بِسْمِ اللَّهِ الرَّحْمَنِ الرَّحِيمِ

محاضرة كيمياء حيوية 2

المستوى الثالث

سلسلة النقل الالكترونى

اعداد

ا.د/امانى محمد بسيونى

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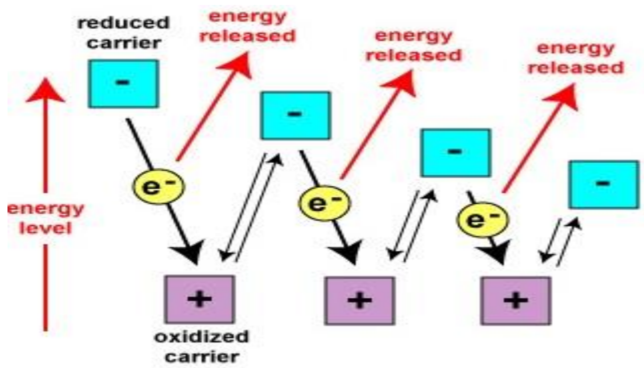
- **Oxidative phosphorylation:**

During various steps in glycolysis and the citric acid cycle, the oxidation of certain intermediate precursor molecules causes the reduction of NAD^+ to NADH + H^+ and FAD to $FADH_2$. NADH and $FADH_2$ then transfer protons and electrons to the electron transport chain to produce additional ATPs by oxidative phosphorylation .

As mentioned in the previous section on energy, during the process of aerobic respiration, coupled oxidation-reduction reactions and electron carriers are often part of what is called an electron transport chain , a series of electron carriers that eventually transfers electrons from NADH and $FADH_2$ to oxygen. The diffusible electron carriers NADH and $FADH_2$ carry hydrogen atoms (protons and electrons) from substrates in exergonic catabolic pathways such as glycolysis and the citric acid cycle to other electron carriers that are embedded in membranes. These membrane-associated electron carriers include flavoproteins, iron-sulfur proteins, quinones, and cytochromes. The last electron carrier in the electron transport chain transfers the electrons to the terminal electron acceptor, oxygen.

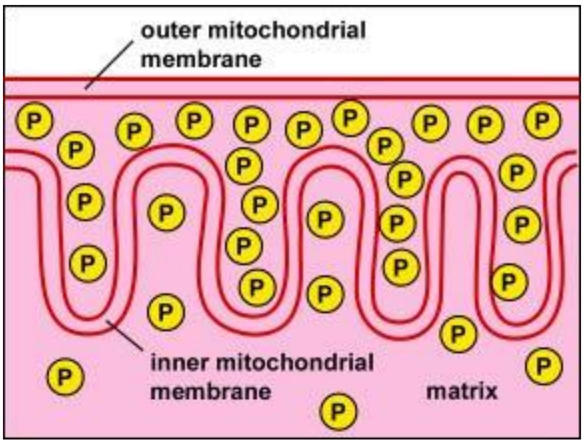


Energy release from an electron transport system. In an electron transport system, electrons pass from carrier to carrier through a series of oxidation-reduction reactions. During each transfer, some energy is released.

The chemiosmotic theory explains the functioning of electron transport chains. According to this theory, the transfer of electrons down an electron transport system through a series of oxidation-reduction reactions releases energy (Figure 1). This energy allows certain carriers in the chain to transport hydrogen ions (H^+ or protons) across a membrane.

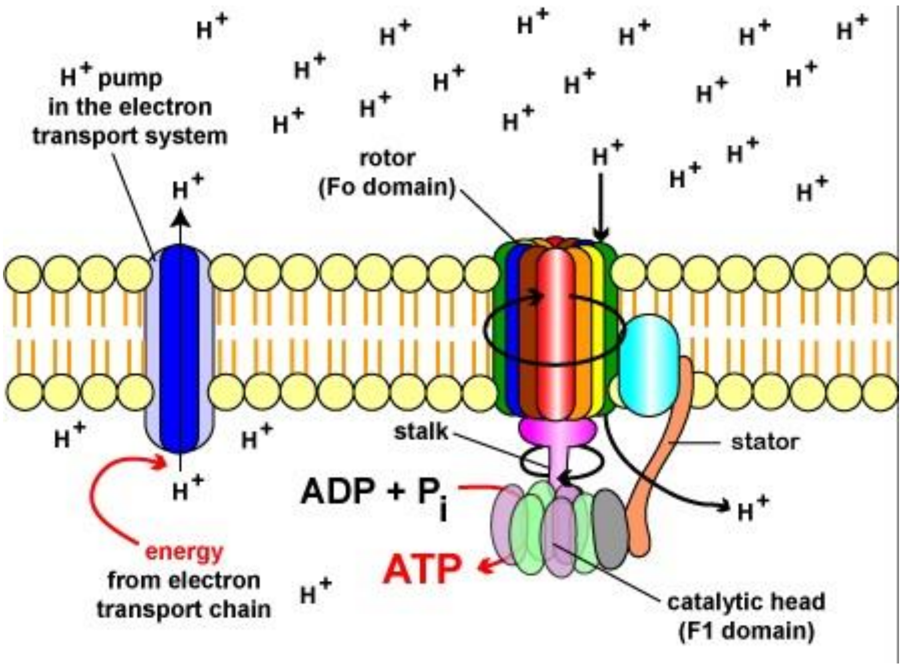
Depending on the type of cell, the electron transport chain may be found in the cytoplasmic membrane or the inner membrane of mitochondria.

- In prokaryotic cells, the protons are transported from the cytoplasm of the bacterium across the cytoplasmic membrane to the periplasmic space located between the cytoplasmic membrane and the cell wall .
- In eukaryotic cells, protons are transported from the matrix of the mitochondria across the inner mitochondrial membrane to the intermembrane space located between the inner and outer mitochondrial membranes .



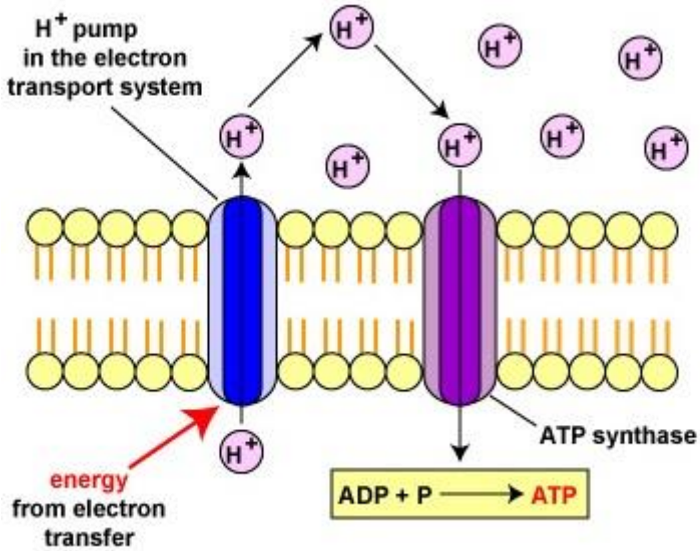
Accumulation of protons within the intermembrane Space of Mitochondria. In the mitochondria of eukaryotic cells, protons (H+) are transported from the matrix to the intermembrane space between the inner and outer mitochondrial membranes to produce proton motive force.

As the hydrogen ions accumulate on one side of a membrane, the concentration of hydrogen ions creates an electrochemical gradient or potential difference (voltage) across the membrane. (The fluid on the side of the membrane where the protons accumulate acquires a positive charge; the fluid on the opposite side of the membrane is left with a negative charge.) The energized state of the membrane as a result of this charge separation is called proton motive force or PMF.



ATP Synthase Generating ATP. The chemiosmotic theory explains the functioning of electron transport chains. According to this theory, the tranfer of electrons down an electron transport system through a series of oxidation-reduction reactions releases energy. This energy allows certain carriers in the chain to transport hydrogen ions (H^+ or protons) across a membrane. As the hydrogen ions accumulate on one side of a membrane, the concentration of hydrogen ions creates an electrochemical gradient or potential difference (voltage) across the membrane. (The fluid on the side of the membrane where the protons accumulate acquires a positive charge; the fluid on the opposite side of the membrane is left with a negative charge.) The energized state of the membrane as a result of this charge separation is called proton motive force or PMF. This proton motive force provides the energy necessary for enzymes called ATP synthases, also located in the membranes mentioned above, to catalyze the synthesis of ATP from ADP and phosphate. This generation of ATP occurs as the protons cross the membrane through the ATP synthase complexes and re-enter either the bacterial cytoplasm or the matrix of the mitochondria. As the protons move down the concentration gradient through the ATP synthase, the energy released causes the rotor and rod of the ATP synthase to rotate. The mechanical energy from this rotation is converted into chemical energy as phosphate is added to ADP form ATP.

This proton motive force provides the energy necessary for enzymes called ATP synthases (see Figure 3), also located in the membranes mentioned above, to catalyze the synthesis of ATP from ADP and phosphate. This generation of ATP occurs as the protons cross the membrane through the ATP synthase complexes and re-enter either the bacterial cytoplasm (Figure 4) or the matrix of the mitochondria. As the protons move down the concentration gradient through the ATP synthase, the energy released causes the rotor and rod of the ATP synthase to rotate. The mechanical energy from this rotation is converted into chemical energy as phosphate is added to ADP to form ATP.



Development of Proton Motive Force from Chemiosmosis and Generation of ATP. In an electron transport system, energy from electron transfer during oxidation-reduction reactions enables certain carriers to transport protons (H+) across a membrane. As the H+ concentration increases on one side of the membrane, an electrochemical gradient called proton motive force develops. Re-entry of the protons through an enzyme complex called ATP synthase provides the energy for the synthesis of ATP from ADP and phosphate.

Proton motive force is also used to transport substances across membranes during active transport and to rotate bacterial flagella.

At the end of the electron transport chain involved in aerobic respiration, the last electron carrier in the membrane transfers 2 electrons to half an oxygen molecule (an oxygen atom) that simultaneously combines with 2 protons from the surrounding medium to produce water as an end product

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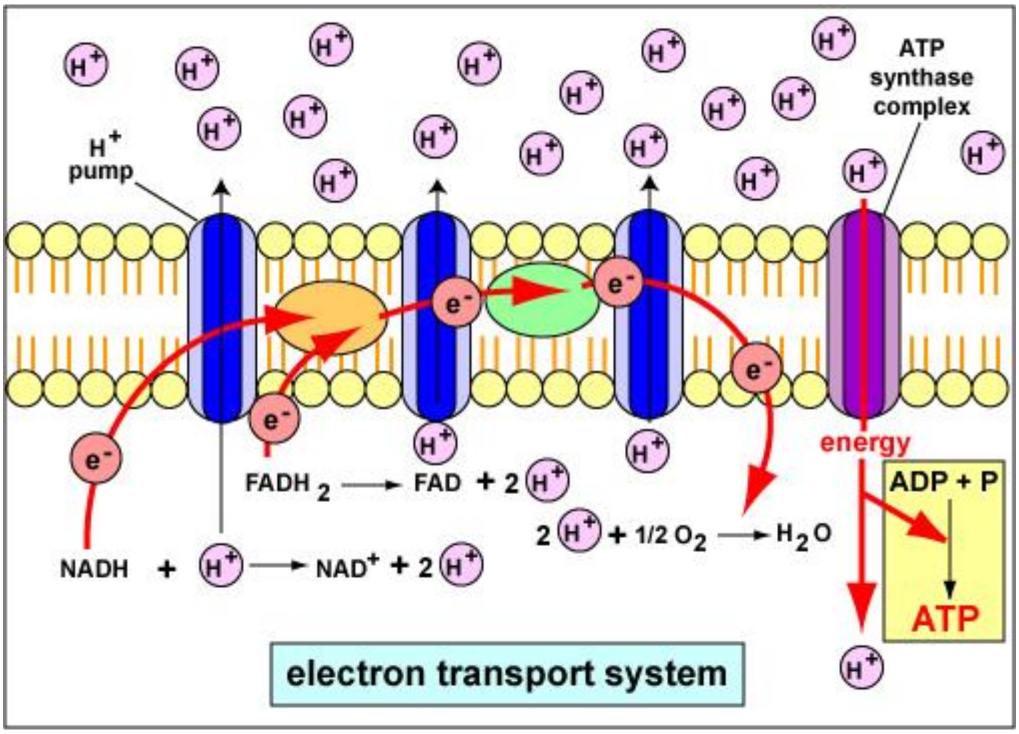

ATP Production during Aerobic Respiration by Oxidative Phosphorylation involving an Electron Transport System and Chemiosmosis. NADH and $FADH_2$ carry protons (H^+) and electrons (e^-) to the electron transport chain located in the membrane. The energy from the transfer of electrons along the chain transports protons across the membrane and creates an electrochemical gradient. As the accumulating protons follow the electrochemical gradient back across the membrane through an ATP synthase complex, the movement of the protons provides energy for synthesizing ATP from ADP and phosphate. At the end of the electron transport system, two protons, two electrons, and half of an oxygen molecule combine to form water. Since oxygen is the final electron acceptor, the process is called aerobic respiration.

Movie illustrating the electron transport system in the mitochondria of eukaryotic cells.

Summary

1. Aerobic respiration involves four stages: glycolysis, a transition reaction that forms acetyl coenzyme A, the citric acid (Krebs) cycle, and an electron transport chain and chemiosmosis.
2. During various steps in glycolysis and the citric acid cycle, the oxidation of certain intermediate precursor molecules causes the reduction of NAD^+ to NADH + H^+ and FAD to $FADH_2$. NADH and $FADH_2$ then transfer protons and electrons to the electron transport chain to produce additional ATPs by oxidative phosphorylation.
3. The electron transport chain consists of a series of electron carriers that eventually transfer electrons from NADH and $FADH_2$ to oxygen.
4. The chemiosmotic theory states that the transfer of electrons down an electron transport system through a series of oxidation-reduction reactions releases energy. This energy allows certain carriers in the chain to transport hydrogen ions (H^+ or protons) across a membrane.
5. As the hydrogen ions accumulate on one side of a membrane, the concentration of hydrogen ions creates an electrochemical gradient or potential difference (voltage) across the membrane called proton motive force.
6. This proton motive force provides the energy necessary for enzymes called ATP synthases, also located in the membranes mentioned above, to catalyze the synthesis of ATP from ADP and phosphate.

7. During aerobic respiration, the last electron carrier in the membrane transfers 2 electrons to half an oxygen molecule (an oxygen atom) that simultaneously combines with 2 protons from the surrounding medium to produce water as an end product.
8. The theoretical maximum yield of ATP for the oxidation of one molecule of glucose during aerobic respiration is 38. In terms of substrate-level phosphorylation, oxidative phosphorylation, and the component pathways involved, briefly explain how this number is obtained.

Determining the exact yield of ATP for aerobic respiration is difficult for a number of reasons. In addition to generating ATP by oxidative phosphorylation in prokaryotic cells, proton motive force is also used for functions such as transporting materials across membranes and rotating flagella. Also, some bacteria use different carriers in their electron transport chain than others and the carriers may vary in the number of protons they transport across the membrane. Furthermore, the number of ATP generated per reduced NADH or $FADH_2$ is not always a whole number. For every pair of electrons transported to the electron transport chain by a molecule of NADH, between 2 and 3 ATP are generated. For each pair of electrons transferred by $FADH_2$, between 1 and 2 ATP are generated. In eukaryotic cells, unlike prokaryotes, NADH generated in the cytoplasm during glycolysis must be transported across the mitochondrial membrane before it can transfer electrons to the electron transport chain and this requires energy. As a result, between 1 and 2 ATP are generated from these NADH.

For simplicity, however, we will look at the theoretical maximum yield of ATP per glucose molecule oxidized by aerobic respiration. We will assume that for each pair of electrons transferred to the electron transport chain by NADH, 3 ATP will be generated; for each electron pair transferred by $FADH_2$, 2 ATP will be generated. Keep in mind, however, that less ATP may actually be generated.

As seen above, one molecule of glucose oxidized by aerobic respiration in prokaryotes yields the following:

- Glycolysis

2 net ATP from substrate-level phosphorylation
2 NADH yields 6 ATP (assuming 3 ATP per NADH) by oxidative phosphorylation

- Transition Reaction

2 NADH yields 6 ATP (assuming 3 ATP per NADH) by oxidative phosphorylation

- Citric Acid Cycle

2 ATP from substrate-level phosphorylation
6 NADH yields 18 ATP (assuming 3 ATP per NADH) by oxidative phosphorylation
2 $FADH_2$ yields 4 ATP (assuming 2 ATP per $FADH_2$) by oxidative phosphorylation

Total Theoretical Maximum Number of ATP Generated per Glucose in Prokaryotes

38 ATP: 4 from substrate-level phosphorylation; 34 from oxidative phosphorylation.

In eukaryotic cells, the theoretical maximum yield of ATP generated per glucose is 36 to 38, depending on how the 2 NADH generated in the cytoplasm during glycolysis enter the mitochondria and whether the resulting yield is 2 or 3 ATP per NADH.