4.4 Electron transport chain

Electron carriers, chemiosmosis and oxidative phosphorylation

Number of molecules made for every molecule of glucose			
Name of molecule produced	Stage of aerobic respiration		
	Glycolysis	Link reaction	Krebs cycle
ATP	2	0	2
$NADH_2$	2	2	6
$FADH_2$	0	0	2

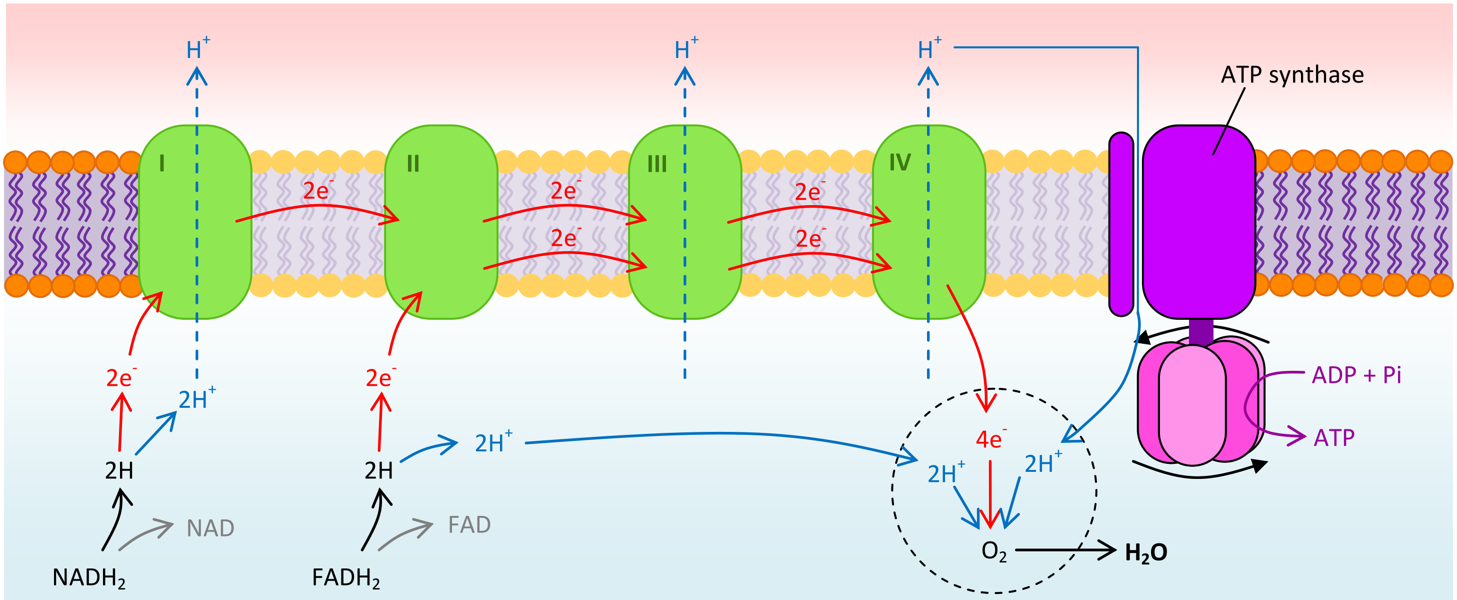
Glycolysis is a series of reactions which has a net production of 2 molecules of ATP (because whilst there are four molecules of ATP produced for every glucose, there are two used up in the process) per molecule of glucose. It also produces two molecules of reduced NAD, or $NADH_2$.

The *link reaction* produces one molecule of reduced NAD for each molecule of pyruvate, so for every molecule of glucose, there are two molecules of $NADH_2$ produced. No ATP is made directly during the link reaction.

During *Krebs cycle*, there is one molecule of ATP produced per each turn of the cycle. Since there is one turn for each molecule of pyruvate, so two per glucose molecule, this means there are 2 ATP produced for each glucose molecule at Krebs. Krebs cycle also produces three molecules of reduced NAD and one molecule of FAD per turn, so each molecule of glucose results in six $NADH_2$ and two $FADH_2$.

Electron transport chain

The fourth and final stage of aerobic respiration involves electron carriers in the inner mitochondrial membrane, called **cytochromes**. These membranes are folded into **cristae** so that there is a larger surface area for the membranes, so there can be more of these chains. The chain of electron carriers is called the **electron transport chain**.



1 The molecules of reduced NAD and reduced FAD are **reoxidised** by donating their two hydrogen atoms to the electron carriers. One hydrogen atom is split into one proton and one electron, so each $NADH_2$ or $FADH_2$ donates two electrons and two protons

2 The electrons of the reduced NAD are accepted by the first electron carrier, a protein complex called complex I, or *reduced NAD dehydrogenase*, and the electrons are passed along the chain to the next carrier, complex II

3 The flow of electrons along the chain releases energy, which is used by complex I to pump protons through to the intermembrane space

4 Two more electrons, donated from the hydrogen atoms of a reduced FAD molecule are accepted by complex II (making there four present electrons in total in complex II)

5 These now four electrons are passed along to complex III (transported by a coenzyme called *coenzyme-Q*), which releases energy – although this is not used by complex II to pump a proton, as complex II cannot pump protons
6 The four electrons are accepted in pairs by complex III, where they are again transported along to complex IV (using the coenzyme *cytochrome c*), and the energy released is used to pump a proton through to the intermembrane space
7 The four electrons are then donated one-by-one to molecular oxygen, which also accepts four protons – two from the reoxidised FAD molecule, and two which are pumped back through the membrane using the enzyme at the end of the electron transport chain, to form water, a waste product

Oxidative phosphorylation

At the end of the electron transport chain is an enzyme embedded in the inner mitochondrial membrane called **ATP synthase** (or ATP synthetase, or ATPase). The process of **oxidative phosphorylation** occurs here. This is the addition of an inorganic phosphate to ADP to form ATP, in the presence of oxygen.

Due to the concentration gradient of protons from the intermembrane space through to the mitochondrial matrix, protons flow through the ATP synthase enzyme. This drives the rotation of the part of the enzyme outside the membrane, allowing a molecule of ADP to join with a phosphate (Pi) to form ATP.

Chemiosmosis

As the electrons are passed along the electron transport chain from carrier to carrier, energy is released, and at the complexes I, III and IV is used to pump the protons over the membrane and into the intermembrane space. This builds a proton gradient from the intermembrane space, where there will be a high concentration of protons, down to the matrix where there are fewer protons. This is also a pH gradient and an electrochemical gradient.

For this reason, potential energy builds up in the intermembrane space, and as the protons cannot diffuse through the phospholipid bilayer down the concentration gradient, the protons have to be transported through ion channels embedded in the membrane, which are associated with the ATP synthase enzyme (as they pass through the channel, this drives the rotation of the ATP synthase leading to oxidative phosphorylation). This flow of protons is called **chemiosmosis**.

Chemiosmotic theory

The theory of chemiosmosis was forwarded by Peter Mitchell in 1961. The theory noted Mitchell's observations, including the movement of protons into the intermembrane space pumped by the cytochromes, and the flow back to the matrix through ion channel proteins attached to enzymes, which drove the rotation, causing oxidative phosphorylation. This movement down the channel driving the rotation was described as **proton motive force**.

Evidence from studies supporting chemiosmotic theory

Researchers treated isolated mitochondria by placing them in solutions of very low water potential so that the outer membrane ruptured, releasing the contents of the intermembrane space. By further treating the resulting **mitoblasts** (mitochondria stripped of their outer membranes) they could rupture the inner membrane, releasing the matrix contents.

This allowed the researchers to identify that the link reaction and Krebs cycle took place in the matrix, but the electron transport chain enzymes were in the inner membrane. Electron transfer in the mitoblasts did not produce any ATP, so they also concluded that the intermembrane space was involved. In the presence of oligomycin, an antibiotic which is now known to block the flow of protons through the ion channel proteins, in intact mitochondria, again no ATP was produced.

Products of the electron transport chain

Before the electron transport chain occurs, there is a net production of 2 ATP molecules during glycolysis and 2 ATP during Krebs cycle for each molecule of glucose. The table on the previous page also outlines the number of reduced NAD and reduced FAD produced at each stage.

During oxidative phosphorylation, each molecule of $NADH_2$ theoretically produces 2.5 ATP, and each molecule of $FADH_2$ theoretically produce 1.5 ATP. Because during the previous stages of aerobic respiration 10 reduced NAD are produced, that should produce 25 molecules of ATP during oxidative phosphorylation. And the 2 molecules of reduced FAD should produce 3 molecules of ATP, making that a net production of 28 ATP in total (and so the total ATP production for aerobic respiration 32). However, this amount is rarely achieved as some protons can leak across the mitochondrial membrane.