molecule and a molecule of carbon dioxide, which is given off as a waste product. High-energy electrons are transferred from the two-carbon molecule to NAD^+, forming a molecule of NADH. The NADH moves to the electron transport chain.
2. **Coenzyme A** A molecule called coenzyme A bonds to the two-carbon molecule made from the breakdown of pyruvate. This intermediate molecule goes to the Krebs cycle.
3. **Citric acid formed** The two-carbon part of the intermediate molecule is added to a four-carbon molecule to form a six-carbon molecule called citric acid. Coenzyme A goes back to step 2.
4. **Citric acid broken down** The citric acid molecule is broken down by an enzyme and a five-carbon molecule is formed. A molecule of NADH is made and moves out of the Krebs cycle. A molecule of carbon dioxide is given off as a waste product.
5. **Five-carbon molecule broken down** The five-carbon molecule is broken down by an enzyme. A four-carbon molecule, a molecule of NADH, and a molecule of ATP are formed. The NADH leaves the Krebs cycle. Carbon dioxide is given off as a waste product.
6. **Four-carbon molecule rearranged** Enzymes rearrange the four-carbon molecule. High-energy electrons are released. Molecules of NADH and $FADH_2$, which is another electron carrier, are made. They leave the Krebs cycle and the four-carbon molecule remains.

FIGURE 4.14 The Krebs Cycle

The Krebs cycle breaks down citric acid and transfers energy to the electron transport chain.





The Krebs cycle takes place in the mitochondrion matrix.

Infer Does glycolysis directly produce as much ATP as the Krebs cycle? Indirectly? Explain your answer.

The products from the breakdown of one molecule of pyruvate are

- three molecules of carbon dioxide that are given off as a waste product
- one molecule of ATP
- four molecules of NADH to the electron transport chain
- one molecule of $FADH_2$ to the electron transport chain

Remember, glycolysis produces two pyruvate molecules. Therefore, the products above are half of what comes from one glucose molecule. The totals are six carbon dioxide, two ATP, eight NADH, and two $FADH_2$ molecules.

Analyze In what two ways is the Krebs cycle important for making ATP?

MAIN IDEA

The electron transport chain is the second main part of cellular respiration.

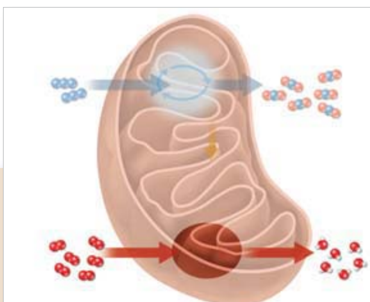
The electron transport chain takes place in and across the inner membrane of a mitochondrion. As with electron transport in photosynthesis, proteins make up the electron transport chain in cellular respiration. The proteins use energy from the electrons supplied by NADH and $FADH_2$ to pump hydrogen ions against a concentration gradient, and across the inner mitochondrial membrane.

The ions later flow back through the membrane to produce ATP. Oxygen is needed at the end of the process to pick up electrons that have gone through the chain. The electron transport chain is shown in **FIGURE 4.15.**

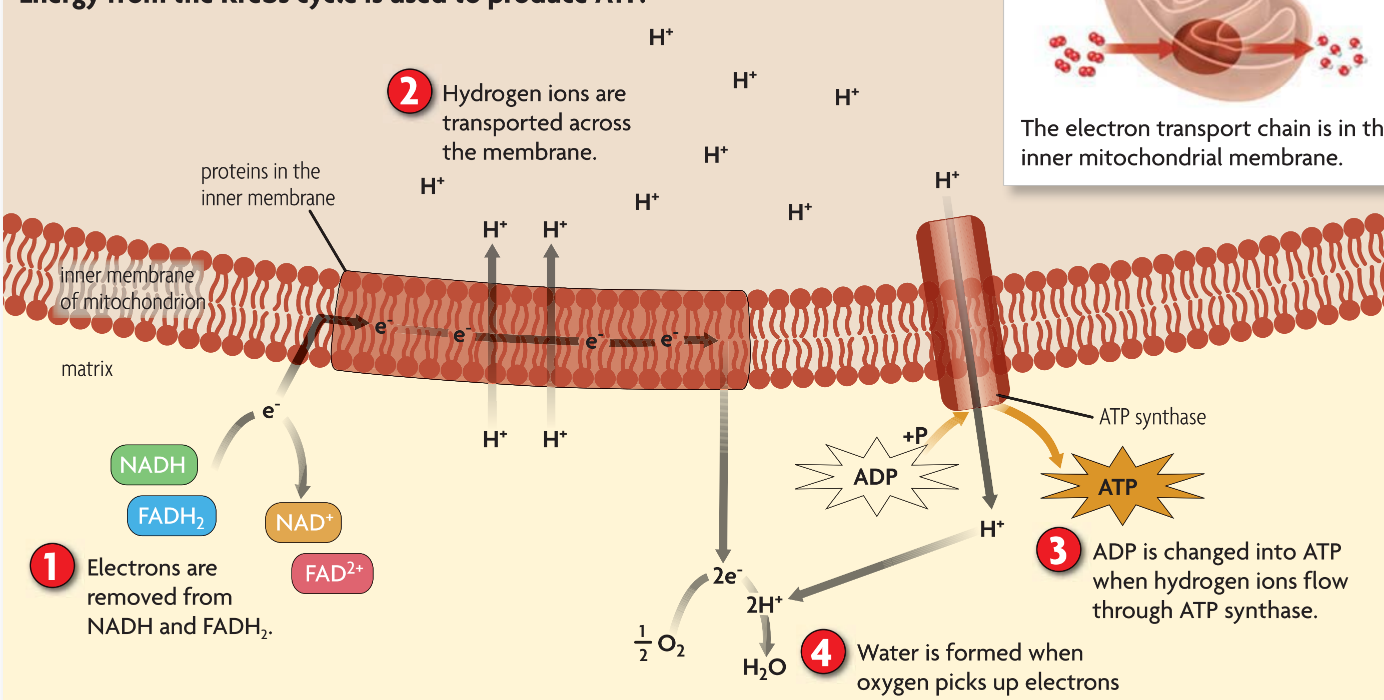
1. **Electrons removed** Proteins inside the inner membrane of the mitochondrion take high-energy electrons from NADH and $FADH_2$. Two molecules of NADH and one molecule of $FADH_2$ are used.
2. **Hydrogen ions transported** High-energy electrons travel through the proteins in the electron transport chain. The proteins use energy from the electrons to pump hydrogen ions across the inner membrane to produce a chemiosmotic gradient, just as in photosynthesis. The hydrogen ions build up on the inside of the inner mitochondrial membrane.
3. **ATP produced** Just as in photosynthesis, the flow of hydrogen ions is used to make ATP. Hydrogen ions diffuse through a protein channel in the inner membrane of the mitochondrion. The channel is part of the ATP synthase enzyme. ATP synthase adds phosphate groups to ADP to make ATP molecules. For each pair of electrons that passes through the electron transport chain, an average of three ATP molecules are made.
4. **Water formed** Oxygen finally enters the cellular respiration process. The oxygen picks up electrons and hydrogen ions to form water. The water molecules are given off as a waste product.

FIGURE 4.15 The Electron Transport Chain

Energy from the Krebs cycle is used to produce ATP.



The electron transport chain is in the inner mitochondrial membrane.



Explain **How are hydrogen ions involved in the electron transport chain?**

The products of cellular respiration—including glycolysis—are

- Carbon dioxide from the Krebs cycle and from the breakdown of pyruvate before the Krebs cycle
- Water from the electron transport chain
- A net gain of up to 38 ATP molecules for every glucose molecule—2 from glycolysis, 2 from the Krebs cycle, and up to 34 from the electron transport chain

FIGURE 4.16 Like sandbags passed down a line of people, high-energy electrons are passed along a chain of proteins in the inner mitochondrial membrane.

Comparing Cellular Respiration and Photosynthesis

Again, think about how photosynthesis and cellular respiration are approximately the reverse of each other. Photosynthesis stores energy from sunlight as chemical energy. In contrast, cellular respiration releases stored energy as ATP and heat. Look at **FIGURE 4.17**, and think about other similarities and differences between the processes.

FIGURE 4.17 PHOTOSYNTHESIS AND CELLULAR RESPIRATION

	PHOTOSYNTHESIS	CELLULAR RESPIRATION
Organelle for process	chloroplast	mitochondrion
Reactants	CO_2 and H_2O	sugars ($C_6H_{12}O_6$) and O_2
Electron transport chain	proteins within thylakoid membrane	proteins within inner mitochondrial membrane
Cycle of chemical reactions	Calvin cycle in stroma of chloroplasts builds sugar molecules	Krebs cycle in matrix of mitochondria breaks down carbon-based molecules
Products	sugars ($C_6H_{12}O_6$) and O_2	CO_2 and H_2O

Recall the roles of electrons, hydrogen ions, and ATP synthase. In both processes, high-energy electrons are transported through proteins. Their energy is used to pump hydrogen ions across a membrane. And the flow of hydrogen ions through ATP synthase produces ATP. As you can see, the parts of the processes are very similar, but their end points are very different.

Analyze How does the electron transport chain depend on the Krebs cycle?

4.5 ASSESSMENT

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REVIEWING MAIN IDEAS

1. What is the role of pyruvate in cellular respiration?
2. Describe in your own words the function of the Krebs cycle.
3. Explain the functions of electrons, hydrogen ions, and oxygen in the electron transport chain.

CRITICAL THINKING

4. **Compare and Contrast** Describe the similarities and differences between the Krebs cycle and the Calvin cycle.
5. **Evaluate** Is oxygen necessary for the production of all ATP in your cells? Why or why not?

Connecting CONCEPTS

6. **Common Ancestry** Protein molecules called cytochromes are part of the electron transport chain. They are nearly identical in every known aerobic organism. How do these molecules show the unity of life on Earth?