CHAPTER 9: HOW CELLS HARVEST ENERGY

CHAPTER SYNOPSIS

Biological endergonic reactions do not occur spontaneously and are generally coupled with reactions that split energy-carrying molecules like ATP. ATP is not a long-term energy storage molecule, it is made only when needed. It is an extremely valuable molecule because it is used to do most of the work in a cell and is used to drive endergonic reactions. Cells generate ATP through two different processes, substrate level phosphorylation and chemiosmosis. The substrate level phosphorylation produces ATP from ADP and phosphate by association with an exergonic reaction and is the more ancient process. Chemiosmosis occurs when protons pumped out through specific transmembrane channels re-enter through other channels coupled to ATP synthesis. Most biological ATP is produced in this manner.

Glycolysis occurs in the cytoplasm of a cell and is catalyzed by enzymes not associated with any membranes or organelles. Glucose is converted to two glyceraldehyde-3-phosphate (G3P) molecules in a reaction that costs two ATP molecules. G3P is then converted to pyruvate and produces four ATPs via substrate level phosphorylation, a process that occurs with or without oxygen. In addition, a pair of electrons and one proton are removed from G3P reducing the coenzyme NAD^+ to NADH. The net energy yield at this point is two ATPs per glucose. Glycolysis continues as long as there is a fresh supply of glucose and there is sufficient NAD^+. It is advantageous for a cell to do something with its NADH other than allowing it to build up because its supply of NAD^+ is generally limited. NADH returns to NAD^+ through aerobic respiration.

The process of aerobic respiration includes the oxidation of pyruvate to acetyl-CoA and the Krebs cycle. Pyruvate is oxidized to a two-carbon molecule, acetyl-CoA, one NAD^+ is reduced to NADH and one molecule of CO_2 is given off. This reaction occurs within the mitochondria of eukaryotes or on special membranes in a few bacteria. The Krebs cycle is a complex set of reactions in which a four-carbon molecule is added to the acetyl-CoA from pyruvate oxidation. During the cycle, two molecules of CO_2 are given off and three NADH, one $FADH_2$, and one ATP are produced. These quantities are, of course, for a single molecule of pyruvate. The degradation of a whole molecule of glucose produces twice the quantity of each substance.

Oxidative respiration in itself produces no more ATP than glycolysis, but it becomes highly efficient only when it is coupled to the fourth stage, the chemiosmotic generation of ATP via an electron transport chain. This process occurs on the inner mitochondrial membrane, requires oxygen as a final electron acceptor, and therefore occurs only in aerobic organisms. In theory, each NADH from the oxidative respiration (a total of eight per glucose) activates three pumps and produces three ATPs (a total of 24). Each $FADH_2$ from the Krebs cycle (two per glucose) activates two pumps and generates two ATPs (a total of four). The cell uses one ATP to get the NADH from glycolysis (a total of two) into the mitochondrion, thus the net value of each is only two ATPs (a total of four). Overall, glycolysis plus complete oxidative respiration produces 32 ATPs via chemiosmosis and four ATPs by substrate level phosphorylation. In actuality, the mitochondrial membrane is leaky, and only 2.5 ATPs are produced per NADH and 1.5 per $FADH_2$. Thus, on average, closer to 30 ATP are produced by chemiosmosis in the electron transport chain.

Proteins and fats are also metabolized. Proteins provide the same efficiency as glucose as constituent amino acids are converted to participants in the Krebs cycle. Fats are metabolized via β-oxidation during which two-carbon chunks are converted to acetyl-CoA, NADH, and $FADH_2$ molecules. A six carbon fatty acid molecule produces 36 actual ATP compared to 30 actual from a six carbon sugar. The NADH produced in glycolysis also returns to NAD^+ through various anaerobic fermentations. A carbohydrate serves as the final electron acceptor in most fermentations. Products of familiar eukaryotic fermentations include ethyl alcohol and carbon dioxide by yeast and lactic acid by overworked muscle cells.

CHAPTER OBJECTIVES

- Understand the value of ATP in biological metabolic reactions.
- Describe two ways in which cells generate ATP and indicate which is a more efficient process.
- Know the location of glycolysis in a generalized eukaryotic cell.
- Understand the differences in the glycolytic reaction under anaerobic and aerobic conditions.
- Describe glycolysis in general terms, including the molecules that exist at its start and its end, as well as its net versus total ATP production.
- Understand the mechanisms that recycle postglycolytic NADH molecules under anaerobic and aerobic conditions.
- Explain why the electron-carrier molecule produced in glycolysis and the two kinds of molecules produced in the Krebs cycle differ from one other in the number of ATP each generates.
- Compare the overall energy efficiency of the complete aerobic degradation of one molecule of glucose with the efficiency of the glycolytic process alone.
- Understand how proteins and fats are metabolized.
- Compare the number of ATPs produced in the degradation of carbohydrates, proteins, and fats.
- Describe alcoholic fermentation in terms of electron acceptors, ATP yield, and end products.
- Explain the process of anaerobic respiration as it occurs in human muscle.

KEY TERMS

acetyl-CoA
aerobic respiration
anaerobic respiration
autotroph
β-oxidation
catabolism
cellular respiration
chemiosmosis
deamination
digestion
electron transport chain
ethanol
fermentation
glycolysis
heterotroph
Krebs cycle
maximum efficiency
NADH dehydrogenase
oxidation
photosynthesis
substrate-level phosphorylation

CHAPTER OUTLINE

9.0 Introduction

I. LIFE IS DRIVEN BY ENERGY

A. Cells Derive Energy From Organic Molecules

B. Convert Energy into ATP fig 9.1

9.1 Cells harvest the energy in chemical bonds

I. USING CHEMICAL ENERGY TO DRIVE METABOLISM

A. All Living Organisms Require Energy
1. Autotrophs are organisms that convert energy into chemical energy
2. Heterotrophs live on the energy produced by autotrophs

B. All Organisms Must Harvest Chemical Energy to Live fig 9.2
   1. Foods contain compounds rich in chemical bonds
   2. Extracting this energy is done in stages
   3. First stage is digestion
   4. Catabolism is the next stage where energy is obtained from C—H bonds

C. Cellular Respiration
   1. C—H bond energy is carried by electrons in the covalent bond
   2. Electrons used to produce ATP
   3. Energy depleted electron donated to another molecule
      a. In aerobic respiration, oxygen accepts H^+, water formed
      b. In anaerobic respiration, a non-oxygen inorganic molecule is the acceptor
      c. In fermentation, an organic molecule is the H^+ recipient
   4. Basic reaction of carbohydrate catabolism
      a. Reactants are carbohydrates and oxygen
      b. Products are carbon dioxide, water, and energy
      c. Change in free energy is –720 kilocalories, energy released
      d. Energy used to produce ATP

D. The ATP Molecule
   1. ATP molecule transfers energy from respiration to other cellular sites
   2. Structure of ATP fig 9.3
      a. Ribose sugar bound to adenine base and chain of three phosphate groups
      b. Linked phosphates store energy of their electrostatic repulsion
      c. Phosphate transfer (phosphorylation) charges that molecule

E. How Cells Use ATP
   1. Used to do most activities that require work
      a. Movement of cell
      b. Movement within cell
   2. Used to drive endergonic reactions
      a. Building molecules takes energy
      b. Chemical bonds of molecules contain more energy than reactants
      c. Reaction needs extra energy from ATP to proceed

F. How ATP Drives Endergonic Reactions
   1. Enzyme catalyzing reaction has two binding sites
      a. Reactant binding site
      b. ATP binding site
   2. ATP site splits ATP molecule, releases 7 kcal of energy
   3. Pushes reactant at other site “uphill” driving reaction
   4. Analogy: Belly-flopping in pool of water
   5. Two parts of reaction occur in concert
      a. Both parts may occur on surface of same enzyme, are physically linked
      b. ATP hi-energy phosphate attaches to and activates catalyst fig 9.4

9.2 Cellular respiration oxidizes food molecules

I. AN OVERVIEW OF GLUCOSE CATABOLISM

A. Cells Make ATP in Two Ways
   1. Substrate-level phosphorylation
      a. Phosphate from intermediate transferred to ADP making ATP fig 9.5
      b. Chemical bonds of glucose shifted around

c. Reactions release more energy than needed to form ATP
2. Aerobic respiration
   a. Electrons harvested passed along electron transport chain
   b. Forms ATP, electrons ultimately donated to oxygen
3. Most organisms combine two processes, reactions occur in four stages
   a. Fist stage is glycolysis, capture by substrate-level phosphorylation
   b. Next three stages oxidize end product of glycolysis

B. Glycolysis
1. Stage one: Glycolysis
   a. Energy from glucose extracted in a 10 reaction biochemical pathway
   b. Produces ATP by substrate-level phosphorylation
2. Glycolytic enzymes are present in the cytoplasm of the cell
3. Enzymes are not bound to any membrane or organelle
4. Two ATP formed by substrate-level phosphorylation
   a. Two ATP used up early in pathway
   b. Four ATP are produced in the phosphorylation
5. Four electrons harvested as NADH, used to make ATP by aerobic respiration
6. Process is not highly efficient, most energy remains in pyruvate

C. Aerobic Respiration fig 9.6
1. Stage two: Pyruvate oxidation
   a. Pyruvate converted to CO_2 and two-carbon acetyl-CoA
   b. One molecule NADH made per pyruvate (two NADH per glucose)
2. Stage three: The Krebs cycle
   a. Cycle of nine reactions
   b. Alternately called the citric acid cycle or tricarboxylic acid cycle
   c. Two more ATP made by substrate-level phosphorylation
   d. Large number of electrons removed by NADH
3. Stage four: Electron transport chain
   a. Electrons carried by NADH
   b. Large number of ATP molecules formed
4. In eukaryotes the second, third, and fourth stages occur in mitochondria
5. Photosynthetic plants exhibit oxidative respiration like other organisms

D. Anaerobic Respiration
1. Other organisms may use other compounds as final electron acceptors
2. Methanogens
   a. Are primitive archaebacteria, including thermophiles
   b. Use CO_2 as electron acceptor
   c. Reduce CO_2 to CH_4 (methane)
3. Sulfur bacteria
   a. Bacteria present in and the source of rocks enriched in sulfur ^{32}S
   b. Electron acceptor is inorganic sulfates (SO_4) reduced to H_2S
   c. High quantities of H_2S helped evolve first form of photosynthesis

II. STAGE ONE: GLYCOLYSIS

A. Glycolysis Synthesizes ATP
1. Occurs in cytoplasm
2. Involves 10 reactions that convert glucose to two 3-C pyruvates fig 9.7
3. Energy yield of 2 ATP by substrate-level phosphorylation

B. Priming
   1. Five reactions convert glucose to 2 molecules of 3-C glyceraldehyde-3-phosphate
   2. Reactions require energy
   3. Step A: Glucose priming
      a. Change glucose into a compound that is readily cleaved in half
      b. Cell uses 2 ATP
   4. Step B: Cleavage and rearrangement fig 9.8
      a. Six-C product of step A split into 2 3-C molecules
      b. One molecule of G3P, other molecule is converted into G3P

C. Substrate-Level Phosphorylation
   1. Five more reactions convert G3P into pyruvate
   2. Yields production of ATP
   3. Step C: Oxidation
      a. Two electrons and one proton transferred from G3P to NAD^+
      b. Forms NADH, one per G3P, two per glucose
      c. Both electrons in new covalent bond from G3P
   4. Step D: ATP generation
      a. G3P converted into pyruvate (two per glucose)
      b. Two ATP made per G3P (four ATP per glucose) fig 9.5
      c. Complete yield of 2 ATP, 2 NADH, 2 pyruvate
   5. Net energy is 24 k/cal per mole of glucose (3.5% of what's available)
   6. Even though amount is small, life survived on it for a billion years
   7. Evolution of glycolysis was backwards like most biochemical reactions
      a. ATP-producing breakdown of G3P evolved first
      b. Synthesis of G3P developed later when original G3P was used up

D. All Cells Use Glycolysis
   1. Glycolysis was among the earliest pathways to evolve
   2. Does not require oxygen, occurs readily in anaerobic environment
   3. Reactions occur freely in the cytoplasm
   4. Most organisms extract additional energy through aerobic respiration
   5. Glycolysis has been added to, but not replaced by other processes
      a. Evolution is an incremental process
      b. Change occurs by improving upon past success

E. Closing the Metabolic Circle: The Regeneration of NAD^+
   1. Three changes occur during glycolysis
   2. Glucose is converted to two pyruvates
   3. Two ADPs are converted to ATPs
   4. Two NAD^+ molecules are converted to NADHs

F. The Need to Recycle NADH
   1. Glycolytic processes cannot continue *ad infinitum*
      a. Cell will ultimately accumulate NADH and run out of NAD^+
      b. NADH must be recycled back to NAD^+ for glycolysis to continue
   2. Recycling occurs in one of two ways fig 9.9
      a. Aerobic respiration
         1) Oxygen is the final electron acceptor, water is final product
         2) This process also called aerobic metabolism
      b. Fermentation
         1) Organic molecules serve as the final electron acceptor
         2) Occurs in many organisms, even those capable of aerobic respiration fig 9.10

3. Pyruvate molecule from glycolysis changed in one of two ways
   a. Anaerobic respiration path changes it to acetyl-CoA and into the Krebs cycle
   b. Fermentation reduces all or part of the pyruvate

III. STAGE TWO: THE OXIDATION OF PYRUVATE

A. Oxidation of Pyruvate Occurs in Two Stages

1. In eukaryotes, occurs only in mitochondria
2. Oxidation of pyruvate into acetyl-CoA
3. Oxidation of acetyl-CoA in Krebs cycle

B. Producing Acetyl-CoA fig 9.11a

1. One carbon of the three-carbon pyruvate is cleaved, leaves as CO_2
2. This is a decarboxylation reaction that leaves
   a. A two-carbon fragment called an acetyl group
   b. A pair of electrons and associated H^+ reduces NAD^+ to NADH
3. Complex reaction involves three intermediate steps
   a. Catalyzed within the mitochondria by a multienzyme complex
   b. Pyruvate dehydrogenase: Enzyme that removes a CO_2 from pyruvate
   c. Acetyl group added to cofactor (co-enzyme A) makes acetyl-CoA
   d. Reaction produces one molecule of NADH
   e. Remaining acetyl-CoA is a more important consequence fig 9.11b
      1) Formed by many metabolic processes
      2) Most molecules catabolized for energy converted to acetyl-CoA
      3) Most acetyl-CoA is directed toward energy storage

C. Using Acetyl-CoA

1. Limited number of processes use acetyl-CoA
   a. Directed toward energy storage (lipid synthesis)
   b. Oxidized in Krebs cycle to produce ATP
2. Choice of option dependent on cell's ATP level
   a. If high, oxidative pathway inhibited, fat synthesis occurs
   b. If low, oxidative pathway stimulated to produce energy

IV. STAGE THREE: THE KREBS CYCLE

A. The Oxidation of Acetyl-CoA fig 9.12

1. Acetyl-CoA is oxidized by binding it to four-carbon oxaloacetate
2. The resulting six-carbon molecule passes through series of reactions
   a. Electron-yielding reactions split off two molecules of CO_2
   b. The four-carbon molecule is regenerated

B. Overview of the Krebs Cycle

1. Consists of nine reactions in two stages
2. Step A: Priming
   a. Acetyl-CoA first joins the cycle
   b. Chemical groups are rearranged
3. Step B: Energy extraction
   a. Four of the six reactions are oxidations, electrons are removed
   b. One reaction generates an ATP equivalent via substrate-level phosphorylation

C. The Reactions of the Krebs Cycle fig 9.13
   1. Reaction 1: Condensation
      a. 2-C acetyl-CoA + 4-C oxaloacetate = 6-C citrate + CoA
      b. Irreversible reaction
      c. Reaction inhibited in presence of large amounts of ATP
      d. Reaction stimulated when ATP is low
   2. Reactions 2 and 3: Isomerization
      a. Hydroxyl group repositioned
      b. Water removed from one carbon, then added to different carbon
      c. Result is change in position of an -H and an -OH
      d. Molecule is now called isocitrate
   3. Reaction 4: The first oxidation
      a. Isocitrate undergoes oxidative decarboxylation reaction
      b. Oxidation produces pair of electrons that reduce NAD^+ to NADH
      c. Oxidized intermediate is decarboxylated, CO_2 is removed
      d. Product is a 5-C molecule of α-ketoglutarate
   4. Reaction 5: The second oxidation
      a. 5-C α-ketoglutarate decarboxylated by multienzyme complex
      b. 4-C succinyl group + CoA = succinyl-CoA
      c. Two electrons extracted reducing another NAD^+ to NADH
   5. Reaction 6: Substrate-level phosphorylation
      a. Bond between succinyl group and coA is high energy
      b. Gives a phosphorylation reaction of GDP to GTP
      c. GTP converted to ATP
      d. Remaining molecule is 4-C succinate
   6. Reaction 7: The third oxidation
      a. Succinate oxidized to fumarate
      b. Free energy can't drive NAD^+ reaction, but can make FAD^+ into $FADH_2$
      c. FAD^+ is an integral part of the inner mitochondrial membrane
      d. $FADH_2$ can contribute electrons to electron transport chain
   7. Reactions 8 and 9: Regeneration of oxaloacetate
      a. Water molecule added to 4-C fumarate, forms 4-C malate
      b. Malate oxidized to 4-C oxaloacetate and two electrons
      c. Electrons drive reaction NAD^+ to NADH
      d. Oxaloacetate can combine with a new molecule of acetyl-CoA

D. The Products of the Krebs Cycle
   1. Glucose totally consumed
   2. 6-C → 2(3-C) → 2(2-C-CoA + CO_2) → 2(2CO_2)
   3. Products are six CO_2, four ATPs, and 12 electron carriers (10 NADH, 2 $FADH_2$)

V. HARVESTING ENERGY BY EXTRACTING ELECTRONS

A. Transfer of Electron's Energy of Position
   1. Is sometimes all-or-none, a complete transfer from one molecule to another
   2. Reduction sometimes just changes the degree of sharing in the covalent bond
   3. Consider what happens when transfer of electrons is incomplete

B. A Closer Look at Oxidation Reduction
   1. In glucose, covalent bonds in C-Hs shared equally
   2. C and H have same affinity for valance electrons (similar electronegativity)
   3. Electrons in new bonds of CO_2 are not shared equally
      a. Shift far towards oxygen which is very electronegative
      b. Carbon atoms are oxidized (lose electrons) and oxygens are reduced (gain electrons)

4. Same thing happens when Hs of glucose combine with oxygen to form water
   a. Oxygen atoms draw shared electrons towards themselves
   b. Oxygen reduced, glucose oxidized
   c. Oxygen is an oxidizing (electron-attracting) agent

C. Releasing Energy
1. Focus on energy of shared electrons
2. Energy added to remove electron from its atom in a covalent bond
3. Energy is released when
   a. Electron shifted away from less electronegative atom
   b. Shifted towards a more electronegative atom
4. Energy released when glucose oxidized, electrons relocated closer to oxygen fig 9.14
5. Glucose has many electrons held far from atoms, all can potentially move to oxygen
6. Some energy released by shifting H atoms from glucose to oxygen
7. Energy also released because of shift of positions of valence electrons, used to make ATP

D. Harvesting the Energy in Stages
1. With large release of energy, most is wasted as heat, less available for work
2. Same amount of energy released if gas explodes or powers car
   a. With explosion all energy released at once
   b. With smaller release, very small explosions push pistons, move car
   c. Energy better utilized when released in small increments
3. Same principle with oxidation of glucose in cell
   a. H transferred to oxygen in one step, explosive waste of energy
   b. Used a little at a time is valuable
   c. Reactions occur in series of stages, NAD^+ is primary electron acceptor fig 9.15

E. Following the Electrons
1. Enzymes extract two hydrogens (two electrons and two protons) from glucose
   a. Both electrons and one proton transferred to NAD^+ forming NADH
   b. Other proton released as hydrogen ion (H^+)
2. Energy captured by NADH not harvested at one time
3. Two electrons pass along electron transport chain in presence of oxygen
4. Structure of chain
   a. Series of molecules (proteins) embedded in inner membranes of mitochondria
   b. Electrons delivered by NADH to top of chain
   c. Captured by oxygen at bottom
   d. Oxygen then combines with hydrogen forming water
5. Position of electrons shift as each moves to a more electronegative carrier
6. Electrons move down an energy gradient, releasing 53 kcal / mole of energy

VI. STAGE FOUR: THE ELECTRON TRANSPORT CHAIN

A. NADH and $FADH_2$ Contain Electrons Gathered from Glucose Breakdown
1. NADH molecules carry their electrons to mitochondrial membrane
2. Transfer electrons to membrane-associated electron transport chain

B. Moving Electrons through the Electron Transport Chain
1. Transfer electrons to NADH dehydrogenase, membrane-embedded protein
2. Ubiquinone carries electrons to bc_1 protein-cytochrome complex
   a. Complex acts as proton pump, drives proton outside of membrane
   b. Cytochromes contain heme groups

3. Cytochrome c carries electron to cytochrome oxidase complex fig 9.16
   a. Four electrons used to reduce one oxygen
   b. Combines with two hydrogens to form water
4. Series of carrier called electron transport chain
5. Slight difference between NADH and $FAHDH_2$
   a. NADH carries electrons to first position in chain
   b. $FADH_2$ carries electrons to ubiquinone, later down the chain
6. The plentiful electron acceptor makes oxidative respiration possible
   a. Process cannot occur in the absence of the molecule
   b. Electron transport chain is similar to the one in aerobic photosynthesis

C. Building an Electrochemical Gradient
1. Inner compartment (matrix) of mitochondrion contains Krebs cycle enzymes
2. Electrons passed along electron transport chain fig 9.16
   a. Energy transports protons to outer compartment (intermembrane space)
   b. Transport accomplished by proton pumps, transmembrane proteins
3. Electrons from NADH activate three pumps
4. Electrons from $FADH_2$ activate two pumps

D. Producing ATP: Chemiosmosis
1. Concentration of protons in outer compartment increases over matrix
   a. Matrix becomes slightly negative in charge
   b. The protons attracted back inward through special channels
   c. ATP is synthesized when protons diffuse through them
   d. ATP leaves the mitochondrion via facilitated diffusion
2. Force driving reaction is similar to osmosis, reaction called chemiosmosis fig 9.17
3. Summarization of ATP production fig 9.18

VII. SUMMARIZING AEROBIC RESPIRATION

A. Theoretical Yield
1. Each NADH activates three pumps, $FADH_2$ activates two
   a. ATP generation expected to be 3ATP and 2ATP respectively
   b. NADH from glycolysis transport into mitochondrion costs energy of 1 ATP
   c. Net ATP production is therefore decreased by two
2. Net theoretical yield = 36 ATP fig 9.18
   a. 4 ATP from substrate-level phosphorylation
   b. 30 ATP from 3 each of 10 molecules of NADH
   c. 4 ATP from 2 each of 2 molecules of $FADH_2$
   d. -2 ATP needed to transport NADH from glycolysis

B. Actual Yield
1. Actual total in eukaryotes is lower than 36
   a. Inner membrane is leaky, some protons reenter without generating ATP
   b. Mitochondria use proton gradient for other purposes
   c. Truer values are 2.5 ATP per NADH and 1.5 ATP per $NADH_2$
   d. Net total closer to 30 ATP (4 + 25 + 3 – 2)
2. Energy efficiency
3. (7.3 x 30) / 686 = 32% efficiency of aerobic oxidation of glucose
4. Efficiency of car engine is 25%
5. High efficiency fostered evolution of heterotrophs

VIII. REGULATING AEROBIC RESPIRATION

A. ATP Levels Determine Whether More ATP Is Produced
1. ATP high, glycolysis, Krebs cycle, and fatty acid breakdown inhibited
   a. Regulation by ATP is example of feedback inhibition
   b. When ATP is low, then ADP is high
   c. ADP activates enzymes of carbohydrate catabolism
2. Control occurs at two key points of catabolic pathway fig 9.20
   a. In glycolysis, control is at phosphofructokinase
      1) Catalyzes conversion of fructose phosphate to fructose bisphosphate
      2) First reaction that is not readily reversible
      3) High ADP stimulate same enzyme, as do low levels of citrate
   b. Control in oxidation of pyruvate at pyruvate decarboxylase step
      1) Inhibited by high levels of NADH
      2) Thus no more NADH needed
   c. Another control point in Krebs cycle is citrate synthetase
      1) Catalyzes oxaloacetate+acetyl-CoA to citrate
      2) High ATP inhibit this enzyme
      3) Also inhibits pyruvate decarboxylase and two other Krebs cycle enzymes

9.3 Catabolism of proteins and fats can yield considerable energy

I. GLUCOSE IS NOT THE ONLY SOURCE OF ENERGY

A. Proteins and Fats Are Also Important Sources of Energy fig 9.21

B. Cellular Respiration of Protein
1. Must first break proteins into constituent amino acids
2. Nitrogen-containing amino group removed from each amino acid: Deamination
3. Remaining carbon chain converted to substance in glycolysis or Krebs cycle
   a. Alanine to pyruvate
   b. Glutamate to α-ketoglutarate fig 9.22
   c. Aspartate to oxaloacetate

C. Cellular Respiration of Fat
1. Fats first degraded to individual fatty acids and glycerol
2. Long carbon chains with many hydrogens hold much energy
3. Fats oxidized in the matrix of the mitochondrion
   a. Enzymes attack the long fatty acid chains
   b. Remove carbons in chunks of 2C acetyl groups
   c. Entire chain converted into acetyl-CoA fig 9.23
   d. Process called β-oxidation
4. Efficiency of metabolizing fats
   a. Each β-oxidation cycle uses one ATP to prime the process
   b. Produces 1 acetyl-CoA + 1 NADH + 1 $FADH_2$
   c. NADH produces 2.5 ATPs
   d. $FADH_2$ produces 1.5 ATPs
   e. Acetyl-CoA produces 10 ATPs
   f. Total number of ATPs from a six carbon fatty acid
      1) Two cuts = 2 NADH + 2 $FADH_2$ = 2(2.5+1.5) – 2 = 6 ATPs
      2) Three acetyl-CoA molecules = 3(10) = 30 ATPs
      3) Total = 36 ATPs
   g. Overall actual yield is 20% more than glucose

h. Fatty acid of same size weighs less than glucose
   1) One gram of fatty acid contains more than twice as many kcal as glucose
   2) Animal bodies would be bulkier if they stored carbohydrates instead of fat

9.4 Cells can metabolize food without oxygen

I. FERMENTATION

A. Bacteria Carry Out Many Different Types of Fermentations
   1. An organic molecule serves as the electron acceptor
      a. NADH is returned to NAD^+
      b. The organic molecule is reduced
   2. Bacteria produce acetic, butyric, propionic, lactic acids, alcohol

B. Ethanol Fermentation
   1. Eukaryotes exhibit only a few types of fermentations
   2. Yeasts decarboxylate pyruvate to produce acetaldehyde and CO_2
      a. NADH and acetaldehyde are converted to ethyl alcohol and NAD^+
      b. Ethanol is another name for ethyl alcohol
      c. This is a commercially important process that makes wine and beer fig 9.24
      d. Ethanol is toxic to cells, kills at 12%, the maximum for natural brewing

C. Lactic Acid Fermentation
   1. Most multicellular animals regenerate NAD^+ without decarboxylation
   2. Utilizes the enzyme lactate dehydrogenase
   3. Muscle cells convert NADH + pyruvate to NAD^+ + lactic acid
   4. Blood circulation removes lactate from muscle cells
      a. With great exertion lactic acid is not removed fast enough
      b. Contributes to muscle fatigue

INSTRUCTIONAL STRATEGY

PRESENTATION ASSISTANCE:

Another analogy to help explain the value of controlled pathways is jumping off a skyscraper. Without controlled pathways, i.e. stairs, you go splat! With a controlled pathway, you may be a little out of breath and have tired legs, but you get down in one piece. Even if you stumble or fall down a few, at least you are not dead! Also, unless you are Superman, you're not going to be able to leap tall buildings in a single bound and do the pathway in reverse. It is possible, albeit exhausting, to climb the stairs.

There must be a clear differentiation between the generation of ATP via substrate-level phosphorylation and chemiosmosis. The former occurs directly in the cytoplasm. The latter requires a membrane bound proton pump. In eukaryotes, chemiosmosis is associated with the mitochondria, the electron transport chain and oxygen as the final electron acceptor. If any of these are not present, NADH will not be converted to ATP. It is important to stress where each of the stages of cellular respiration occur, how ATP from each is generated, and whether it relies on NAD^+ or FAD^+ as electron carriers. Figures 9.8 and 9.13 are especially valuable in presenting "the big picture."

Remind students that the products of the Krebs cycle must be doubled for each molecule of glucose degraded. However, the products of glycolysis are not doubled. Also remind them to be careful in converting NADH to ATP. Those produced in the cytoplasm (through glycolysis) are worth only 2 theoretical (or 1.5 actual) ATP, those produced in the mitochondria are worth 3 theoretical (or 2.5 actual) ATPs. You may find it valuable to colorcode or specially label the energy products of each stage as you go through. Instruct the students to do the same in their class notes.

VISUAL RESOURCES:

Prepare bunches of colored cards, a different color to represent ADP, ATP, NAD^+, NADH, FAD^+, and $FADH_2$. This currency can be distributed as you present each stage of cellular respiration. For example, a bacteria cell ready for fermentation starts with two ATPs and two NAD^+. Take the two ATPs to start glycolysis. Then take the two NAD^+ and give out two NADH and four ATPs. When you try to run through glycolysis again, there are no NAD^+. After alcoholic fermentation occurs, trade the two NADH for two NAD^+ and do another glycolysis reaction. Aerobic respiration can be done in a similar manner.