Life 23 - Respiration in Air – Raven & Johnson Ch. 53 (part)

Objectives

1: Compare the properties of air and water as media for respiration, and the consequences for the evolution of respiratory systems

2: Describe the anatomy of the human lung and the mechanics of breathing

3: Compare respiration in air-breathing fish, amphibians, and mammals

4: Explain the action and advantages of the unique respiratory system of birds

5: Describe the structure, function, and modifications of the tracheal respiratory system in insects

Air and water compared

Differ as media for respiration in terms of concentration and rate of diffusion of oxygen, and density of the medium

1: Much more oxygen in air than in water in equilibrium with air, because of the low solubility coefficient α. 1 L of air contains 210 mL oxygen, while 1 L water contains 7 mL oxygen (at 15 C)

So the concentration of oxygen in air is 30 × that in water at the same partial pressure / tension. Respiratory surface area can be smaller for same oxygen uptake

2: Rate of diffusion of oxygen is about 300 000 × greater in air than in water, for the same gradient of partial pressure / tension, because of their diffusion coefficients **D**

So the diffusion distance **d** can be much longer in air than in water. Movement of the medium over the respiratory surface is less important, as deoxygenated boundary layer forms less easily

For example compare annelid worms living in burrows or tubes. Aquatic worms have gills to increase surface area for diffusion **A**

They also ventilate the burrow to pass water over the gills, using undulatory movements, to maintain a high concentration gradient Δ**p**

In contrast the general body surface is sufficient in earthworms, and they do not ventilate their burrows - due to high oxygen content and diffusion in air

3: Density of air is very much lower than density of water. Combining density and oxygen concentration: 1 g of oxygen is found in 3.5 g of air, but only in 100 kg of water

Much less work has to be done moving air than moving water, to obtain the same oxygen. So one-way flow is less important in air

Respiratory organs in air

Main drawback of respiration in air is the problem of water loss. If a surface is permeable to gases, it is also permeable to water molecules

Body surface can only be used in a moist atmosphere - earthworms quickly die from water loss in dry air

So respiratory organs in air are usually lungs rather than gills. Water loss is minimised by having an internal respiratory surface. Two types of lungs:

Diffusion lungs in small animals, e.g. pulmonate molluscs. Gills have been lost and the mantle cavity has blood vessels in the walls for gas exchange. Oxygen diffuses into the lung

Larger animals including all vertebrates have ventilation lungs. Oxygen enters the lung with bulk movement of air, caused by muscles

Human lung
Brief - expected to know (A level). Respiratory tract comprises the trachea, bronchi, and bronchioles, terminating in blind sacs or alveoli (Fig. 53.9)

Flow of air is tidal, moving into and out of the alveoli along the same path

Gas exchange is in the alveoli. Rest of the system is just connecting tubes - dead space where no exchange occurs

Capillaries in walls of the alveoli. Oxygen enters the blood by diffusion through the air, then through the alveolus epithelium and the capillary endothelium

150 million alveoli in each lung of man, each 200 μm in diameter, giving a total lung area of 80 m^2. Maximum diffusion distance through the air is thus 100 μm, 10 x the distance in fish gills

But main diffusion barrier is the alveolar walls, where oxygen diffuses in solution. Thickness of these walls is only about 0.4 μm (1/20 of the diameter of a red blood cell), but this is equivalent to about 10 cm of air

Main effect of the large number of alveoli is thus to increase surface area - reducing the length of the diffusion path in air is not important

Lungs of amphibians are simple sacs because their low metabolism does not need a large surface area - diffusion may occur over a few mm in these lungs

Ventilation is by negative pressure in the thoracic cavity. Caused by the intercostal muscles between the ribs, and contraction of the muscular diaphragm (Fig. 53.12)

Amphibians
Amphibians use both lungs and skin for gas exchange. Salamanders with very low metabolism (Plethodontids) have lost lungs, use skin only – moist and many blood capillaries (highly vascularised)

Lining of the mouth is also highly vascular and gas exchange occurs in the buccal cavity. Between breaths, the nostrils are open but the glottis closes the lungs (Fig. 53.8)

Floor of the mouth moves up and down to change the air in the buccal cavity – obvious in a live frog

Filling the lungs is by positive pressure - buccal pumping:

1: Buccal cavity expands, air taken in through the nostrils. Lung closed by the glottis
2: Nostrils close and the glottis opens. Air from the buccal cavity is pushed

into the lungs under positive pressure

Fish

Gills collapse in air, as the lamellae stick together by surface tension. Surface area is greatly reduced and the fish dies of suffocation. Some fish breathe air

African lungfish *Protopterus* can survive in a burrow in dried mud for several years, breathing air. It also breathes air when in water, and drowns if denied access to air - an obligate air breather

Lungfish has paired lungs, gills are reduced - less than 10% of the oxygen uptake is through the gills. Ventilates by buccal pumping similar to the frog

Several other fish species also breathe air. Most of them are from tropical freshwater, often deoxygenated by high temperature and decomposition

Air breathing overcomes low oxygen tension, not for survival out of water

Any moist surface will do for gas exchange as long as it has access to air and a blood supply

Apart from lungs, air-breathing fish use skin, buccal & opercular cavities, modified gills, stomach, intestine, swim bladder

Birds

The structure and action of the lung system in birds is very different from that of other vertebrates

The lungs of lungfish, amphibians, reptiles and mammals are large sacs with thin, flexible walls, divided by partitions to increase the surface area

Bird lungs are small and compact, but they are connected to large air sacs. These air sacs lie between the organs and inside the bones

Compare the bird & mammal respiratory systems (1 kg animals):

	Bird	Mammal
Lung volume (mL)	30	53
Air sac volume (mL)	127	-
Total volume (mL)	161	54
Breathing frequency (min^{-1})	17	53

Birds lungs are half the volume of mammal lungs, but the total volume of the bird system is 3 $\times$ that of the mammal

Finest branches in the bird lung (parabronchi) permit the through flow of air. Air spaces extend into walls, closely mingled with blood capillaries (Fig. 53.10a)

Trachea divides into 2 main bronchi, and paired lungs and air sacs. Air sacs in two functional groups, anterior and posterior (Fig. 53.10b)

Basic question about the air sacs is whether they are used for gas exchange. Anatomical evidence suggests not - they have no partitions to increase surface area, and poor blood supply

In a simple experiment carbon monoxide was injected into a sealed air sac of a bird. This gas diffuses as easily as oxygen, but the bird showed no signs of poisoning, so not absorbed from sac

Instead, the air sacs act as a bellows system to move air in and out. Follow a single breath of air (red in Fig. 53.10c) as it passes through the system

This work was done with ostriches given a single breath of oxygen, which is harmless and can be followed with an oxygen electrode. Ostriches were used as they have a low breathing rate, once every 10 s

First inspiration. Air passes directly into the posterior sacs from the main bronchi

First expiration. Air from the posterior sacs passes into the lung

Second inspiration. Air from the lung passes into the anterior sacs

Second expiration. Air passes from the anterior sacs to the outside

It takes 2 cycles to move one breath of air completely through the system. Air passes through the lung in one direction, posterior to anterior

Flow of blood in the capillaries is at 90 degrees to the flow of air in parabronchi: crosscurrent flow. More effective than concurrent flow, but not as effective as countercurrent flow

So a bird extracts more oxygen from air, takes fewer breaths than a mammal

The effectiveness is seen especially at high altitude where partial pressure of oxygen is low. Birds can fly where mammals would be incapacitated

Principles of lung respiration

1: Oxygen diffuses quickly in air, so the diffusion distance can be long. Partitions of lungs are for large surface area, not small diffusion distance

2: Fast diffusion also means that a deoxygenated boundary layer is less of a problem. Continuous flow of air across the respiratory surface not needed

3: Air has low density and inertia, so reversal of flow is not energetically expensive. Tidal systems are therefore common (except for birds)

Insects

Gas exchange in insects is along internal air capillaries or tracheae, which connect to the atmosphere through spiracles. The tracheae branch and extend to all parts of the body - down legs (Schmidt-Nielsen Fig. 1.31)

Smallest tracheae are 2-5 μm in diameter, and end in a tuft of tracheoles, each less than 1 μm in diameter, where gas exchange occurs - no significant exchange occurs through the tracheae (cuticle lining)

Tracheoles can extend into single cells, e.g. flight muscle fibres, high oxygen demand. All cells are usually less than 3 others away from a tracheole

Tracheoles have a thin cuticle, 40-70 nm thick – only 5-10 × that of a plasma membrane (7nm). They also have a large total surface area

The basic mechanism of the tracheal system is diffusion (fast in air): it is the only mechanism in small insects and inactive larger insects

The main diffusion barrier is the ends of the finest tracheoles, filled with interstitial fluid, not air (OHP Figure). Level of the fluid depends on balance between:

1: Capillary attraction draws fluid into tracheoloes, and
2: Osmotic pressure of the tissues pulls fluid out of tracheoles

When the insect is active, the concentration of the tissue fluids increases because of metabolic end products such as lactate

Draws the interstitial fluid from the tracheoles, and air extends further along them towards the tissues. This increases the diffusion of oxygen to the tissues

An automatic mechanism. The opening of the spiracles is also regulated, under nervous control. See the control of respiration in lecture 25

Modifications of tracheal system

A: A typical tracheal system. Spiracles connected by two longitudinal trunks, connected by cross branches (Schmidt-Nielsen Fig. 1.32)

B: Compressible air sacs. Tracheae have circular or spiral thickenings, incompressible. Large active insects often have thin-walled air sacs in the system

Volumes of these sacs are altered by body movements. This gives some ventilation during activity, when diffusion is insufficient. E.g. locusts

C: Most spiracles are sealed in aquatic insects, only the posterior ones open. The insect can penetrate the water surface with tip of abdomen to breathe. E.g. mosquito larvae

D: Tracheal system may be completely sealed in small aquatic insects. Gas exchange by diffusion through the cuticle, closed tracheae extend into gills

Tracheal system is still needed for internal gas transport, which would be too slow by diffusion through the body fluids. E.g. midge larvae