

Cellular Respiration

4: Respiration

- Before food can be used to perform work, its energy must be released through the process of respiration.
- Two main types of respiration exist in living things. Both begin with glycolysis.
 - Glycolysis: a process by which one glucose molecule is broken down into two pyruvic acid molecules.
 - Fermentation: pyruvic acid is broken down without the use of oxygen
 - Oxidative Respiration (aerobic respiration): pyruvic acid is metabolized using oxygen

Glycolysis

- Glycolysis occurs in the cytoplasm. It does not require oxygen. Each of its four stages is catalyzed by a specific enzyme.
- **Steps:**
 1. Glucose is a stable energy-storage molecule. For its energy to be released, the glucose must be converted into a reactive compound. This conversion occurs through the phosphorylation of a molecule of glucose by two molecules of ATP.
 2. The six-carbon product of glucose phosphorylation, called glucose-6-phosphate, ultimately breaks into 2 three-carbon molecules of PGAL.
 3. A phosphate group is added to each PGAL molecule and hydrogen atoms are removed. The hydrogen is picked up by a molecule called NAD^+ . Since there are two PGAL molecules, two molecules of $\text{NADH} + \text{H}^+$ are formed.
 4. As the phosphate bonds formed in stage 3 are broken, ATP is generated. Two molecules are generated as each of the original PGAL molecules is converted to pyruvic acid. Therefore, a total of four ATP molecules are produced in the fourth stage of glycolysis.
- 4 ATP (gross) – 2 ATP = 2 ATP (net)

Fermentation (Anaerobic Respiration)

- Fermentation is the breakdown of pyruvic acid without the use of oxygen.
- Glycolysis + Fermentation = Anaerobic Respiration
- **The metabolism of pyruvic acid during fermentation does not produce any ATP. Instead, the function of fermentation is to break down pyruvic acid and regenerate NAD^+ for reuse in glycolysis.**
- There are two forms of fermentation:
 - Lactic Acid Fermentation
 - Lactic acid fermentation occurs in animal cells and some unicellular organisms when O_2 is in short supply.
 - Lactic Acid forms when pyruvic acid accepts hydrogen from $\text{NADH} + \text{H}^+$:
 - $\text{pyruvic acid} + \text{NADH} + \text{H}^+ \rightarrow \text{lactic acid} + \text{NAD}^+$
 - Lactic acid accumulates in body tissues and makes muscles feel tired and sore.
 - Lactic acid is then transported to the liver where it is converted to glucose.
 - Alcoholic Fermentation
 - Alcoholic fermentation occurs in some plant cells and some unicellular organisms (yeast).
 - In alcoholic fermentation pyruvic acid is converted to ethyl alcohol (ethanol- found in beer and wine):
 - $\text{PA} + \text{NADH} + \text{H}^+ \rightarrow \text{ethanol} + \text{CO}_2 + \text{NAD}^+$

Aerobic Respiration

- The result of glycolysis and aerobic respiration is shown by the reaction:
 - $C_6H_{12}O_6 + 6 O_2 \rightarrow 6 H_2O + 6 CO_2 + 38 ATP$
- Aerobic respiration occurs in the mitochondria
 - outer and inner membrane
 - matrix: dense solution enclosed by inner membrane
 - cristae: the folds of the inner membrane that house the electron transport chain and ATP synthase
- The first step of aerobic respiration is the conversion of pyruvic acid to a molecule called acetyl-CoA.
 1. 3-C pyruvic acid molecule loses CO_2 and becomes a 2-C acetyl group
 2. This acetyl group combines with coenzyme A (CoA) forming acetyl-CoA
 3. During this transformation, pyruvic acid loses hydrogen
 4. NAD^+ accepts the hydrogen and a molecule of $NADH + H^+$ forms
 - $PA + CoA + NAD^+ \rightarrow acetyl-CoA + CO_2 + NADH + H^+$
 - 2 molecules of acetyl-CoA per glucose now enter the Krebs Cycle.

The Krebs Cycle

- The Krebs Cycle is the central biochemical pathway of aerobic respiration. It is named after its discoverer, Sir Hans Krebs. Because citric acid is formed in the process, it is also known as the Citric Acid Cycle.
- **Steps:**
 1. Acetyl-CoA (2-C) combines with a 4-C molecule to form citric acid (6-C).
 2. The citric acid is immediately oxidized by enzymes in the mitochondria.
 3. Two carbon atoms are removed and form two CO_2 molecules and eight hydrogen atoms are released.
 4. These hydrogen atoms are picked up by two molecules- NAD^+ and a related molecule called FAD.
 5. A 4-C compound (oxaloacetic acid) then combines with another acetyl-CoA molecule to start the cycle again.
- One turn of the cycle produces three molecules of $NADH + H^+$ (6 total), one molecule of $FADH_2$ (2 total), and one molecule of ATP (2 total).

Electron Transport Chain

- Glycolysis, the conversion of PA to acetyl-CoA, and the Krebs Cycle complete the breakdown of glucose.
- Up to this point:
 - 4 ATP (2 from glycolysis, 2 from Krebs)
 - 10 $NADH + H^+$ (2 from glycolysis, 2 from the conversion of PA, 6 from Krebs)
 - 2 $FADH_2$ (from Krebs)
- $NADH + H^+$ and $FADH_2$ carry electrons to an electron transport chain, where additional ATP is produced.
- **Steps:**
 1. $NADH + H^+$ and $FADH_2$ carry electrons to the ETC.
 2. As electrons move down the energy gradient in the inner membrane of the mitochondrion, hydrogen ions are pumped across the membrane into the matrix.
 3. An electrochemical gradient forms, and hydrogen ions diffuse through channels that contain ATP synthetase.
 4. The energy generated by the movement of hydrogen ions is used by ATP synthetase to make ATP.

5. O_2 is the final hydrogen acceptor:
- $\frac{1}{2} O_2 + 2 H^+ \rightarrow H_2O$
- Each molecule of $NADH + H^+$ yields 3 molecules of ATP. $FADH_2$ yields 2 molecules of ATP.
 - $10 NADH + H^+ = 30 ATP$
 - $2 FADH_2 = 4 ATP$
 - The ETC yields a maximum of 34 molecules of ATP.

Energy Yield

- Aerobic respiration produces a maximum of 38 ATP.
 - 2 ATP from Glycolysis
 - 2 ATP from Krebs
 - 34 ATP from ETC
- Reasons why ATP yield can be less than 38:
 - Sometimes energy is required to transport $NADH + H^+$ formed by glycolysis from the cytoplasm through the inner mitochondrial membrane.
 - Some H^+ in chemiosmosis may leak through the membrane.
- Aerobic Respiration is generally 19 times more efficient than anaerobic respiration.
- The ATP produced during aerobic respiration represents about 1/2 of the energy stored in a molecule of glucose.