THE HEART

The heart undergoes contraction (systole) and relaxation (diastole) rhythmically throughout the animal's life. In man its performance is prodigious: in the course of a normal life span it beats over 2.5 x 10^9 times, pumping more than 150 million dm^3 of blood from the ventricle. Although we shall mainly discuss the mammalian heart, it should be borne in mind that this basic function applies to any heart, be it a whale, goldfish or lungworm.

Blood returning via the great veins enters the right atrium. The resulting pressure in this chamber forces open the flaps of the atrio-ventricular valve(also known as the tricuspid valve because it consists of three flaps)with the result that blood flows through the atrio-ventricular opening into the right ventricle. When the atrium and ventricle are full of blood the atrium suddenly contracts, propelling the remaining blood into the ventricle. The contraction spread from the right atrium over the rest of the heart. Atrial systole is comparatively weak but the ventricles, being particularly well endowed with muscle, contract much more powerfully. As a result blood is forced from the right ventricle into the pulmonary artery. It is prevented from flowing back into the atrium by flaps of the atrio-ventricular valves, which close tightly over the atrio-ventricular aperture. They are prevented from turning inside out by tough strands of connective tissue, the tendinous cords (heart strings) which run from their undersides to the walls of the ventricle. Once in the pulmonary artery, blood is prevented from flowing back into the ventricule by pocket valves guarding the opening of the artery.

From the lungs oxygenated blood returns to the left atrium via the pulmonary veins. It is then conveyed to the left ventricle and so into the aortic (systemic) arch. This movement of blood takes place in the same way as on the right side of the heart. Although systole starts at the right atrium, it spread quickly to the left so that the whole heart appears to contract synchronously. Thus deoxygenated blood is pumped from the right ventricle into the pulmonary artery at the same time oxygenated blood is pumped from the left ventricle into the aortic arch.

Systole is followed by diastole during which the heart refills with blood again. The entire sequence of events is known as the cardiac cycle. And is accompanied by electrical activity in the wall of the heart and by 'sounds' corresponding to the closing of the various valves.

One of the most remarkable features of the heart is its ability to contract rhythmically without fatigue.It owes this property to its muscle. Known as cardiac muscle, it consists of a network of interconnected muscle fibres. The fibres are divided up into uninucleate cells containing fine longitudinal contractile fibrils. The muscle fibres show the same kind of cross-banding as skeletal muscle, and the mechanism of contraction is believed to be substantially the same. The interconnections between the fibres ensure a rapid and uniform spread of excitation throughout the wall of the heart, which in turn ensure a synchronous contraction.

THE BEATING OF THE HEART

What initiates the beating of the heart? Most muscles contract as a result of impulses reaching them from nerves. This is not, however, true of the heart, which will continue beating rhythmically even after its nerve supply has been severed. Indeed the heart will go on beating after it has been cut right out of the body. Cardiac muscle is, therefore, myogenic, its rhythmical contraction arising from within the muscle tissue itself.

What, then, initiates this rhythm? The mammalian heart has a specialized plexus of fine cardiac fibres embedded in the wall of the right atrium close to where the great veins enter it. This called the sino-atrial node(SAN) experiments have shown that it serves as a pacemaker. If excised, it will continue to beat at the normal rate of about 70 beats per minute. Other pieces of excised atrium will also beat on their own, but at a slower rate of about 60 beats per minute. Pieces of excised ventricle very much more slowly: about 25 beats per minute.

These experiments indicate that different parts of the heart are capable of beating at their own intrinsic rate. However, in the intact heart the beating of the ventricle is dependent on the atria, and atria on the SAN. In other words the SAN, the region of the heart with the fastest intrinsic rhythm, sets the rate at which the rest of the heart beats.

Confirmation that the SAN is the pacemaker has come from recording electrical activity from various parts of the heart wall. It has been found that contraction of the heart is preceded by a wave of electrical excitation. This starts at the SAN and then spreads over the atria. When the wave reaches the junction between the atria and ventricles, it excites another specialized group of cardiac muscle fibres called the atrio-ventricular node(AVN). Continuous with the AVN is a bundle of modified cardiac muscle fibres called Purkinje tissue, which runs down the interventricular septum and fans over the walls of the ventricles where it breaks up into a sheet-like reticulum just beneath the endothelial lining.When the AVN receives excitation from the atria, it sends impulses down the Purkinje tissues, and these then spread through the walls of the ventricles. Thus the pacemaker sends out rhythmical waves of electrical excitation which are transmitted first over the atria and then, via the AVN and Purkinje tissue, to the ventricles. This spread of excitation is accompanied by muscular contraction. The most remarkable aspect of the whole performance is that the rhythmical initiation of the excitatory waves is quite independent of nervous control.

INNERVATION OF THE HEART

The fact that pacemaker initiates the rhythmical beating of the hearth does not mean that it has no nerve supply. On the contrary it receives two nerves, a branch of the sympathetic nervous system and a branch of the vagus nerve. These do not initiate the beating of the heart, but can modify the activity of the pacemaker, thereby speeding up or slowing down the rate at which the heart beats. This can be demonstrated in an animal like the frog or turtle by attaching the heart to a lever that writes on a slowly revolving drum. The sympathetic and vagus nerves are hooked onto fine electrodes through which weak electrical shocks can be delivered. In this way impulses can be generated in one or other of the two nerves. If the sympathetic nerve is stimulated the heart speeds up; if the vagus is stimulated it slows down. The vagus and sympathetic nerves are thus antagonistic in their effects. This double innervation makes the animal's transport system much adaptable than would otherwise be the case. It means that the speed at which respiratory gases are transported round the body can be modified to suit the needs of the animal as occasion demands.

BLOOD FLOW THROUGH THE ARTERIES AND VEINS

Blood isexpelled from the heart only when it contracts. Blood flow through the arteries is therefore intermittent, the blood flowing rapidly during systole and slowly during diastole. However, by the time the blood reaches the capillaries it is flowing evenly. The gradual change from intermittent to even flow is made possible by the elasticity of the arterial walls contain much elastic tissue and smooth muscle. When blood is pumped into the arteries, the semilunar valves prevent the blood returning to the heart and the wall of the first part of the artery is distended. As the heart relaxes, the distended section of the artery constricts, which distends the next section- and so on. Thus a wave of distension followed by constriction (the pulse wave) progresses along the artery. The blood itself flows more slowly than the pulse wave, falling to less than 1 mm/s by the time it reaches the capillaries. To some extent the blood is kept flowing by wave-like contractions of the smooth muscle in the walls of the smaller arteries.

Veins have thinner walls and a larger lumen than arteries. Blood flow through them, which has to occur against gravity, is assisted by contraction of the skeletal muscles which squeezes the blood along. Back flow prevented by valves, and large diameter of the veins minimizes resistance to flow. Also the negative pressure developed in the thorax during inspiration will tend to draw blood back to the heart.

THE CAPILLARIES

As a transport system, the job of the circulation is to take up materials in one part of the body and deliver them to another. There must therefore be an

Intimate relationship between the circulatory system and the tissues. This is achieved by the capillaries. Fig 11.15 shows a small part of a capillary network. In contrast to artries and venis, the capilariesare narrow (an average of 10/min in diameter) and thin-walled. The wall consist of a single layer of pavement endothelium which presents very little resistance to the diffusion of dissolved substances into or out of the capillary the cells are bathed in tissue fluid derived from the blood plasma which provides a medium through which diffusion can take place. The close proximity between the capillaries andd the tissue cells, and thinnessof the barrier between them, facilitates this exchange of materials.

The capillaries provide the means by which transport of materials can be regulated. Rings of musle surround the capillaries at the points where they arise from the arterioles. Under the influence of nerves, hormones or local conditions, these sphincter musles contract or relax, therby decreasing or increasing the flow of blood through them. In some parts of the body large muscular vessels form a direct connection between arteries and veins, therby bypassing the capillaries. By constricting or dilating, these arterio- venous shunt vessels can regulate the amount of blood which flows through a particular set of capillaries at any given time.

The capillaries are thus like a vast irrigation system different parts of which can be opened or closed according to local needs and conditions. This, coupled with the fact that the heart can vary its rate of beating, makes the mammalian circulation a highly adaptable transport system.

Single and Double Circulations

In Fig 11.16 the heart of the mammal is compared with the fish and frog. The fish has the simplest system: deoxygenated blood from the body is pumped to the gills whence it flows to various parts of the body and then returns to the heart. The heart has only one atrium and ventricle. As blood flows only once through the heart for every complete circuit of the body, this is spoken of as a single circulation.

The snag about this arrangement is that blood has to pass through two capillary system, the capillaries of the gills and then those of the body, before returning to the heart. Capillaries offer considerable resistance to the flow of blood, and this means that in fishes there is a marked drop in blood pressure before the blood complete a circuit. For this reason the blood-flow tends to be sluggish on the venous side. In fishes this has been overcome to some extent by replacing the veins with large sinuses that offer minimum resistance to blood-flow. Nevertheless the problem of getting blood back to the heart is an acute one and probably imposes severe limitations on the activities of many fishes.

In mammals the problems has been overcome by the development of a double circulation. Blood is pumped from the heart to the lungs, whence it returns to the heart and is then re-pumed to the body. To prevent mixing of deoxygenated and

oxygenated blood, the heart is divided into right and left sides, the right side dealing with deoxygenated and the left side with oxygenated blood. This we have already seen and there is no need to elaborate on it further.

The frog shows an interest intermediate condition. It has a double circulation in that blood is returned to the heart after passing through the lungs, and there are two atria as in the mammal. However, the ventricule is completely undivided, as is the conus arterious into which the blood is pumped before entering the vessels leading to the lungsand body.On purely structural grounds it would seem that deoxygenated and oxygenated blood would be inextricably mixed in the single ventricle. Over the years, there has been much speculation on the extent to which this is so. This is certainly not the place to go into the details of so specialized a point. Suffice it to say that, despite the apparent anatomical shortcomings, separation of the two bloodstreams is surprisingly complete, mainly deoxygenated blood being sent to the lungs and oxygenated blood to the blood. Exactly how this is achieved is not known but the various folding in the wall of the ventricle, aided possibly by the spiral valve in the conus arteriosus, play an important part. Research on order vertebrates with incompletely divided hearts indicates the same thing: a high degree of separation of deoxygenated from oxygenated blood. The general principle which this illustrates is that if a double circulation is to be develop0ed, it must be coupled with some kind of mechanism for keeping the deoxygenated and oxygenated bloodstreams apart.

Of course developing a double circulation is not the only way of overcoming the pressure problem seen in fishes. An alternative solution would be to have two separate hearts, one for pumping blood to the body, the other for pumping blood to the respiratory organs. This is precisely what has happened in octopuses and squids. Blood is pumeds from the main heart to various parts of the body. It then flows through a system of sinuses to a pair of branchial hearts which pump it through the gills. The blood then returns to the main heart for distribution to the body. Octopuses and squids are on a quite different evolutionary line from vertebrates. But like vertebrates they are active crreaturs, and comparing their circulation shows us how the same physiological problem can be solved in two quite different ways.

Open and Closed Circulation

In the circulations considered so far the blood is confined to vessels, or in some cases sinses, that are quite distinct from the general body cavity. However, in certain invertebrates, notable arthrpods, the blood is contained in the body cavity. The reason lies in the way arthropods develop. In most animals the embryological cavity (coelom) that eventually becomes the main body cavity expands at the expence of the cavity (blastocoel) which eventually forms the blood vessels . in arthropods the

reverse is the case. The coelemic cavities remain small and the blastocoel becomes the main body cavity. Since in this case the body cavity contains blood it is known as a haemocoel. The whole system is known as an open circulation, in contrast with the closed circulations of other animals.

In insects the haemocoel is divided by a transverse pericardial membrane into a pericardial cavity dorsally and a perivisceral cavity ventrally. The only blood vessel as such is a tabular heart which is suspended in the pericardial cavity by slender ligaments. The heart, which extends through the thorax and abdomen, is expended in each segment to form a small chamber which is pierced by a pair of tiny holes or ostia. In the pericardial membrane is a series of alary musles corresponding in position to the heart chamb

Blood is propelled forwards through the heart by waves of contraction (systole) which commence at the rear and work theirway towards the anterior end. The blood then leaves the heart and enters the haemocoel through which it flows. How does the blood re-enter the heart? During systole the heart ligaments are starched with the result that during diastole they pull the walls of the heart outwards. This result in blood being sucked into the heart through the ostia. The latter are equipped with valves that allow blood to enter, but not leave, the heart through them. Expansion of the heart is aided by contraction of the alary muscles which increases the tension on the ligaments. Contraction of the alary musles also has the effect of pulling the pericardial membrane downwards, thereby raising the blood pressure in the pervisceral cavity and decrease it in the pericardial cavity. This encourages the flow of blood from the former to the latter.

As we saw in chapter8 gaseous exchange in insect takes place through the tracheal system. The circulatory system is therefore not directly concerned with transport of respiratory gases. Accordingly it lacks a respiratory pigment, though it does contain phagocytes and plays an important part in the distribution of food substances and elimination of nitrogenous waste matter. The insect, with its tracheal system and open circulation, has solved the problem of transport by means that contrast sharply with those evolved by the vertebrates.

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The Mammalian Respiratory System

Starting with the larynx, a box-like structure that lies on the ventral side at the base of the head, and opens into the pharynx by the glottis, which is guarded by an epiglottis (serves to close it).

On the ventro-lateral side of the larynx and the anterior part of the trachea there is a reddish glandular structure, the thyroid gland, formed of two lateral lobes, connected by a transverse isthmus.

The larynx leads to the trachea, which is recognized by its complete cartilageneous rings and lies along the ventral side of the oesophagus.
On entering into the thoracic cavity, the trachea divides into two bronchi, each passing into a lung.
Each lung lies in a pleural cavity, enclosed by two peritoneal layers which form the pleura.
Examine the disphragm and note that it is convex anteriorly, concave postiriorly, and formed of a central tendinous portion and an outer muscular portion which is inserted on the inner thoracic wall.
Identify the two phrenic nerves, one on each side, which supply the diaphragm. Each arises as a branch of the cervical plexus.
Larynx= the area at the top of the throat that contains the vocal cord.
Laryngitis= an infection of the larynx that makes speaking painful