Chapter 8: Harvesting Energy: Glycolysis and Cellular Respiration

OVERVIEW

You will learn about the processes of glycolysis and cellular respiration in this chapter. The authors explain glycolysis and fermentation and discuss the role of mitochondria in converting the chemical energy of organic molecules, especially glucose, into the usable energy of ATP during aerobic respiration. Hummingbirds have extraordinary energy demands, since their wings beat 60 times a second. They burn calories 50 times faster than do humans. Consequently, hummingbirds must eat frequently, gaining energy from sugar-rich nectar from flowers and protein from eating insects. How do hummingbirds extract energy from sugar and then store the energy in their cells?

1) How Is Glucose Metabolized?

Virtually all cells break down glucose for energy. The metabolism of glucose is relatively simple compared to other molecules. When cells use other molecules for energy, they usually convert those molecules to glucose or glucose-like molecules.

The chemical equations for glucose formation by photosynthesis and the complete metabolism of glucose are nearly symmetrical:

Photosynthesis:
$6\ CO_2 + 6\ H_2O + \text{solar energy} \rightarrow C_6H_{12}O_6 + 6\ O_2$

Complete glucose metabolism:
$C_6H_{12}O_6 + 6\ O_2 \rightarrow 6\ CO_2 + 6\ H_2O + \text{chemical energy and heat energy}$

The conversion of energy into different forms always results in the decrease of the amount of concentrated, useful energy, as explained by the second law of thermodynamics. So, lots of heat energy is produced when glucose is metabolized. The major steps in glucose metabolism in eukaryotic cells are: (1) glycolysis, which does not require oxygen and splits apart a glucose molecule into two three-carbon molecules of **pyruvate**, releasing a small amount of energy used to make 2 molecules of ATP. If no oxygen is present, the pyruvate is converted by fermentation into lactate or ethanol. (2) If oxygen is present, cellular respiration occurs in the mitochondria, breaking down the pyruvate into carbon dioxide and water, generating an additional 34–36 molecules of ATP.

2) How Is the Energy of Glucose Harvested During Glycolysis?

In all living cells, the first step of glucose metabolism is called **glycolysis** ("to break apart a sweet thing"), and glycolysis proceeds the same either in the presence (aerobic) or absence (anaerobic) of oxygen. Glycolysis consists of two major steps: glucose activation and energy harvest.

Glycolysis breaks down glucose to pyruvate, releasing chemical energy. In glucose activation, energy from two ATPs is used to convert stable glucose into unstable fructose bisphosphate. During energy harvest, fructose bisphosphate is split apart into two three-carbon molecules of glyceraldehyde 3-phosphate (G3P). The G3P molecules are then converted into pyruvate, during which two ATP are generated for each G3P (4 ATP molecules made in all), so that there is a net gain of two ATPs per glucose molecule. In addition, two NAD^+ molecules are converted into NADH electron carriers using energy released when fructose

bisphosphate is converted into pyruvate. So, each molecule of glucose is broken down into two molecules of pyruvate and two ATP molecules, and two NADH electron carriers are formed.

Some cells ferment pyruvate to form lactate. Under anaerobic conditions in animal muscle, **fermentation** of pyruvate to produce lactate occurs. The lactate gains electrons and hydrogen ions when NADH is converted into NAD^+. Lactate is toxic when concentrated, causing discomfort and fatigue. When oxygen is present, lactate is converted back into pyruvate which enters cellular respiration.

Other cells ferment pyruvate to alcohol. Anaerobic conditions in many microorganisms produce alcoholic fermentation: pyruvate is converted into ethanol and CO_2, gaining electrons and hydrogen ions when NADH is converted into NAD^+. Alcoholic fermentation in yeast is useful in the brewing (ethanol) and baking (CO_2 makes bread rise) industries.

3) How Does Cellular Respiration Generate Still More Energy from Glucose?

Cellular respiration is a series of reactions, occurring under aerobic conditions, during which large amounts of ATP are produced. During aerobic cellular respiration in the mitochondria of eukaryotic cells, pyruvate is converted into $CO_2 + H_2O$, plus many ATP molecules. The final reaction requires oxygen because oxygen is the final acceptor of electrons.

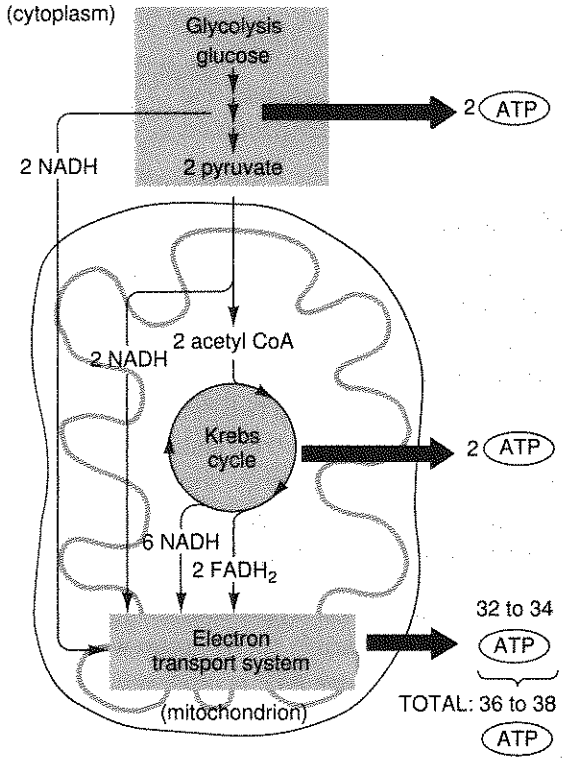
Mitochondria have two membranes that produce two compartments: an inner compartment enclosed by the inner membrane and that contains the fluid **matrix**, and an **intermembrane compartment** between the two membranes. Most ATP made during cellular respiration is generated by reactions catalyzed by enzymes in the mitochondrial matrix, electron transfer proteins in the inner membrane, and movement of hydrogen ions through ATP-synthesizing proteins in the inner membrane. The steps involved are as follows:

(1) The two molecules of pyruvate are transported across both membranes into the mitochondrial matrix;
(2) Each pyruvate is split into CO_2 and a two-carbon acetyl group which enters the Kreb's cycle, during which the remaining carbons become CO_2, one ATP is produced, and energetic electrons are donated to several electron-carrying molecules;
(3) The electron carriers donate their energetic electrons to the electron transport system (ETS) of the inner membrane where the energy is used to transport hydrogen ions from the matrix to the intermembrane compartment where electrons combine with hydrogen ions and oxygen to make H_2O;
(4) In chemiosmosis, the hydrogen ion gradient (high in the intermembrane compartment, low in the matrix) created by the ETS discharges through pores in the ATP-synthesizing enzymes located in the inner membrane, and the energy is used to make ATP;
(5) The ATP is transported out of the mitochondria into the cytoplasm.

Pyruvate diffuses down its concentration gradient into the mitochondrial matrix through pores in the membranes. Then pyruvate reacts with coenzyme A molecules, and each pyruvate is split into CO_2 and a two-carbon acetyl group, which attaches to coenzyme A (CoA), forming an acetyl-coemzyme A complex (*acetyl CoA*). During this reaction, two energetic electrons and a hydrogen ion are transferred to NAD^+, forming NADH. Then a cyclic pathway called the **Krebs Cycle** (or *citric acid cycle*) occurs. Each acetyl CoA combines with *oxaloacetate*. The two-carbon acetyl group bonds to the four-carbon oxaloacetate to form the six-carbon *citrate*. CoA is released to be reused. The citrate then is rearranged to regenerate oxaloacetate, give off two CO_2 molecules, release energy to make one ATP, and four electron carriers (one $FADH_2$, flavin adenine dinucleotide, and three NADH).

Up to this point, from the energy of each glucose broken down, the cell has made 4 ATP, 10 NADH, and 2 $FADH_2$ molecules. The carriers deposit their electrons in **electron transport systems** (ETSs) located in the inner mitochondrial membrane. The energetic electrons move from molecule to molecule along the ETSs, releasing energy used to pump in hydrogen ions from the matrix across the inner membrane during **chemiosmosis**. At the end of the ETSs, oxygen and hydrogen ions accept the low energy electrons to form water. Without oxygen, the electrons would "pile up" in the ETS, stopping the reactions.

Chemiosmosis captures energy stored in a hydrogen ion gradient and produces ATP. Hydrogen ion pumping produces a large concentration gradient (high in the intermembrane compartment and low in the matrix). Energy is released when the ions move down their concentration gradient and the energy is captured to make 32 to 34 ATP molecules. The ATP diffuses out of the mitochondria into the cytoplasm.



Glycolysis and cellular respiration influence the way entire organisms function. Cyanide kills quickly because it reacts with one of the proteins of the ETS, blocking the movement of electrons and halting cellular respiration. Now, consider Olympic runners. During the 100 meter dash, runners' leg muscles use far more ATP than cellular respiration can supply because their bodies cannot supply oxygen to the muscles fast enough. Glycolysis and lactate fermentation can supply a little more ATP, but lactate buildup causes fatigue and cramps. Runners in the 100 meter dash can rely on anaerobic respiration for that short time, but long distance runners must pace themselves so that cellular respiration can occur, saving the anaerobic sprint for the finish. Marathon runners practice running 50–100 miles a week to build up their respiratory and circulatory systems to deliver enough oxygen to their muscles. Sustaining life depends on efficiently obtaining, storing, and using energy.

Case study revisited. To fly over 600 miles of open water, the ruby throated hummingbird (weighing as much as a penny) must store a great deal of energy as fat (another penny's worth by weight). The cells of a hummer's wings are packed with mitochondria to produce the maximum amount of ATP, and its respiratory system is designed to extract oxygen from the air even while exhaling, to supply the wing cells with oxygen for cellular respiration

KEY TERMS AND CONCEPTS

Fill-In: Write the answers in the numbered blanks in the table below.

1.

Name of metabolic process:	Is oxygen necessary?	Part of a cell where it occurs:	Number of ATP molecules produced:	Types of molecules produced:
glycolysis				
alcoholic fermentation				
lactate fermentation				
Krebs cycle				
electron transport system and chemiosmosis				

Key Terms and Definitions

cellular respiration: the oxygen requiring reactions, occurring in mitochondria, that break down the end products of glycolysis into carbon dioxide and water while capturing large amounts of energy as ATP.

chemiosmosis (ke-mē-oz-mō´-sis): a process of ATP generation in chloroplasts and mitochondria. The movement of electrons down an electron transport system is used to pump hydrogen ions across a membrane, thereby building up a concentration gradient of hydrogen ions across the membrane; the hydrogen ions diffuse back across the membrane through the pores of ATP-synthesizing enzymes; the energy of their movement down their concentration gradient drives ATP synthesis.

citric acid cycle: see *Krebs cycle*.

electron transport system: a series of electron carrier molecules, found in the thylakoid membranes of chloroplasts and the inner membrane of mitochondria, that extract energy from electrons and generate ATP or other energetic molecules.

fermentation: anaerobic reactions that convert the pyruvic acid produced by glycolysis into lactic acid or alcohol and CO_2.

glycolysis (glī-kol´-i-sis): reactions, carried out in the cytoplasm, that break down glucose into two molecules of pyruvic acid, producing two ATP molecules; does not require oxygen but can proceed when oxygen is present.

intermembrane compartment: the fluid-filled space between the inner and outer membranes of a mitochondrion.

Krebs cycle: a cyclic series of reactions, occurring in the matrix of mitochondria, in which the acetyl groups from the pyruvic acids produced by glycolysis are broken down to CO_2, accompanied by the formation of ATP and electron carriers; also called *citric acid cycle*.

matrix: the fluid contained within the inner membrane of a mitochondrion.

pyruvate: a three-carbon molecule that is formed by glycolysis and then used in fermentation or cellular respiration.

THINKING THROUGH THE CONCEPTS

True or False: Determine if the statement given is true or false. If it is false, change the underlined word(s) so that the statement reads true.

2. _____ Aerobic forms of life evolved before anaerobic forms.
3. _____ Aerobic (cellular) respiration uses O_2 and produces CO_2.
4. _____ Glycolysis requires oxygen in order to function.
5. _____ Glycolysis occurs in the mitochondria of a cell.
6. _____ Pyruvic acid (pyruvate) is produced by glycolysis.
7. _____ The chemical energy in sugar is used to make O_2.
8. _____ When NADH becomes NAD^+, the hydrogens are used to make sugar.
9. _____ Lactic acid (lactate) fermentation occurs when oxygen is abundant in muscle cells.
10. _____ When each pyruvic acid is completely broken down, six CO_2 molecules are released.
11. _____ Each glucose molecule releases enough energy to make 100 molecules of ATP.

Matching: Glucose metabolism.

12. _____ most of the ATP is made
13. _____ occurs only under anaerobic conditions
14. _____ occurs only under aerobic conditions
15. _____ occurs under either anaerobic or aerobic conditions
16. _____ glucose is split into 2 pyruvate molecules
17. _____ occurs in mitochondria
18. _____ lactate is formed
19. _____ occurs in the cytoplasm
20. _____ produces CO_2 and ATP
21. _____ requires some ATP energy to get started
22. _____ produces ethanol
23. _____ acetyl-CoA is used
24. _____ Krebs cycle occurs
25. _____ fructose diphosphate is produced

Choices:

a. glycolysis
b. fermentation
c. both a. and b.
d. cellular respiration

Short answer.

26. Explain, using chemical equations, how photosynthesis and aerobic cellular respiration are "complementary" processes.

Multiple choice: Pick the most correct choice for each question:

27. During glycolysis, what provides the initial energy to break down glucose?
    a. ATP
    b. pyruvate
    c. NADH
    d. cytoplasmic enzymes
    e. mitochondria

28. At the end of glycolysis, where are the original carbons of the glucose molecule located?
    a. in six molecules of carbon dioxide
    b. in two molecules of NADH
    c. in two molecules of pyruvate
    d. in two molecules of citric acid

29. When oxygen is present
    a. most eukaryotic cells utilize aerobic cellular respiration
    b. most animal cells carry out lactate fermentation
    c. most bacteria and yeast carry out alcoholic fermentation
    d. glucose is broken down to produce 2 ATP molecules
    e. mitochondria are less likely to function normally

30. The anaerobic breakdown of glucose is called
    a. artificial respiration
    b. glycolysis
    c. photosynthesis
    d. fermentation
    e. b and d

31. What happens when pyruvate is converted into lactate?
    a. the lactate enters the Krebs cycle
    b. the mitochondria are activated
    c. NAD^+ is regenerated for use in glycolysis
    d. oxidation of pyruvate occurs
    e. oxygen gas is liberated

32. Oxygen is necessary for cellular respiration because oxygen
    a. combines with electrons and hydrogen ions to form water
    b. combines with carbon to form carbon dioxide
    c. combines with carbon dioxide and water to form glucose
    d. breaks down glucose into carbon dioxide and water
    e. allows glucose to be converted into pyruvic acid

APPLYING THE CONCEPTS

These practice questions are intended to sharpen your ability to apply critical thinking and analysis to biological concepts covered in this chapter.

33. Why can drowning, suffocation, or carbon monoxide poisoning lead to death? The obvious initial response is that they prevent oxygen from reaching our cells, but go beyond that to explain why this can cause death.

34. Some animals that live in deserts survive without actually drinking water. They do eat food containing a little water, but most of the water they need is made within their cells and called "metabolic water." From what you have read in this chapter, explain one way by which metabolic water is produced.

35. Why are runners in the 100 meter dash and marathon runners forced to employ different running strategies in order to win their respective races?

36. "Have you thanked a green plant today?" is a common bumper sticker. Why are plants necessary in order for animals to survive?

37. In the wine-making process, why do yeast consume glucose quicker in the absence of oxygen, and why do yeast produce alcohol only in the absence of oxygen?

38. What would a scientist look for in various types of cells that might accurately predict the rates of cellular respiration?

39. Why couldn't the ruby throated hummingbird fly 600 miles to Guatemala if it stored energy as glycogen instead of as fat?

40. The electron carriers used in cellular respiration, FAD and NAD^+, are derived from the B vitamins riboflavin and niacin, respectively. Why is it that a person needs to consume lots of food each day, but only tiny amounts of these B vitamins?

41. Explain how the mitochondria of plants and animals and the chloroplasts of plants "cooperate" to create cycles of carbon dioxide, oxygen, and energy throughout the biosphere.