Life 24 - Blood and Circulation – Raven & Johnson Ch 52 & 53 (parts)

Objectives

1: Understand the importance of oxygen carrier molecules in respiration

2: Describe the characteristics and locations of the different respiratory pigments

3: Explain the features of the oxygen dissociation curve, and how this is modified by temperature and pH

4: Understand the properties and functions of myoglobin compared to haemoglobin

5: Compare the anatomy and efficiency of open and closed circulatory systems

6: Describe the major features of the circulatory systems of fish, amphibians and mammals

Blood and circulation
Oxygen supply to the cells in very small animals can be by diffusion across the general body surface and then within the tissues

Larger animals need respiratory organs for gas exchange, and a transport system between these organs and the tissues. Tracheal system of insects serves both purposes, oxygen piped directly to the cells

Other animals use a fluid transport system for gases. Blood used here as a general term for any fluid circulated within the body, including coelomic fluid, haemolymph, water vascular system fluid

Blood has other functions, e.g. moving nutrients from the digestive tract to the tissues, chemical communication, and defence against infection (read Chapter 52). Insects need blood circulation in addition to the tracheal system

Oxygen transport by blood (transport of CO_2 in lecture 25)

In many invertebrates oxygen is carried in solution, dissolved in the fluid. But the solubility of oxygen is low, especially at high body temperatures and in fluids with other solutes (OHP Table – not in notes)

The dissolved oxygen in mammalian blood plasma is only about 2 mL L^{-1}, compared to 7 mL L^{-1} in water. But the oxygen carrying capacity of blood is 10-100 $\times$ that of water, because of molecular oxygen carriers

These are proteins that contain a metal ion, either iron or copper, and are often coloured and so termed respiratory pigments. There are four of these:

Haemoglobin: Red when oxygenated, blue-red when deoxygenated.
Protein + Haem (porphyrin ring) + Fe^{2+}

In solution or in cells. Molecular weight very variable, 17 thousand - 3 million.
Most widely distributed - almost all vertebrates, some molluscs, crustaceans, annelids, nematodes

Chlorocruorin: Green. Protein + Haem + Fe^{2+}
Note that this has haem, but haemerythrin and haemocyanin do not

Similar structure to haemoglobin, slightly modified haem. In solution.
MW 2.7 million. Four families of polychaetes

Haemerythrin: Violet – colourless. Protein + Fe^{2+}. In cells. MW 100 000.
Sipunculid, priapulid and polychaete worms

Haemocyanin: Blue – colourless. Protein + Cu^{2+}. In solution
MW 300 000 to 9 million. Cephalopods & pulmonate molluscs, crustaceans

Oxygen binding site is at the metal ion, but the metal is not oxidised. Oxidised iron in haemoglobin to Fe^{3+}, gives non-functional methaemoglobin

The oxygen-binding capacity of the metal ion is 1 O_2 per ion in haemoglobin & chlorocruorin, and 1 O_2 per 2 ions in haemerythrin & haemocyanin

Each pigment has characteristic optical absorption spectra in the oxygenated and deoxygenated states. The figure shows absorbance for haemerythrin. Measure spectra for haemoglobin in the practical (OHP Figure)

In some animals the pigments are enclosed in cells, and in others they are free in solution. When pigments are enclosed in cells, their molecular weights are relatively low, tens of thousands (OHP Table, not in notes)

When they are free in solution, their molecular weights are much higher, a few million. These large molecules are aggregates of smaller molecules

Large molecules increase the total amount of pigment, and therefore the amount of oxygen that can be carried

But they do not increase the number of protein molecules, which would increase the osmotic pressure and affect other physiological systems

Another advantage of pigment inside cells is that the environment can be different from that of the plasma. The conditions in the cells can be changed to alter the properties of the carrier (e.g. pregnancy, below)

Oxygen dissociation curves

The reversible binding of oxygen to the pigment molecule can be written as an ordinary chemical reaction, e.g. for haemoglobin:

$$Hb + O_2 \leftrightarrow HbO_2$$

At high oxygen tension the haemoglobin (Hb) combines with oxygen to form oxyhaemoglobin (HbO_2) and the reaction goes to the right

At low tension, oxygen is given up again and the reaction goes to the left. If the oxygen tension is reduced to zero, the haemoglobin gives up all its oxygen

At any given oxygen tension there is a definite proportion of haemoglobin and oxyhaemoglobin. Plotting this gives the oxygen dissociation curve (Fig. 53.16)

The haemoglobin is saturated with oxygen above a tension of about 100 mmHg – it can take up no more oxygen. E.g. in the lungs

As the oxygen tension decreases, more and more oxygen is given off, until the haemoglobin is fully deoxygenated at zero oxygen tension. Oxygen is released in the tissues, where the oxygen tension is lower

If the dissociation curve is shifted to the right, the haemoglobin is less saturated at a given tension of oxygen. It has a lower affinity for oxygen - the blood gives up oxygen more easily.

If the dissociation curve is shifted to the left, the haemoglobin gives up oxygen less easily - higher affinity for oxygen. The position depends on:

1: **Temperature**. Increased temperature weakens the bond between oxygen and haemoglobin. The haemoglobin gives up oxygen more easily, and the curve shifts to the right. 20 C $\rightarrow$ 43 C (Fig. 53.17)

Important in animals with variable body temperatures. Increased temperature causes an increase in oxygen consumption, and haemoglobin delivers oxygen more easily at higher temperature

2: **pH and carbon dioxide**. Increase in carbonic or other acids lowers the pH, and this shifts the dissociation curve to the right. pH 7.6 $\rightarrow$ 7.2

A tissue using much oxygen also produces much CO_2. Shifting the dissociation curve causes haemoglobin to give up more oxygen where it is needed

3. **Organic phosphates**. Organic phosphates such as ATP and DPG (diphosphoglycerate) decrease the oxygen affinity of haemoglobin, and shift the dissociation curve to the right

Provides a mechanism for adaptation without changing the haemoglobin itself. Increase in DPG in red blood cells in pregnancy. Curve shifts to the right, gives up oxygen more easily to the foetal blood

Myoglobin

Haemoglobin occurs not only in blood, but also in tissues, especially muscles where it is termed myoglobin. This is a single unit molecule; haemoglobin is a group of 4 subunits (Fig. 53.15)

Myoglobin has a dissociation curve well to the left of haemoglobin, so it takes up oxygen from haemoglobin. The curve is of a different shape, hyperbolic instead of sigmoid (OHP Figure)

This is due to its being a single unit. The higher the oxygen tension, the less the effect of an increase in tension on the saturation level. There are fewer unoxygenated myoglobin molecules left to combine with oxygen

The sigmoid shape for haemoglobin is due to the multi-unit structure. There are cooperative effects between the subunits

Binding of one unit with oxygen increases the probability that other units will become oxygenated. So there is an accelerated increase in the percentage saturation with increase in oxygen tension

All respiratory pigments have this subunit structure, and so sigmoid oxygen dissociation curves. The function is to release oxygen at low oxygen tension. Hyperbolic curve does not release oxygen easily

Myoglobin also acts as an oxygen store within the muscle. It is an important oxygen supply for short-term activity, especially in diving animals

Compare oxygen stores (mL kg^{-1}) in man and seal:

	Lung	Blood	Muscle	Dissolved	Total
Man	12	14	1	2	29
Seal	13	37	27	2	79

Seal has higher blood haemoglobin, and especially muscle myoglobin. Overall nearly 3 × greater oxygen stores

The other function of myoglobin is to increase the rate of diffusion of oxygen through the muscles. All haemoglobins show facilitated diffusion of oxygen

Oxygen diffuses 8 × faster through haemoglobin solution than water. Other gases diffuse slightly slower through haemoglobin solution than water

Facilitated diffusion increases the supply of oxygen through the muscle. Oxygen is passed between the myoglobin or haemoglobin molecules

Depends on Brownian motion, so higher in myoglobin than in the larger haemoglobin. Other respiratory pigments do not have this property

Circulation

Blood moves in circulatory system, basically made up of pumps and channels. The pumping mechanism may be either:

1: Cilia or flagella, e.g. echinoderms water vascular system

2: Tubular peristaltic pump, as in most invertebrates. A constriction moves along the tube, pushing blood before it

3: Chamber pump, in vertebrates. Walls contract simultaneously and expel blood from an internal chamber, with valves for one-way flow

4: External muscles. E.g. skeletal muscles in human legs, veins with valves. Contraction of muscles compresses vein, forces blood upwards (Fig. 52.9). Also caudal heart in hagfish (*Myxine*)

Blood may circulate entirely within channels - a closed circulation, found in vertebrates, cephalopods, echinoderms & annelids (Fig. 52.2)

In many invertebrates the blood vessels terminate, and blood (haemolymph) flows through spaces in the tissues. This is an open circulation, found in most arthropods and molluscs (seen in mollusc gill)

Closed systems have several advantages:

1: Blood pressure can be high, 100 mmHg or more. Open systems have low pressure of a few mmHg, as this cannot exceed the pressure of the tissues. Gives fast circulation

2: High pressure can also be used to push blood through a high resistance such as a capillary network

3: Distribution of blood to different organs can be well controlled

Closed system - fish

There is a single circulation route, with the gas exchanger (gills) in series with the general body circulation. Haemoglobin is oxygenated in the gills (→ red) and delivers oxygen to the tissues (→ purple) (Fig. 52.12)

Sinus venosus collects blood, ensures a supply for continuous flow to the heart. Heart has two chambers.

One with thick walls specialised for pressure generation (ventricle), the other with thinner walls (atrium), a pump primer

Blood can be forced into thin-walled atrium under low pressure, then atrium contracts to fill ventricle. Low blood pressure in veins could not expand the muscular venticle unaided

Then the elastic-walled conus arteriosus, receives blood in pulses and evens out the pressure changes, more continuous flow

Tetrapods

Amphibians have incompletely divided hearts. Two atria but single ventricle. Blood does not mix in the heart in normal conditions due to a spiral valve or septum in the conus arteriosus (Fig. 52.13)

Oxygen tensions in blood show almost complete separation. Deoxygenated blood from body goes mostly to lungs (purple). Oxygenated blood from lung goes mostly to body (red)

Birds and mammals have a completely divided heart, with two atria and two ventricles. There is a double circulation, one ventricle to body & head, other to the lungs (Fig. 52.14)

Advantage is not in preventing mixing, as this already largely achieved in amphibians. Separate systemic (body) and pulmonary (lung) circuits can have different blood pressure

Pulmonary circuit has much lower pressure as it is a shorter path (not all round the body). Blood capillaries in lungs can thus be very thin walled

This increases gas exchange - main diffusion barrier in the lung is the intracellular fluid of the epithelium & endothelium, not the air