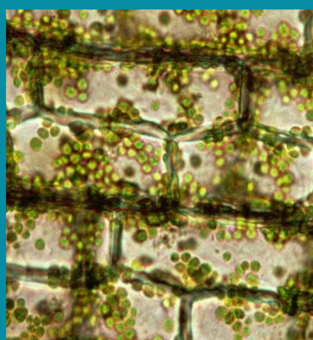
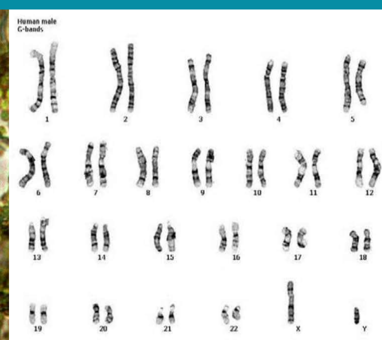
SLE 132 – Form and Function
The Respiratory System





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Learning Objectives – Aquatic gas exchange

- What is gas exchange?
- How do simple animals exchange gasses?
- What structures do aquatic animals use to exchange gas?
- What are the advantages and disadvantages of water as a respiratory medium?
- Describe the structure and function of fish gills (countercurrent exchange)

Learning Objectives – Terrestrial gas exchange

- What are the advantages and disadvantages of using air as a respiratory medium?
- Describe the structure and function of the respiratory organs of
  - Insects
  - Mammals (humans)
  - birds

Learning Objectives – General properties of gases

- Describe how breathing is controlled in humans
- Explain the properties (partial pressure and concentration) of gases in air and water
- Using differences in partial pressure explain how oxygen and carbon dioxide are exchanged at the lungs and the tissues

Learning Objectives – Respiratory pigments

- Why do we require respiratory pigments?
- What respiratory pigments do
  - Molluscs and crustaceans posses?
  - Vertebrates posses?
- What is the chemical composition of these two pigments
- Explain how vertebrates use haemoglobin to transport oxygen between the lungs and the tissues

Learning Objectives – Gaseous transport

- How are oxygen and carbon dioxide transported in the blood
- Explain how carbon dioxide is exchanged at the tissues and lungs

Bioflix – Gas exchange

https://www.youtube.com/watch?v=AyUtdqiOgCA

Two meanings for respiration

1. **Cell level:** Cellular respiration - we refer to the breakdown of glucose (production of ATP) as respiration (SLE111)

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + ATP$$

Glucose Oxygen Carbon Dioxide Water (Energy)

2. **Whole organism level:** Gaseous exchange is commonly referred to as respiration:

O_2 (fuel for cellular respiration) into the organism

CO_2 (a waste product) out of the organism

Gas exchange

There are three basic processes that occur:

1. **Gas exchange** between the organism and the environment
   – may involve bulk transport of gases (Breathing)
   – diffusion across a respiratory surface

2. **Distribution of gases** throughout the organism
   (involves some sort of transport system)

3. **Movement of gases** in and out of the cells

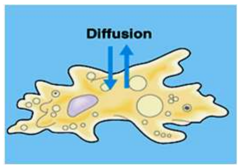
Source of Oxygen

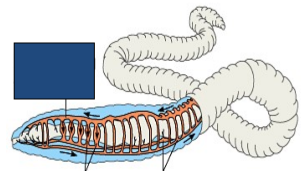
- **Air**
  – Atmosphere – 21% O_2 (by volume)

- **Water**
  – O_2 dissolved in water
  – Concentration varies, but much less that air (approx. 40 times less than concentration in air)

Exchange of Gases

- Diffusion of gases across cell membranes is the simplest means of gas exchange



- Note that gases cannot diffuse across cell membranes directly, the gases must first dissolve in water
  - This means **respiratory surfaces must be kept moist**
- The respiratory surface is the part of an animal where the O_2 diffuses across the cell membranes into the animal and CO_2 diffuses out.

Efficient respiratory membranes

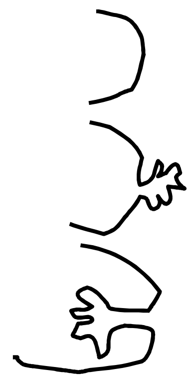
Efficient membranes are:
- thin
- large in surface area
- well ventilated
- moist

Problems:
- must avoid the surfaces drying out
- need to support the surfaces in some way

Gas exchange structures

The respiratory structures of <u>most</u> animals fall into one of 4 main groups:

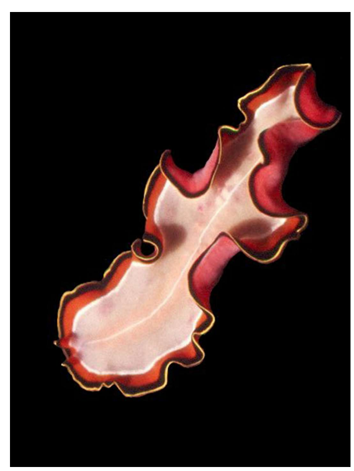
– **Skin (outer surface)**
  - only suitable for animals that are small, & either long and thin or flat
  - i.e. high Surface Area: Volume ratio
– **Gills** (mostly in aquatic organisms)
– **Tracheae** (air breathing tubes)
– **Lungs** (air breathing sacs)



Gas exchange structures

1. Skin (outer surface) breathers

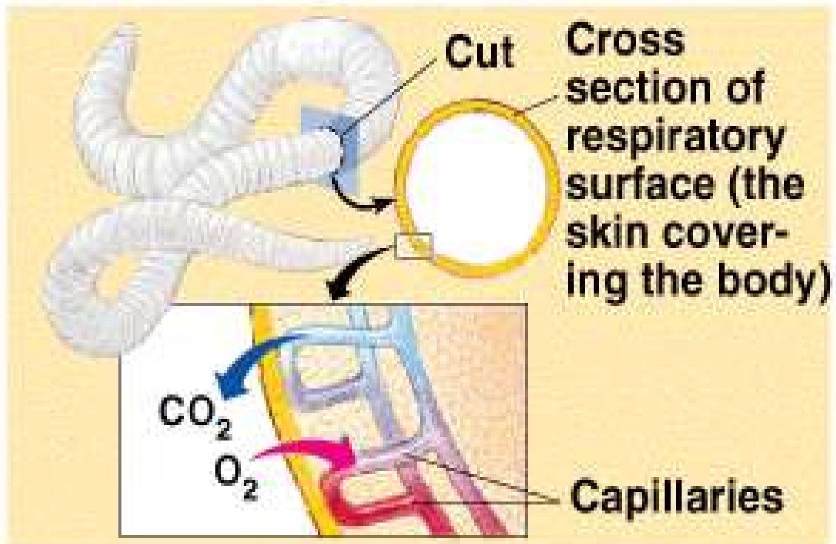
- No specialized respiratory structures
- Body surface must be kept moist
  - therefore tend to live in water or damp places
- Limited to small, or flat, or long and thin animals
- O_2 diffusion distance small (0.5mm)
  - large surface area:volume ratio thus the entire body can be used as a respiratory organ
  - may have an underlying blood surface to facilitate exchange
- Examples include *Hydra*, jellyfish, earthworms



Example:

Earthworm

Oxygen diffuses into a dense net of thin walled capillaries just beneath the skin



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2. Gills

- Out-foldings of the body surface specialised for gas exchange.
    - Thin walled
    - Large SA

In some invertebrates:

- gills very simple
- over much of body

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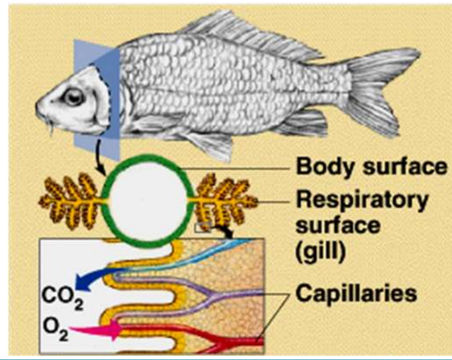
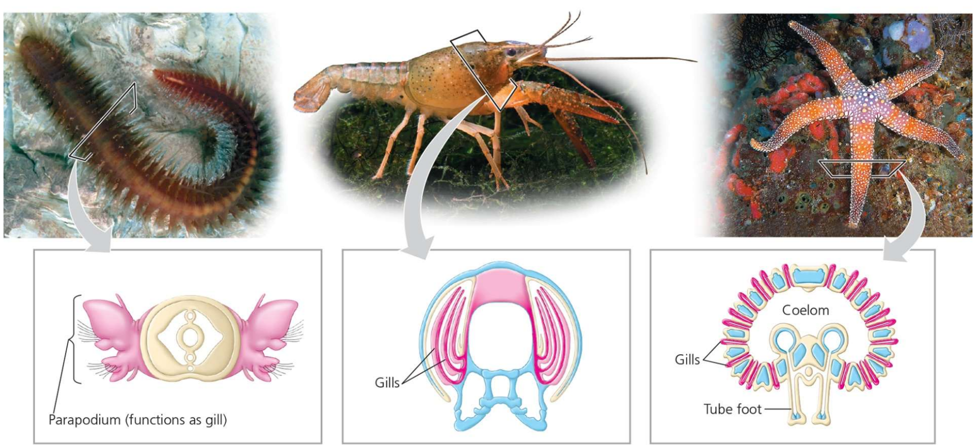
Gills

- In many animals, they are restricted to a local body region
  - eg. gills of clams, crayfish, and many other animals
  - in these need transport system
- Example: Fish
  - In water so easy to keep surfaces moist
  - AND to keep them supported





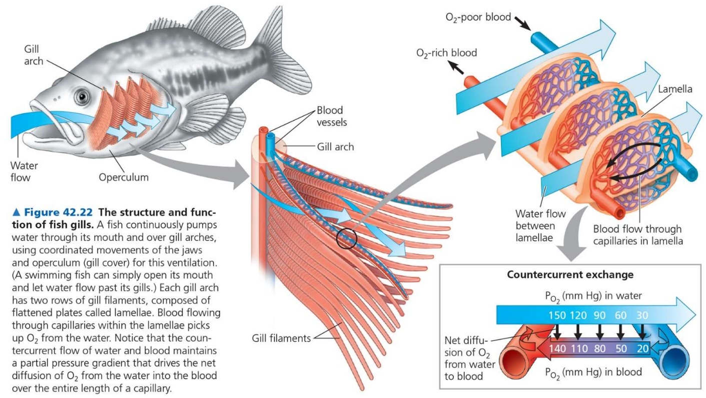
(a) Marine worm. Many polychaetes (marine worms of the phylum Annelida) have a pair of flattened appendages called parapodia on each body segment. The parapodia serve as gills and also function in crawling and swimming.

(b) Crayfish. Crayfish and other crustaceans have long, feathery gills covered by the exoskeleton. Specialised body appendages drive water over the gill surfaces.

(c) Sea star. The gills of a sea star are simple tubular projections of the skin. The hollow core of each gill is an extension of the coelom (body cavity). Gas exchange occurs by diffusion across the gill surfaces, and fluid in the coelom circulates in and out of the gills, aiding gas transport. The tube feet surfaces also function in gas exchange.

▲ Figure 42.21 Diversity in the structure of gills, external body surfaces that function in gas exchange.

Further details of gas exchange in fish

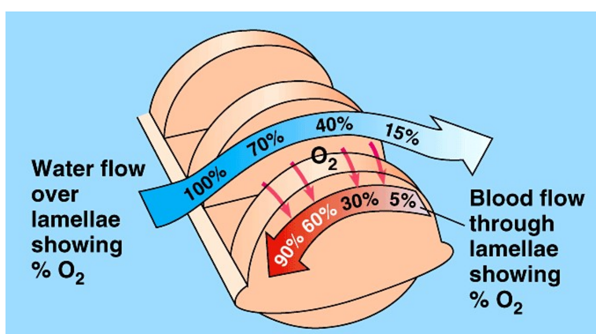


▲ **Figure 42.22 The structure and function of fish gills.** A fish continuously pumps water through its mouth and over gill arches, using coordinated movements of the jaws and operculum (gill cover) for this ventilation. (A swimming fish can simply open its mouth and let water flow past its gills.) Each gill arch has two rows of gill filaments, composed of flattened plates called lamellae. Blood flowing through capillaries within the lamellae picks up O_2 from the water. Notice that the countercurrent flow of water and blood maintains a partial pressure gradient that drives the net diffusion of O_2 from the water into the blood over the entire length of a capillary.

- Water pumped through the mouth and over the gills
  - unidirectional flow of water over the gills
- Allows development of **counter current exchange**
- Blood flowing through capillaries inside gill filaments picks up O_2 from the water

Counter-current exchange

- Blood flows through gills in opposite direction from the flow of water over gill surface
- This allows the **transfer of much more O_2** out of the water and into the blood
- **Sets up gradients** to aid diffusion of Oxygen



Air breathing

Advantages of breathing air

- more oxygen in air (21% in air, ~1% in water)
- air is lighter than water
  - so less energy needed to breath air than water

Disadvantage of breathing air

- dehydration

Gills in air?

- gills collapse & stick together in air
- there is considerable water loss from exposed gills
- generally not suited for use in air

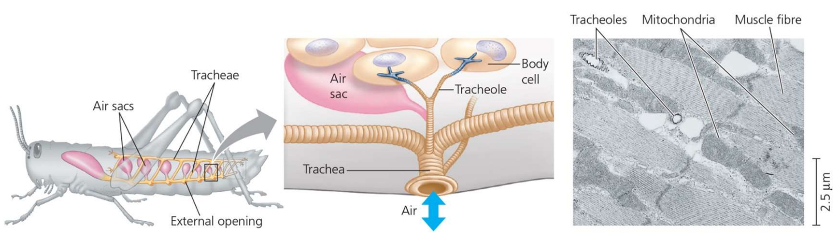
A more suitable design for air

- infolding of the body surface

Respiratory structures in air-breathing animals…….

Tracheal system of insects

- Consists of a system of air tubes spread throughout the insect body
- **Structures:** trachea (tracheae), tracheoles, air sacs, spiracles (exterior openings)



(a) The respiratory system of an insect consists of branched internal tubes. The largest tubes, called *tracheae*, connect to external openings spaced along the insect's body surface. Air sacs formed from enlarged portions of the tracheae are found near organs that require a large supply of oxygen.

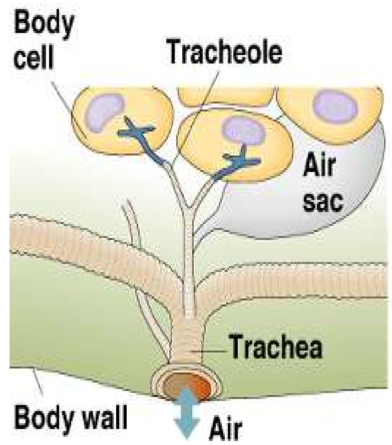
(b) Rings of chitin keep the tracheae open, allowing air to enter and pass into smaller tubes called *tracheoles*. The branched tracheoles deliver air directly to cells throughout the body. Tracheoles have closed ends filled with fluid (blue-grey). When the animal is active and using more O_2, most of the fluid is withdrawn into the body. This increases the surface area of air-filled tracheoles in contact with cells.

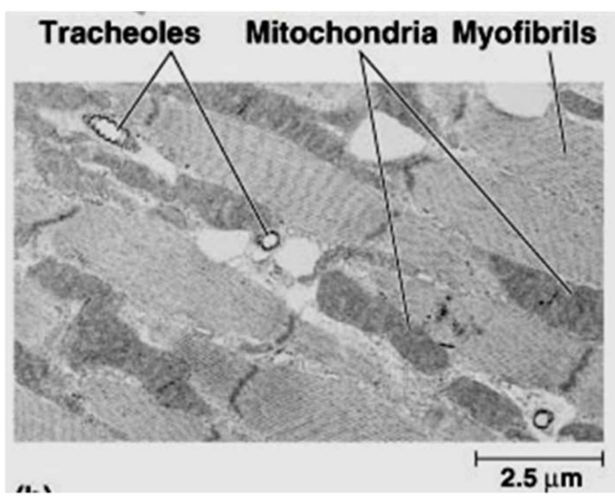
(c) The TEM above shows cross-sections of tracheoles in a tiny piece of insect flight muscle. Each of the numerous mitochondria in the muscle cells lies within about 5 µm of a tracheole.

▲ **Figure 42.23** **A tracheal system.**

Key features of Insect Tracheal system

- **small diffusion distances** - tracheoles come close to all cells of the body
- **the blood system is not involved** in transport of respiratory gases in insects
- Gas exchange is primarily through **diffusion**, and is all that is required in small insects
- **Contraction of the body muscles** against the air sacs helps the pump gases in larger insects
- **Respiratory surfaces are deep inside the body** - reducing water loss
- **Tips of the tracheoles are closed and contain water** – O_2 diffuses into water & then into the body cells





Electron micrograph showing cross sections through tracheoles in a tiny piece of insect muscle

Lungs

Lungs are sacs, located internally

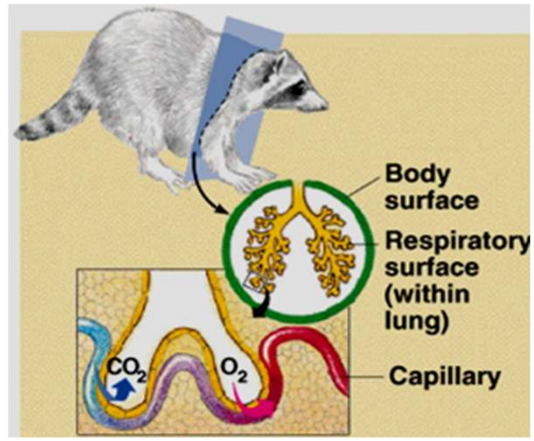
- reduces water loss

Restricted to just one location in the body

- so require a circulatory system to transport gases to cells

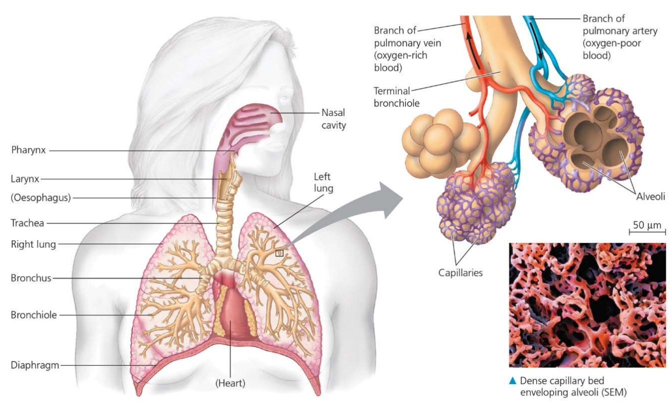
Lungs have evolved separately in:

- spiders
- terrestrial snails & slugs
- vertebrates



Structure of lungs in humans

- **Air tubes lined with epithelium**
  - mucus secreting
  - ciliated
- Alveoli are internal sacs lined with a **moist squamous epithelium**
- Humans 300 million alveoli per lung = surface area of $80M^2$



▲ **Figure 42.24 The mammalian respiratory system.** From the nasal cavity and pharynx, inhaled air passes through the larynx, trachea, and bronchi to the bronchioles, which end in microscopic alveoli lined by a thin, moist epithelium. Branches of the pulmonary arteries convey oxygen-poor blood to the alveoli; branches of the pulmonary veins transport oxygen-rich blood from the alveoli back to the heart.

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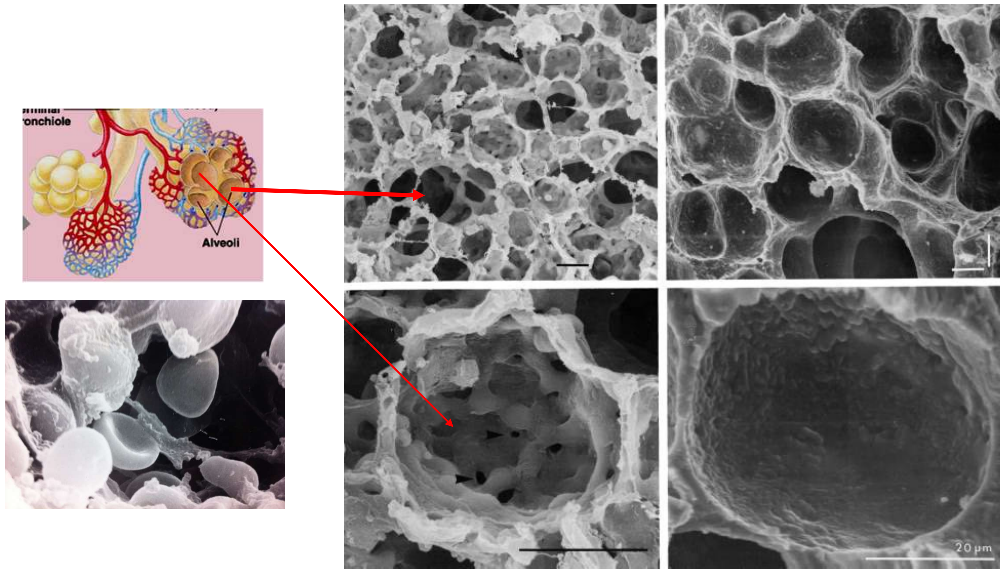
Electron micrographs of the lungs



Breathing ventilates the lungs – mammals

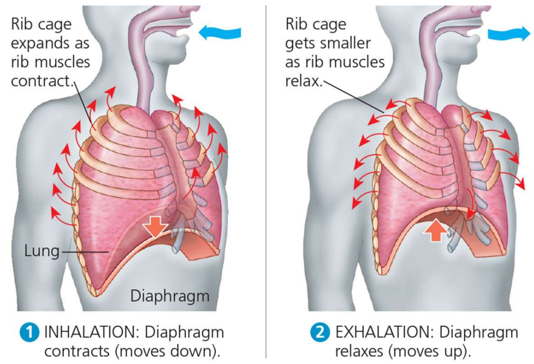
- Respiratory system of mammals has a single opening: **the trachea**
  - exhalation and inhalation occur through the trachea
- Volume of air that is inhaled and exhaled in a normal breath is about 0.5 L **(Tidal volume)**
- maximum volume of air that can be inhaled and exhaled by the lungs is 3.5 L to 4.8 L **(Vital capacity)**

How breathing operates in Mammals

Mammals use a process known as <u>negative pressure ventilation</u>

Inhalation: diaphragm & rib muscles contract → volume chest cavity increases → lungs expand → air sucked in

Exhalation: diaphragm & rib muscles relax → volume of chest cavity decreases → pressure in lungs increases → air is forced out



▲ **Figure 42.27 Negative pressure breathing.** A mammal breathes by changing the air pressure within its lungs relative to the pressure of the outside atmosphere.

WHAT IF? *The walls of alveoli contain elastic fibres that allow the alveoli to expand and contract with each breath. If the alveoli lost their elasticity, how would that affect gas exchange in the lungs?*

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Breathing in other vertebrates : Frogs

- Frogs use <u>positive pressure ventilation</u>
  - lungs are simple, vascular sacs with no folding or branching
  - Note that frogs also breathe through their skin = **cutaneous respiration**

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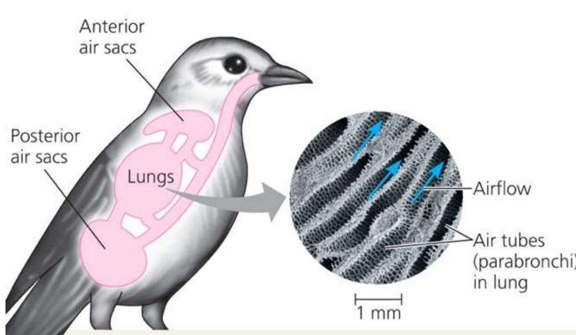
- **Inhalation in frogs:**
  - muscles lower the floor of the buccal cavity (mouth) drawing air inside
  - Then mouth and nostrils closed – muscles raise the floor of the buccal cavity which forces air into the lungs

- **Exhalation in frogs:**
  - elastic recoil of lungs forces air out of lungs, along with compression of the body wall

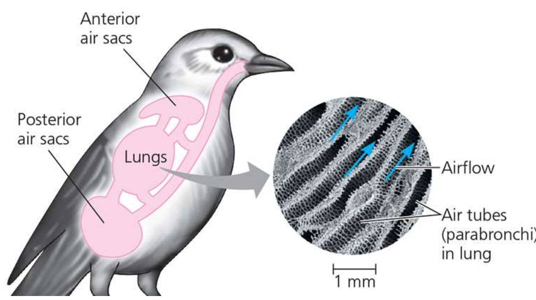
Breathing in other vertebrates: Birds

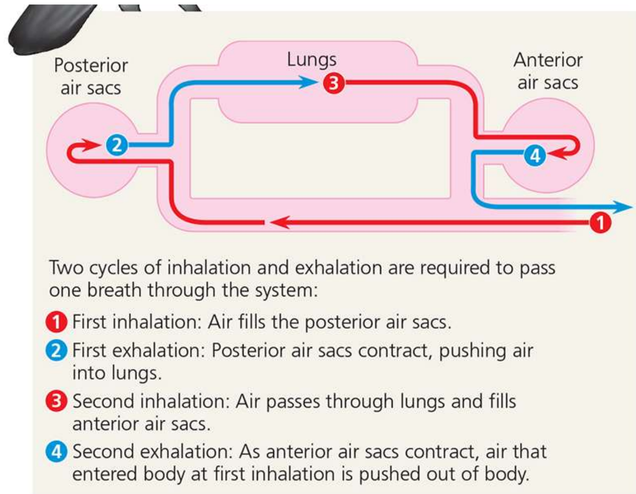
More efficient respiratory system than mammals

- They have 2 sets of air sacs that allow for **one-way flow through the lungs** (positive pressure, like frogs).
- **Fresh and stale air do not mix**
- air tubes in lungs (not alveoli) allow for countercurrent exch.



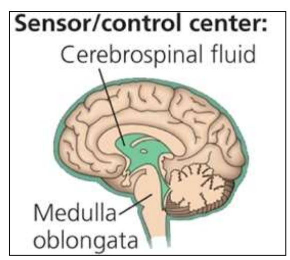
Birds have two cycles of inhalation and exhalation





▲ **Figure 42.26 The avian respiratory system.** This diagram traces a breath of air through the respiratory system of a bird. As shown, two cycles of inhalation and exhalation are required for the air to pass all the way through the system and out of the bird.

Control of Breathing



Can be voluntary, but is generally automatic

e.g.: The breathing control centre in humans is at the base of the brain (**the medulla oblongata**)

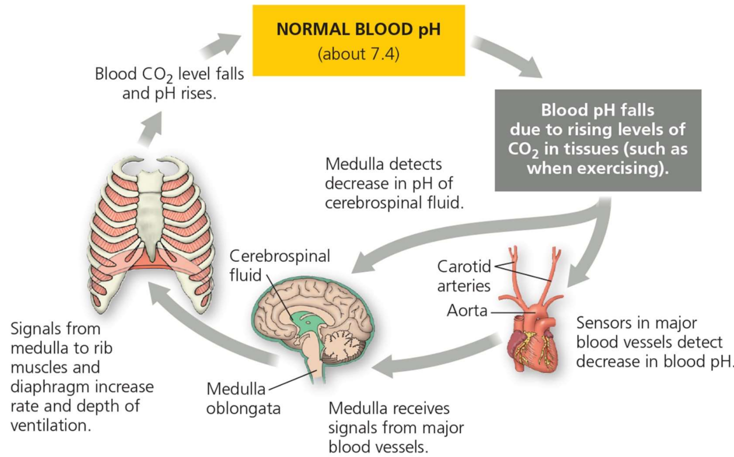
- nerves to the muscles of ribs and diaphragm (control rate & depth of breathing)
- MO responds to changes in blood pH, via cerebrospinal fluid
  - blood pH falls (*more acidic*) as CO_2 level increases

$$CO_2 + H_2O \rightleftharpoons H_2CO_3 \rightleftharpoons HCO_3^- + H^+$$

Blood [CO_2] is important in controlling respiratory rate

(H_2CO_3 = carbonic acid, HCO_3^- = bicarbonate ion)

- There are also sensors in arteries monitor blood pH & O_2, and send nerve impulses to medulla
- O_2 monitoring is completed by arteries
- Monitoring is important at high altitudes, where $[O_2]$ is low



▲ **Figure 42.28** **Homeostatic control of breathing.**

WHAT IF? *Suppose a person began breathing very rapidly while resting. Describe the effect on blood CO_2 levels and the steps by which the negative-feedback circuit would restore homeostasis.*

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Gases diffuse down pressure gradients

- How a gas diffuses in air or water (or in an organism) depends on differences in the partial pressure.
- Each kind of gas in a mixture such as air, accounts for a portion of the total pressure exerted by the mixture – eg. each gas in air exerts a pressure
  - eg: air pressure =760mm Hg, Air has 21% oxygen
  - pressure exerted by O_2 = 0.21 X 760 = 160mm Hg
  - **We say partial pressure of O_2 (P_{O_2}) =160 mmHg**
- the more molecules of a gas (e.g. O_2) present in a certain volume of a gas the greater the pressure is

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Crocodiles
Birds
Mammals

Here **gases are being exchanged** between the air in the alveolar spaces, and the blood in the alveolar capillaries

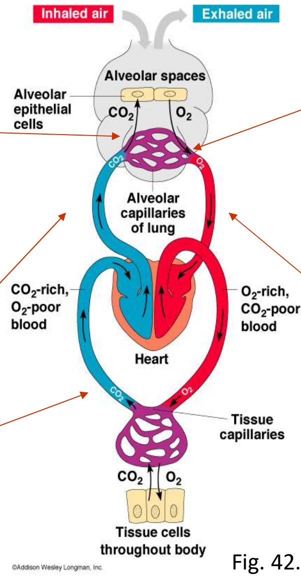


Fig. 42.27

Blood leaving the alveolar capillaries – **having lost CO_2 and gained O_2**

The heart pumps **O_2 poor blood** from capillaries in the tissues to the alveolar capillaries in the lungs

This **O_2 rich blood** returns to the heart – pumps it out to the body tissues

Transport of Oxygen in circulatory systems

- **A small amount of O_2 will dissolve in the blood** fluid this may be sufficient for some smaller invertebrates .
- larger, more active animals have **respiratory pigments**
  - For example in mammalian blood:
  - O_2 dissolved in blood - 0.2 ml of O_2/100ml blood
  - In Blood + bound to pigment - 20ml of O_2/100ml blood

ie. pigment gives blood >100 times the O_2 carrying capacity

In most vertebrates the pigment is haemoglobin

(Many invertebrates use other pigments *e.g.,* haemocyanin)

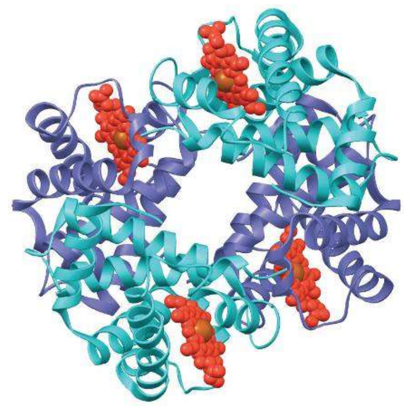
Haemoglobin

- is located in red blood cells
- Binds with O_2

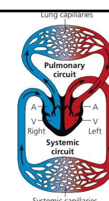
$$Hb + O_2 \rightleftharpoons HbO_2$$

- If O_2 is high, then equation driven to right
- If O_2 is low, then equation driven to left

So, the amount of HbO_2 present depends on the concentration of O_2



Haemoglobin (vertebrates)

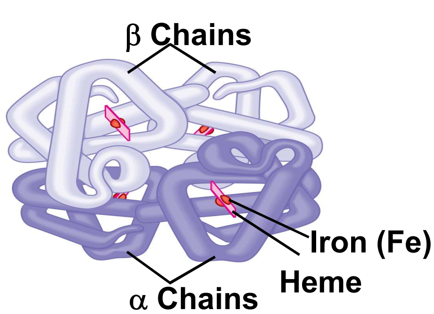


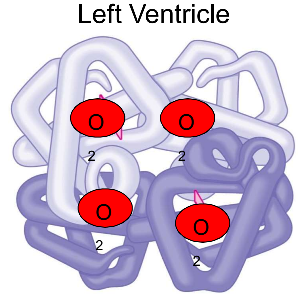
Blue
Deoxygenated blood
Right Ventricle
Pulmonary Artery

→ Lungs

← Body Tissues

Red
Oxygenated blood
Pulmonary Vein
Left Ventricle

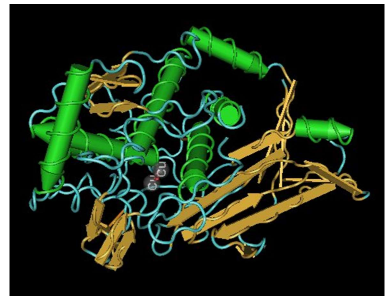




Fe^{+} binds O_2

4 O_2 binding sites

Haemocyanin



- Pigment used in invertebrates (eg spiders, squid and octopus)

- **Copper is the metal – blue**

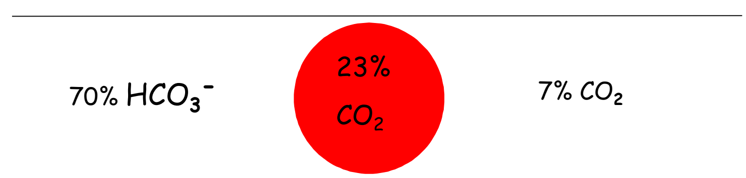
- Found in the haemolymph (not enclosed within red blood cells)

Gas Transport – CO_2

Carbon dioxide

- 7% dissolves in the plasma
- 23% binds to haemoglobin in the red blood cells

  (attaches to amino acids not iron)
- 70% as bicarbonate ions (HCO_3^-) in the plasma

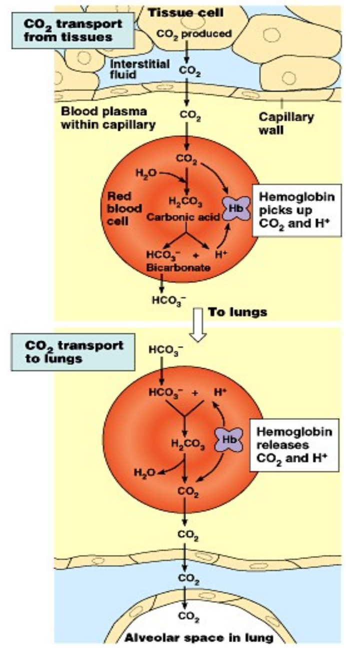


Red Blood cells are important for CO_2 transport

- CO_2 diffuses from cells into capillaries & into Red blood cells
- Converted to bicarbonate ions & H+ ions:

$$\mathbf{CO_2 + H_2O \rightarrow H_2CO_3 \rightarrow HCO_3^{-} + H^{+}}$$

- bicarbonate ions move into plasma
- At the lungs, the reverse reaction occurs → CO_2 which diffuses into alveoli



The Weddell seal

- Smaller lungs than a human
- Can dive for 20 minutes
- Holds 70% oxygen in blood, 5% in its lungs (small), 25% in muscles
- In humans, 51% in blood, 36% in lungs and 13% in the muscles

The Weddell seal

- Seal spleen holds 24 litres of blood
- **Seal has twice the blood/kg size**
- During dive, blood is directed to the essential tissues (brain, less to muscles as they can rely on anaerobic respiration
- Heart rate and oxygen consumption decrease

Quick Question

Which of the following features do all gas exchange systems have in common?

a) The exchange surfaces are moist
b) They are enclosed within the ribs
c) They are exposed to air
d) They are maintained at a constant temperature

Quick Question

Countercurrent exchange in the fish gill helps to maximise…….

a) endocytosis
b) Blood pressure
c) Diffusion
d) Active transport
e) osmosis

Quick Question

How is most of the carbon dioxide transported by the blood in humans?

a) Bicarbonate ions in the plasma
b) Carbon dioxide attached to haemoglobin
c) Carbonic acid in the erythrocytes
d) Carbon dioxide dissolved in the plasma
e) Bicarbonate attached to heamoglobin

Putting it all together…mammals

Using any visual method (diagrams, text or a combination) and information from the lecture notes and text book, describe the path of an oxygen molecule (O_2) from the air into your body, throughout the body and into a cell, then the path of a carbon dioxide molecule out of the body.