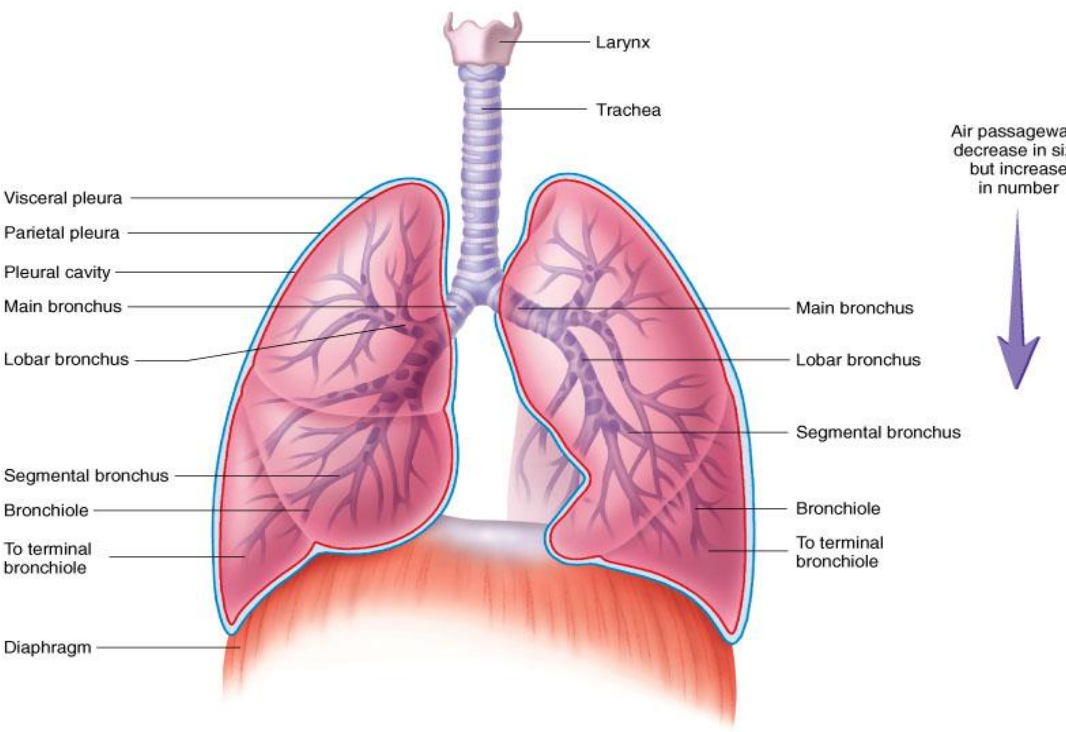
The Respiratory system

1. Anatomy of the respiratory system.

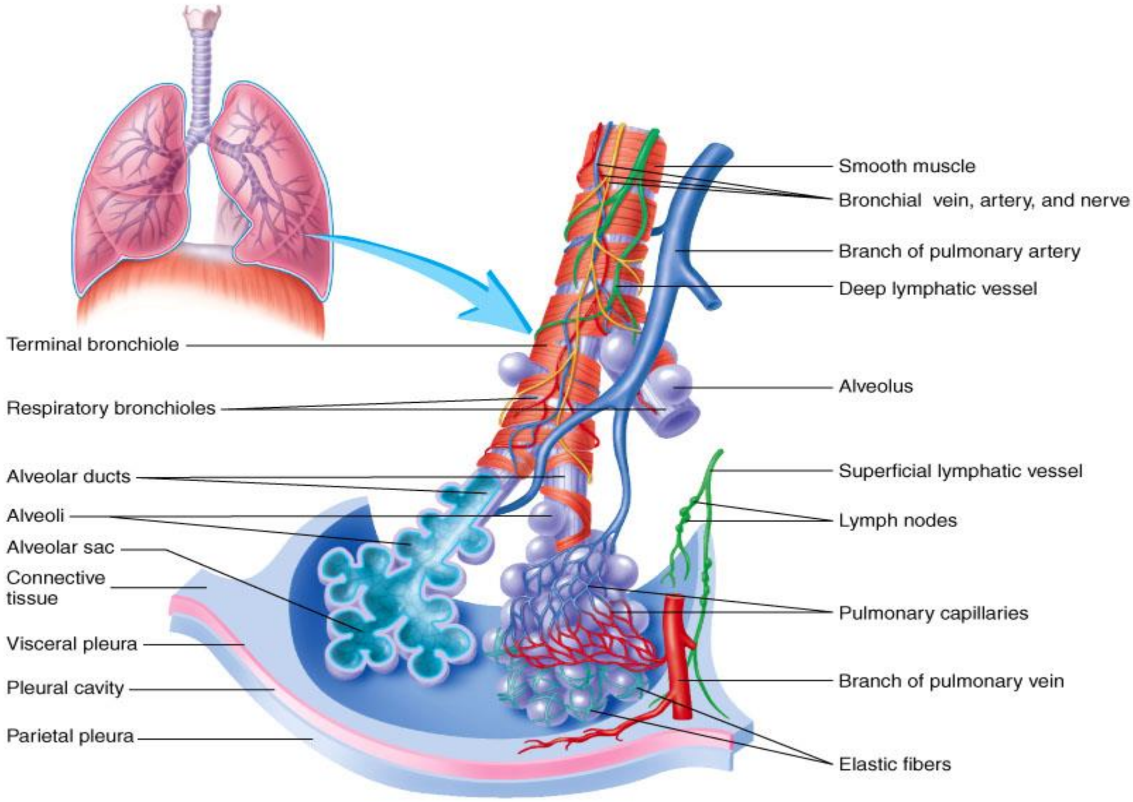
The air enters as follows:

- The air enters the **nose or mouth** into the trachea.
- The **trachea** is a tube leading to the lungs. It is lined with **'C' shaped rings of cartilage**, which prevent the collapse of the tube when the air pressure is reduced during inspiration (otherwise breathing would be impossible). The dorsal surface has no cartilage, but instead has smooth muscle. The muscle:
    - contracts to reduce the size of the trachea, e.g. during coughing or during an asthma attack.
    - relaxes during swallowing (food passing down the oesophagus projects into the trachea) and also to expand the trachea during exercise (so air breathed in faster).

  The inner surface of the trachea (and bronchi + bronchioles) is lined with mucus secreting goblet cells (the mucus traps foreign particles, e.g. dust and parasites) and ciliated cells carrying the mucus to the nose.
- The trachea divides into 2 **bronchi** (1 for each lung), which subdivide into many **bronchioles** inside the lungs.
- The **lungs** are subdivided into **3 right and 2 left lobes**, each served by a bronchiole ending in a mass of 300m tiny air sacs = **alveoli**. The wall of an alveolus consists of a single layer of flattened squamous epithelial cells, through which the gases will diffuse. The alveoli are then surrounded by capillaries, which collect the oxygen and give off CO_2



Anterior view



2. Ventilation of the lungs.

Breathing (ventilation) exchanges the gas in the lungs, to get rid of the old air (from which oxygen has been removed and CO_2 has been added) and replace it with fresh air.

- **Inspiration** (breathing in) results from expanding the thorax → greater lung volume → lower alveolar pressure → air sucked in. When **resting,** the thorax is expanded by:
    - **Contracting the diaphragm muscles** flattens and thus lowers the diaphragm.
    - **Contracting the external intercostal muscles** (between the ribs) lifts the ribs up and out.

  When **active**, the volume of inspiration can be increased further by contraction of the **Pectoralis minor muscle** to lift the ribs more than during normal breathing, and also by greater contractions of the diaphragm.

- **Expiration** (breath out) can be either:
    - When **resting (= tidal ventilation**), the **diaphragm muscles relax** (so diaphragm curves upwards in resting position) and the **external intercostals relax** (so the ribs collapse down). Both actions squeeze out the air from the alveoli.
    - When **active**, more air can be squeezed out by contracting **internal intercostals to** pulling the ribs down more than normal, or even more air can be squeezed out by also contracting **abdominal muscles**.
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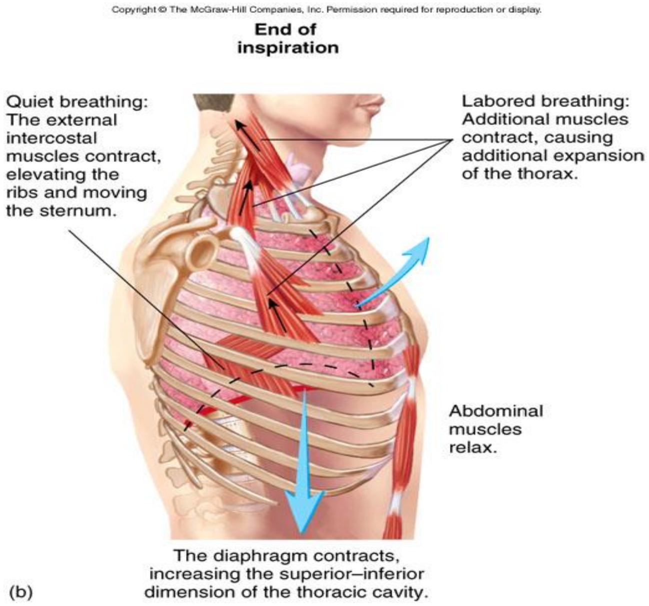

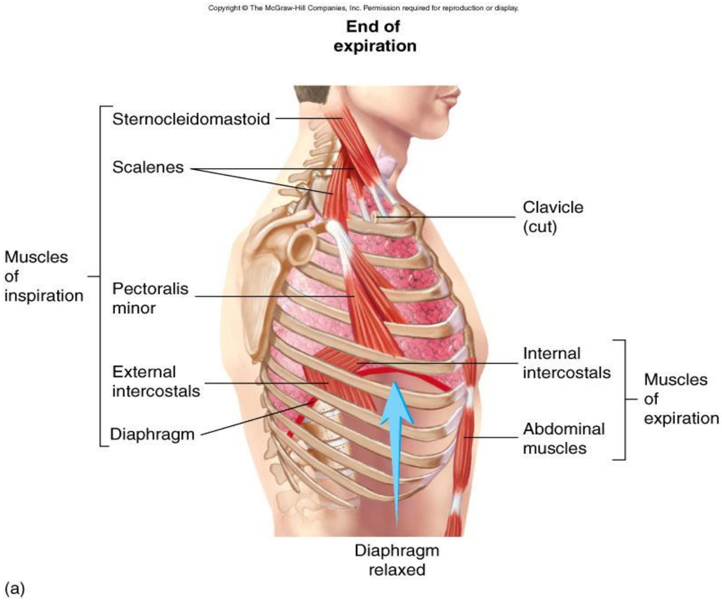

Air flow is thus due to pressure differences:

- During inspiration, expansion of the thorax reduces the alveolar pressure, so air is sucked in until the alveolar pressures rises back to = the atmospheric pressure.
- During expiration, contraction of the thorax squeezes the alveoli to raise the alveolar pressure above atmospheric pressure. Thus air flow out of the lungs until the alveolar pressure reduces back to the atmospheric pressure and air movement stops.
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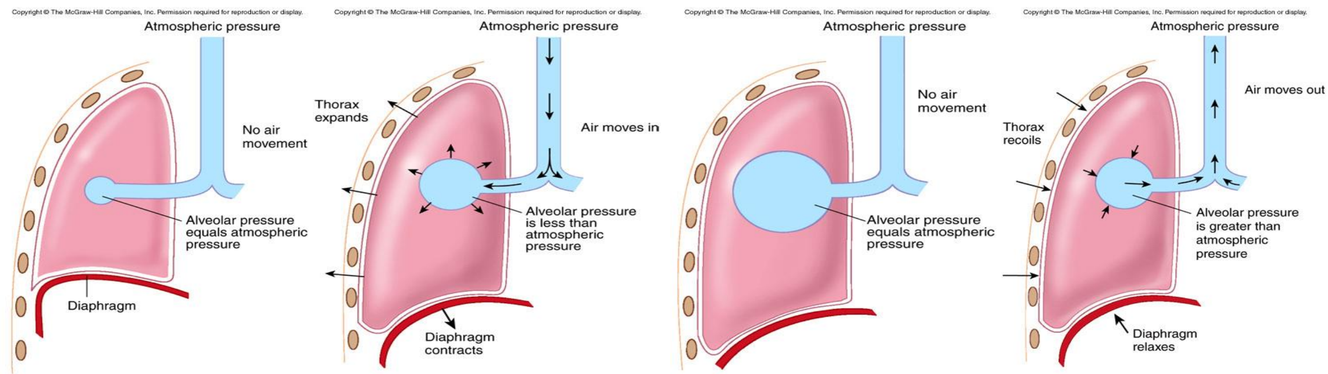

1. At the end of expiration, alveolar pressure is equal to atmospheric pressure. Therefore, there is no air movement.
2. During inspiration, increased thoracic volume results in decreased pressure inside the alveoli. Therefore, air moves into the lungs.
3. At the end of inspiration, alveolar pressure is equal to atmospheric pressure. Therefore, there is no air movement.
4. During expiration, decreased thoracic volume results in increased pressure inside the alveoli. Therefore, air moves out of the lungs.

3. Lung capacity

A typical person has a **lung capacity of 5,800 ml** (depending on their sex and body size). When resting, you normal only ventilate about **500ml** (you take shallow breaths). This is the **tidal volume**. When active, the ventilated volume increases, as you need more oxygen. The maximum amount of air you can ventilate (the **vital capacity**) is about **4,600ml**. However the **vital capacity is reduced**:

- In **women** (about 20% less than men).
- As you get **older**, your lungs become stiffer and so do not expand easily.
- If you are **unfit** (do no exercise), your lungs also become stiffer due to lack of use.
- If you are **fat or shorter** than normal.

There is still **1,200ml** of air in the lungs that you cannot ventilate. This is the **residual volume**. It has 2 functions:-

- To **prevents collapse of the lungs**. The alveoli are wet (see below), so if the walls came into contact with each other, the surface tension would be so strong that you could not reinflate the alveolus (like wetting the inside of a plastic bag and then trying to open it). A small amount of air thus always remains inside the alveoli.

- **Allow CO_2 to continually escape from the blood**. Without air remaining in your alveoli during expiration, CO_2 removal from the blood would have to stop until you reinflated your lungs, making your blood increasingly acidic (due to carbonic acid).
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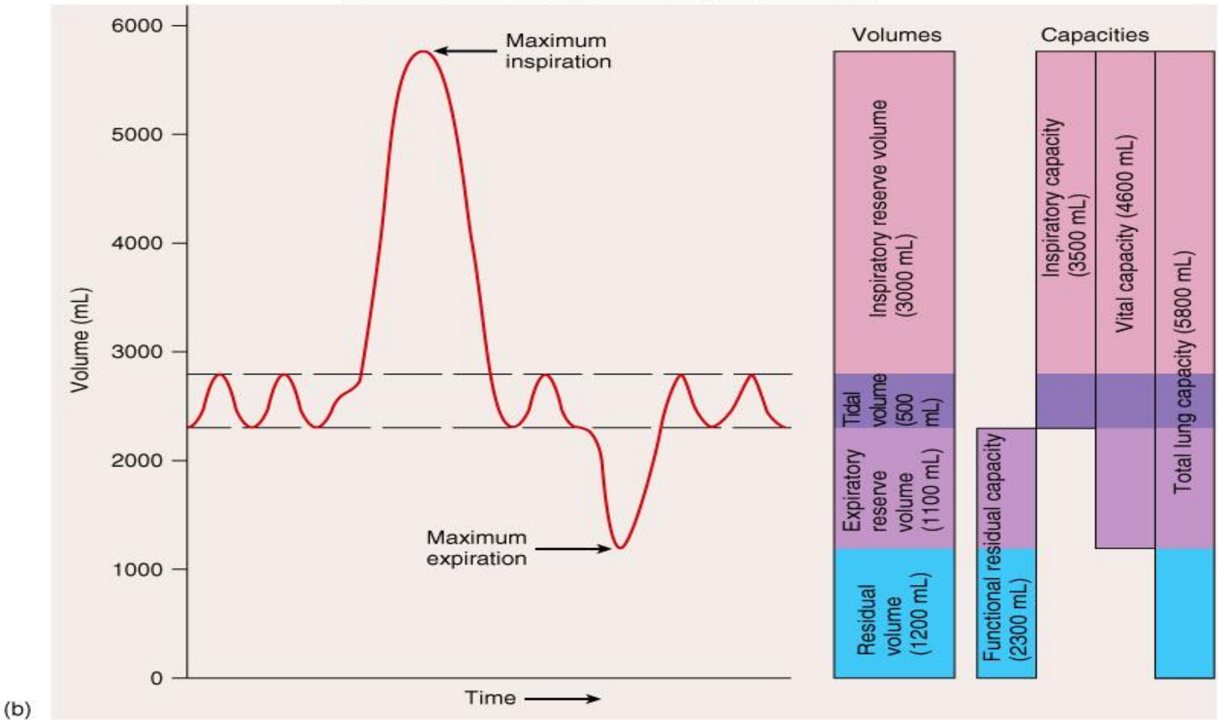


The **dead space** is the air filling the trachea, bronchi etc, which thus never reached the lungs, and so O_2 is not extracted from it before it is expired again.

Medics are less interested in the vital capacity than the **forced expiratory vital capacity,** which is the **rate** at which you can expire air (vol./ sec). This may be abnormally low if you suffer from:-

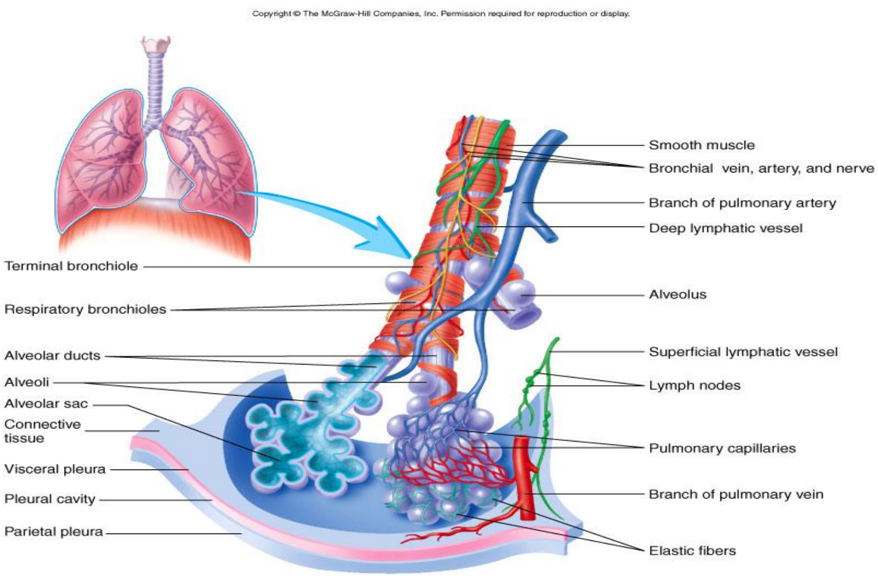
- **Asthma** results in secretion of histamine. This not only results in the alveoli filling with plasma (reducing vital capacity), but also constricts the bronchi, so that it takes longer to breath in and out.
- **Bronchitis** (=inflammation of the bronchioles). Swelling of the walls of the bronchioles and bronchi reduces air passage through them (like asthma, but for different reason).
- **Emphysema** results in damage to the alveoli, so that the walls become less elastic (taking longer to inflate and deflate).

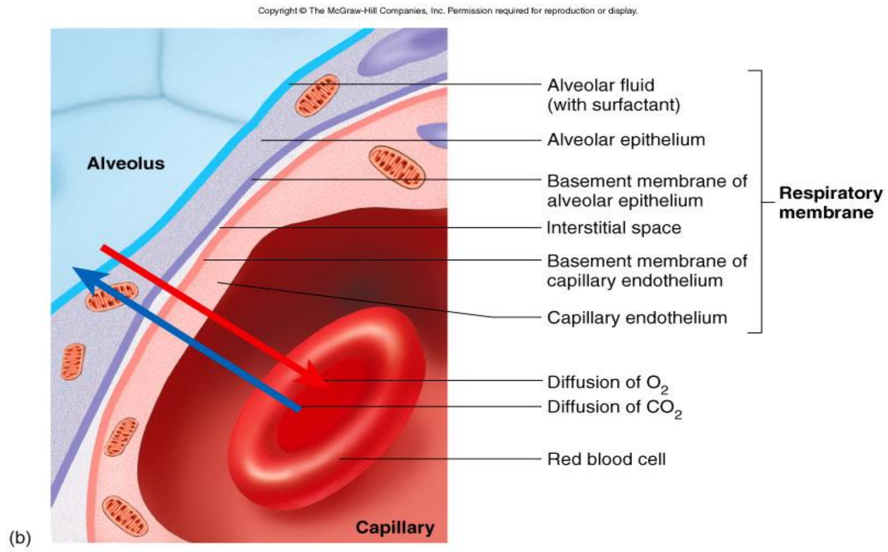
4. Gas exchange.

The alveoli are a respiratory membrane and so have to solve the following problems:-

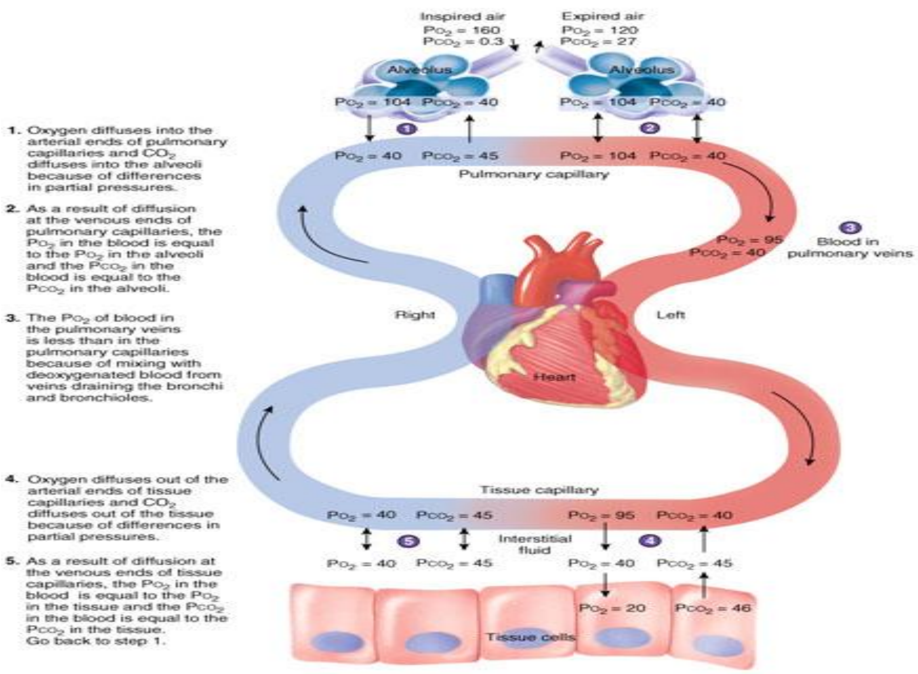
- The alveoli must be covered in a **layer of water** (plasma). O_2 in the air must first dissolve in the plasma before diffusing into the alveolar cells. The plasma also contains **surfactants,** to stop the lungs collapsing by greatly reducing the surface tension.
- The alveoli must have a **very large surface area**. O_2 has a very low solubility (2.5 ml/l) and so needs a very large surface area of 70 m^2. This is achieved by the bubble-structure of the alveoli, packing a huge surface area into a small space (your thorax).
- There must be a **very short diffusion path between the lungs and the blood**. Oxygen diffusion through a liquid is extremely slow, and through cells is even slower still (12 hours for 2 cm of

tissue). The diffusion path is just 2 layers of flattened squamous epithelia (1 layer = walls of alveolus; other layer = walls of capillary).





- There must be a **very extensive capillary network** in the lungs picking up the oxygen. Each alveolus is surrounded by several capillaries.
- The oxygen must have a **big concentration gradient** for rapid diffusion in the lungs. The rate of diffusion of a gas across a respiratory membrane is proportional to its surface area x the concentration gradient (this is **Fick's Law**). The concentration of O_2 is measured as its partial pressure (= Po_2). Atmospheric pressure is 760 mm Hg; 21% of this is oxygen, so the Po_2 in air is 160 mm Hg (= 21% of 760). Thus:
  - The **air in the alveoli** varies from a **Po_2 = 160** (during inspiration) to **Po_2 = 104** mm Hg (during expiration), but the **blood entering the capillary** around the alveolus has a **Po_2 of only 40 mm** Hg (giving a huge gradient and thus rapid diffusion). As the blood continues around the alveolus, it picks up more and more O_2, until it leaves with a Po_2 = 95 mm Hg.
  - Because of the thick walls of the arteries, no further diffusion occurs as the blood is pumped around the body until the **tissue capillaries**. These still have a **Po_2 = 95**, but are surrounded by cells with a **Po_2 below 20** (if metabolically active). There is thus a huge gradient from **Po_2 = 95 to Po_2 = 20**, giving rapid diffusion from blood to tissue cells.



5. Oxygen transport

- Oxygen is **transported** through the blood in 2 ways:
  - Oxygen has a very low solubility in water (2.5ml/ l), so only **1.5%** of oxygen is transported by **dissolving in the plasma**.
  - **98.5%** of the oxygen combines with haemoglobin to form **oxyhaemoglobin**. This **association** occurs in the lungs.
- Oxygen is **released to the tissues** by the **dissociation** of oxyhaemoglobin into haemoglobin + 4 O_2. However, since the amount of oxygen being carried by a capillary is limited, the dissociation must be controlled. The amount of oxygen released must correspond with the needs of the tissue. If the capillary immediately gives up all its oxygen to the 1^{st} tissue it reaches, then there will be no oxygen for tissues further along the capillary. The **amount of oxygen dissociated depends on**:-
  - **The Po_2 of the tissue**. The less oxygen available in the tissue (because it is actively using oxygen), the more oxygen will be given up by the blood. However, an active muscle would have already run low in oxygen, and so needs a mechanism to persuade the blood to give up oxygen before this happens. These indicators of present metabolic activity (and thus lack of oxygen in the near future) are:-
  - **The Pco_2 of the tissue**. Metabolically active tissues produce CO_2 at the same rate as they use up oxygen. But, the muscle stores oxygen in myoglobin. Thus as it becomes active, there is initially no shortage of oxygen, but CO_2 is immediately being produced (indicating a lack of oxygen soon).
  - **The acidity of the tissue**. CO_2 produced by metabolism dissolves in the plasma to form carbonic acid. Other metabolites include lactic acid. A low pH thus shows metabolic activity.
  - **Rise in tissue temperature**. Metabolically active tissue, e.g. contracting muscles, is hot. Heat thus indicates that oxygen is being used up and needs replacing.

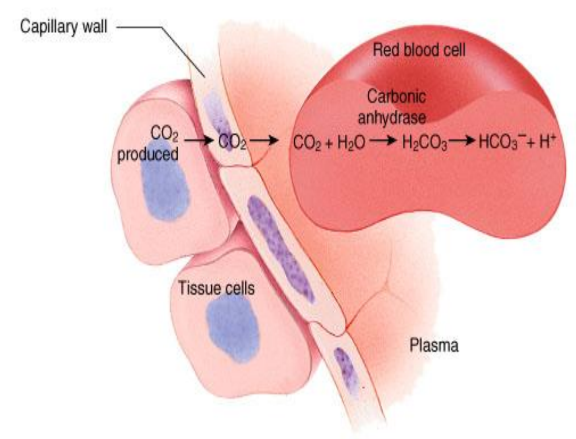
When your body is resting, capillaries may only give up **23%** of the O_2; but when muscles are active, the capillaries may dissociate up to **73%** of the O_2.

6. Carbon dioxide transport.

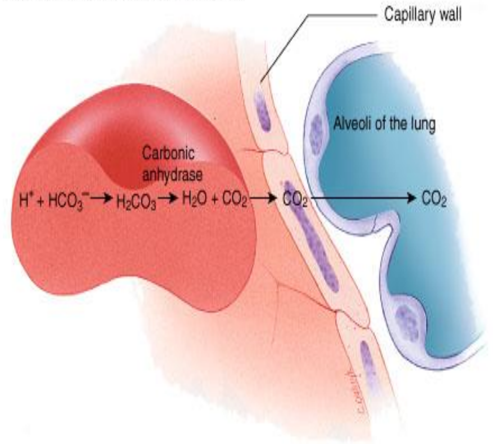
This occurs in the following ways:-

- **7% dissolves** in the plasma (it is much more soluble than oxygen).
- **23% attaches to the haemoglobin** (like oxygen, but there is not room for both, so the larger CO_2 pushes off = dissociates the O_2).
- **70% is ionised**. It combines with water to form carbonic acid:- $CO_2 + H_2O \rightarrow H^+ + HCO_3^-$ catalysed by the enzyme **carbonic anhydrase** (found in the erythrocytes). Although this reaction is reversible (using the same enzyme), the H^+ are buffered (= removed by attachment to the haemoglobin) and only reversed in the lungs (to release the CO_2).

(a) In the tissue capillaries, CO_2 released from tissue cells diffuses into red blood cells and combines with H_2O to form carbonic acid, a reaction catalyzed by the enzyme carbonic anhydrase. Carbonic acid then dissociates to form H and HCO_3^-. This process promotes the uptake and transport of CO_2 by red blood cells.



(b) In the pulmonary capillaries, CO_2 diffuses out of red blood cells into the aveoli. The loss of CO_2 promotes the formation of additional CO_2 from carbonic acid, a reaction catalyzed by carbonic anhydrase. H and HCO_3^- then combine to replace the carbonic acid. This process promotes the formation and release of CO_2 by red blood cells.

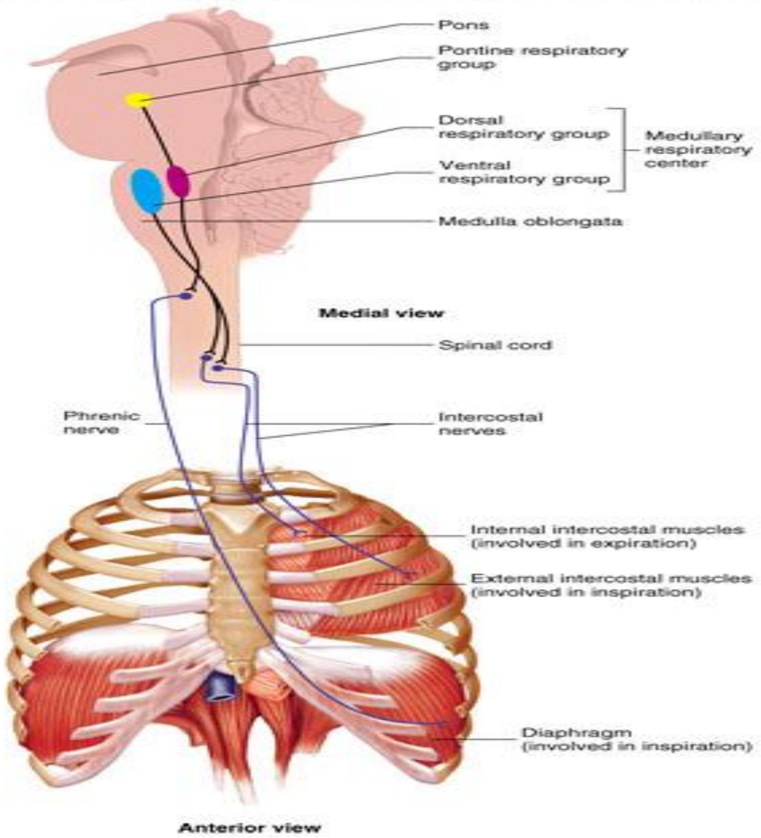


7. Control of ventilation

- **Control centers**. The **respiratory center** is mainly in the **medulla** and spontaneously produces a rhythm of inspiration and expiration. It is in 2 parts:
  - **2 Dorsal groups of the medulla** control contraction of the **diaphragm muscles**.
  - **2 Ventral groups of the medulla** control the contraction of the **intercostal** and other thoracic muscles.

  In addition, the **pons** (just above the medulla) is also involved in **inspiration/ expiration**.

  The respiratory center gives a resting ventilation of 12-20 ventilations/ minute and a tidal volume of 0.5 litres. But during exercise, both the ventilation volume and frequency will increase (as will the cardiac output = volume x frequency of heart beat).



Nervous control of the respiratory center.

- You can **consciously control** your breathing.
- The **speech center** alters breathing when talking.
- **Reflexes such as sneezing and coughing.**
- **Reflexes from skin receptors** e.g. heat and pain can cause you to gasp.

▪ **Chemical feedback to the respiratory center.**

- **pH receptors.** During metabolism, $O_2 \rightarrow CO_2$. The main receptors are pH receptors in the **medulla**. CO_2 dissolves in the plasma as carbonic acid, so **pH receptors are indirectly measuring CO_2** rather than O_2 concentrations.
- **Oxygen receptors.** The **carotid and aortic bodies** (in the carotid artery and aorta) measure blood oxygen. However, blood oxygen is fairly stable due to the efficiency with which haemoglobin picks up oxygen in the lungs and so is normally unimportant.
  - But during extreme activity, the medulla probably responds to the increasing **fluctuations of blood oxygen within each ventilation cycle** (oxygen uptake largely stops during expiration).

  An overall low oxygen level will only occur during certain situations. E.g.:
  - **High altitudes**: Although P_{O2} = 160 mm Hg at sea level, it decreases to 110 at 3,000m. The small gradient → slower O_2 diffusion → less O_2 in the blood. [But the amount of CO_2 in the blood does not change, since metabolism is the same].
  - **Emphysema**: damage to the lungs reduces their surface area. Because CO_2 is very soluble, it is little affected (so no build up in CO_2 in the blood), but oxygen having a much lower solubility, will have a reduced uptake.