10.2: Introduction to Electron Transport Chains and Respiration

Introduction to Respiration and Electron Transport Chains

General Overview and Points to Keep In Mind

In the next few modules, we start to learn about the process of respiration and the roles that electron transport chains play in this process. A definition of the word "respiration" that most people are familiar with is "the act of breathing". When we breathe, air including molecular oxygen is brought into our lungs from outside of the body, the oxygen then becomes reduced, and waste products, including the reduced oxygen in the form of water, are exhaled. More generically, some reactant comes into the organism and then gets reduced and leaves the body as a waste product.

This generic idea, in a nutshell, can be generally applied across biology. Note that oxygen need not always be the compound that brought in, reduced, and dumped as waste. The compounds onto which the electrons that are "dumped" are more specifically known as "terminal electron acceptors." The molecules from which the electrons originate vary greatly across biology (we have only looked at one possible source - the reduced carbon-based molecule glucose).

In between the original electron source and the terminal electron acceptor are a series of biochemical reactions involving at least one red/ox reaction. These red/ox reactions harvest energy for the cell by coupling exergonic red/ox reaction to an energy-requiring reaction in the cell. In respiration, a special set of enzymes carry out a linked series of red/ox reactions that ultimately transfer electrons to the terminal electron acceptor.

These "chains" of red/ox enzymes and electron carriers are called electron transport chains (ETC). In aerobically...
respiring eukaryotic cells the ETC is composed of four large, multi-protein complexes embedded in the inner mitochondrial membrane and two small diffusible electron carriers shuttling electrons between them. The electrons are passed from enzyme to enzyme through a series of red/ox reactions. These reactions couple exergonic red/ox reactions to the endergonic transport of hydrogen ions across the inner mitochondrial membrane. This process contributes to the creation of a transmembrane electrochemical gradient. The electrons passing through the ETC gradually lose potential energy up until the point they are deposited on the terminal electron acceptor which is typically removed as waste from the cell. When oxygen acts as the final electron acceptor, the free energy difference of this multi-step red/ox process is ~-60 kcal/mol when NADH donates electrons or ~-45 kcal/mol when FADH$_2$ donates.

Note: Oxygen is not the only, nor most frequently used, terminal electron acceptor in nature

Recall, that we use oxygen as an example of only one of numerous possible terminal electron acceptors that can be found in nature. The free energy differences associated with respiration in anaerobic organisms will be different.

In prior modules we discussed the general concept of red/ox reactions in biology and introduced the Electron Tower, a tool to help you understand red/ox chemistry and to estimate the direction and magnitude of potential energy differences for various red/ox couples. In later modules, substrate level phosphorylation and fermentation were discussed and we saw how exergonic red/ox reactions could be directly coupled by enzymes to the endergonic synthesis of ATP.

These processes are hypothesized to be one of the oldest forms of energy production used by cells. In this section we discuss the next evolutionary advancement in cellular energy metabolism, oxidative phosphorylation. First and foremost recall that, oxidative phosphorylation does not imply the use of oxygen. Rather the term oxidative phosphorylation is used because this process of ATP synthesis relies on red/ox reactions to generate a electrochemical transmembrane potential that can then be used by the cell to do the work of ATP synthesis.

**A Quick Overview of Principles Relevant to Electron Transport Chains**

An ETC begins with the addition of electrons, donated from NADH, FADH$_2$ or other reduced compounds. These electrons move through a series of electron transporters, enzymes that are embedded in a membrane, or other carriers that undergo red/ox reactions. The free energy transferred from these exergonic red/ox reactions is often coupled to the endergonic movement of protons across a membrane. Since the membrane is an effective barrier to charged species, this pumping results in an unequal accumulation of protons on either side of the membrane. This in turn "polarizes" or "charges" the membrane, with a net positive (protons) on one side of the membrane and a negative charge on the other side of the membrane. The separation of charge creates an electrical potential. In addition, the accumulation of protons also causes a pH gradient known as a chemical potential across the membrane. Together these two gradients (electrical and chemical) are called an electro-chemical gradient.

**Review: The Electron Tower**

Since red/ox chemistry is so central to the topic we begin with a quick review of the table of reduction potential - sometimes called the "red/ox tower" or "electron tower". You may hear your instructors use these terms interchangeably.
As we discussed in previous modules, all kinds of compounds can participate in biological red/ox reactions. Making sense of all of this information and ranking potential red/ox pairs can be confusing. A tool has been developed to rate red/ox half reactions based on their reduction potentials or $E_0'$ values. Whether a particular compound can act as an electron donor (reductant) or electron acceptor (oxidant) depends on what other compound it is interacting with. The red/ox tower ranks a variety of common compounds (their half reactions) from most negative $E_0'$, compounds that readily get rid of electrons, to the most positive $E_0'$, compounds most likely to accept electrons. The tower organizes these half reactions based on the ability of electrons to accept electrons. In addition, in many red/ox towers each half reaction is written by convention with the oxidized form on the left followed by the reduced form to its right. The two forms may be either separated by a slash, for example the half reaction for the reduction of NAD$^+$ to NADH is written: NAD$^+$/NADH + 2e$^-$, or by separate columns. An electron tower is shown below.

![Redox Tower Diagram](https://bio.libretexts.org/Courses/University_of_California_Davis/BIS_2A%3A_Introductory_Biology_(Easley)/Readings/10.2%...)
Use the red/ox tower above as a reference guide to orient you as to the reduction potential of the various compounds in the ETC. Red/ox reactions may be either exergonic or endergonic depending on the relative red/ox potentials of the donor and acceptor. Also remember there are many different ways of looking at this conceptually; this type of red/ox tower is just one way.

Note: **Language shortcuts reappear**

In the red/ox table above some entries seem to be written in unconventional ways. For instance Cytochrome \( c_{\text{ox/red}} \). There only appears to be one form listed. Why? This is another example of language shortcuts (likely because someone was too lazy to write cytochrome twice) that can be confusing - particularly to students. The notation above could be rewritten as Cytochrome \( c_{\text{ox}} \)/Cytochrome \( c_{\text{red}} \) to indicate that the cytochrome \( c \) protein can exist in either and oxidized state Cytochrome \( c_{\text{ox}} \) or reduced state Cytochrome \( c_{\text{red}} \).

**Review Red/ox Tower Video**

For a short video on how to use the red/ox tower in red/ox problems click [here](https://bio.libretexts.org/Courses/University_of_California_Davis/BIS_2A%3A_Introductory_Biology_(Easlon)/Readings/10.2%20Red/ox%20towers). This video was made by Dr. Easlon for Bis2A students.

**Using the red/ox tower: A tool to help understand electron transport chains**

By convention the tower half reactions are written with the oxidized form of the compound on the left and the reduced
form on the right. Notice that compounds such as glucose and hydrogen gas are excellent electron donors and have very low reduction potentials $E_0'$. Compounds, such as oxygen and nitrite, whose half reactions have relatively high positive reduction potentials ($E_0'$) generally make good electron acceptors are found at the opposite end of the table.

Example: **Menaquinone**

Let's look at menaquinone$_{\text{ox/red}}$. This compound sits in the middle of the red/ox tower with an half-reaction $E_0'$ value of -0.074 eV. Menaquinone$_{\text{ox}}$ can spontaneously ($\Delta G<0$) accept electrons from reduced forms of compounds with lower half-reaction $E_0'$. Such transfers form menaquinone$_{\text{red}}$ and the oxidized form of the original electron donor. In the table above, examples of compounds that could act as electron donors to menaquinone include FADH$_2$, an $E_0'$ value of -0.22, or NADH, with an $E_0'$ value of -0.32 eV. Remember the reduced forms are on the right hand side of the red/ox pair.

Once menaquinone has been reduced, it can now spontaneously ($\Delta G<0$) donate electrons to any compound with a higher half-reaction $E_0'$ value. Possible electron acceptors include cytochrome b$_{\text{ox}}$ with an $E_0'$ value of 0.035 eV; or ubiquinone$_{\text{ox}}$ with an $E_0'$ of 0.11 eV. Remember that the oxidized forms lie on the left side of the half reaction.