

Chapter 9- Cellular Respiration: Harvesting Chemical Energy

(Key Concepts are Underlined)

Principles of Energy Harvest

Cellular respiration and fermentation are catabolic (energy-yielding) pathways

- organic molecules store energy in their arrangement of atoms

Fermentation- partial decomposition of sugars without oxygen

Cellular Respiration- oxygen is the oxidizer of organic fuel

Combustion: Organic Compound + Oxygen → Carbon Dioxide + Water + Energy

Cells recycle the ATP they use for work

-phosphorylation primes a molecule to undergo some kind of change to do work

Redox reactions release energy when electrons move closer to electronegative atoms

Oxidation-

Reduction-

Oxidizing Agent-

Reducing Agent-

Electrons “fall” from organic molecules to oxygen during cellular respiration

- the “fall” of electrons is controlled and occurs in enzyme mediated steps

The fall of electrons during respiration is stepwise, via NAD^+ and an electron transport chain

NAD^+ - nicotinamide adenine dinucleotide is a coenzyme functions as an oxidizing agent by accepting electrons
- dehydrogenase removes 2 hydrogen atoms from the substrate and gives one to NAD^+ to yield NADH (reduced form) and H^+ ; electrons lose very little potential energy in this process

Electron transport chain- breaks the “fall” of electrons to terminal, electronegative oxygen into several energy-releasing steps; NADH shuttles electrons from food to the beginning of the chain

The Process of Cellular Respiration

Respiration involves glycolysis, the Krebs cycle, and electron transport: an overview

Glycolysis- occurs in cytosol; breaks down glucose into two molecules called pyruvate

Krebs cycle- occurs in mitochondrial matrix; decomposes derivatives of pyruvate to carbon dioxide

Oxidative phosphorylation- ATP synthesis by redox reactions, where electrons transferred go from food to oxygen; occurs at the inner mitochondrial membrane (i.e. electron transport chain)

Substrate-level phosphorylation- enzyme transfers a phosphate group from a substrate to ATP (e.g. glycolysis and Krebs cycle)

Glycolysis harvests chemical energy by oxidizing glucose to pyruvate: a closer look

- Two phases: 1) Energy-Investment Phase (requires 2 ATP) and 2) Energy-Payoff Phase (4 ATP and 2 NADH)

from two 3 carbon sugars); net product per glucose molecule = 2 pyruvate molecules, 2 ATP and 2 NADH
- occurs in cytosol without oxygen and no CO₂ is produced

The Krebs cycle completes the energy-yielding oxidation of organic molecules: *a closer look*

- Pyruvate is converted into **actyl CoA** before entering the Krebs cycle by the following steps: 1) transported from the cytosol into the mitochondrial matrix via a transport protein, 2) carboxyl group is converted to CO₂, 3) NAD⁺ is reduced to NADH, and 4) the remaining 2-carbon fragment (acetate) attaches to coenzyme A (CoA)
- acetyl CoA enters the Krebs cycle by attaching to oxaloacetate to form citrate → 2 CO₂ molecules are given off by the subsequent decomposition of citrate and regeneration of oxaloacetate (thus going full “cycle”)
- Krebs cycle energy harvest: 1 ATP, 3 NADH, and 1 FADH₂ per acetyl CoA (but twice this amount per glucose molecule- 2 turns per glucose!)

The inner mitochondrial membrane couples electron transport to ATP synthesis: *a closer look*

- thousands of electron chains within the inner membrane of a mitochondrion due to the many folds called cristae (increases surface area)
- most of these chains are proteins with enzyme-helping prosthetic groups, which oscillate between reduced and oxidized forms
- NADH delivers its electrons to FMN (a flavoprotein) → Fe-S (Iron-sulfur) protein → Q (lipid called ubiquinone) → a chain of cyt's, or cytochromes (contain prosthetic heme groups containing iron) → cyt a₃ (last cytochrome) → ½ O₂

(2 NADH required to reduce molecular oxygen) \rightarrow O_2 picks up 2 H^+ to form water

- $FADH_2$ delivers its electrons lower in the chain, which consequently provides less energy for ATP synthesis
- the inner membrane of the mitochondrion contains many copies of a protein complex called ATP synthase, which makes ATP via oxidative phosphorylation by allowing H^+ to diffuse down its concentration (or pH) gradient generated by the electron transport chain
- the exergonic flow of electrons in the electron transport chain pump H^+ from the mitochondrial matrix to the innermembrane space, thus creating a **proton-motive force** (the capacity of the proton gradient to do work)

Chemiosmosis- the coupling mechanism for oxidative phosphorylation (i.e. H^+ gradient generated by the electron transport chain coupled with the phosphorylation of ATP)

- ATP synthase's catalytic sites are activated from the rotation of its components, facilitated by the flow of H^+ through its cylinder
- chemiosmosis is the central energy-coupling mechanism in mitochondria, chloroplasts, and bacteria

Cellular respiration generates many ATP molecules for each sugar molecule it oxidizes: *a review*

Substrate-level phosphorylation (glycolysis and Krebs cycle) = **2 to 4 ATP** (depends on the electron shuttle system of cytosolic NADH across the innermembrane)

Oxidative phosphorylation- **34 ATP** (each NADH yields about 3 ATP and $FADH_2$ about 2 ATP)

Maximum ATP/glucose = **38 ATP**

- Cellular Respiration is approximately **40% efficient**

Related Metabolic Processes

Fermentation enables some cells to produce ATP without the help of oxygen

Aerobic

Anaerobic

Fermentation- the anaerobic catabolism of organic nutrients via substrate-level phosphorylation; NADH (reduced form of NAD^+) is recycled by transferring its electrons to pyruvate (or its derivatives)

Alcohol Fermentation- pyruvate is converted to ethanol (CO_2 is released)

Lactic Acid Fermentation- pyruvate is converted to lactate (no release of CO_2); occurs in human muscle cells when ATP production outpaces O_2 supply during strenuous exercise

Cellular Respiration vs. Fermentation- CR yields 19 times more ATP; no Krebs Cycle in Fermentation; final electron acceptor is O_2 in CR; CR ATP yield is primarily due to oxidative phosphorylation, where fermentation is substrate-level phosphorylation

Facultative Anaerobes- species who survive on fermentation as their ATP generating source

- “Glycolysis is a metabolic heirloom from the earliest cells that continues to function in fermentation and as the first stage in the breakdown of organic molecules by respiration.”

Glycolysis and the Krebs cycle connect to many other metabolic pathways

- other carbohydrates, fats, and proteins can be catabolized where its derivatives are inserted into various points of the metabolic pathway of cellular respiration

- compounds formed as intermediates of glycolysis and Krebs may be diverted as precursors into anabolic pathways

Feedback mechanisms control cellular respiration

- the end-product of an anabolic pathway inhibits an enzyme catalyzing an early step in its pathway
- when ATP concentration drops, respiration increases (and vice versa); a key allosteric enzyme, called phosphofructokinase (controls 3rd step in glycolysis), is inhibited by ATP and stimulated by AMP (and citrate)