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HUMAN PERFORMANCE AND LIMITATIONS

CHAPTER 8 – CARDIO RESPIRATORY SYSTEM

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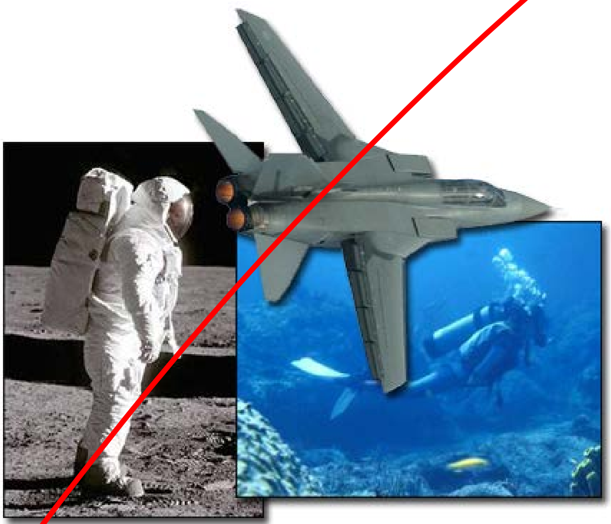
CARDIO RESPIRATORY SYSTEM

8.1 The Atmosphere

8.1.1 Introduction



In order for humans to explore environments other than their natural habitat (the Earth's surface), adequate time for physiological conditioning is needed or artificial life support systems need to be employed to avoid serious, and possibly fatal, injuries depending on altitudes (or depths) involved and the duration of exposure.

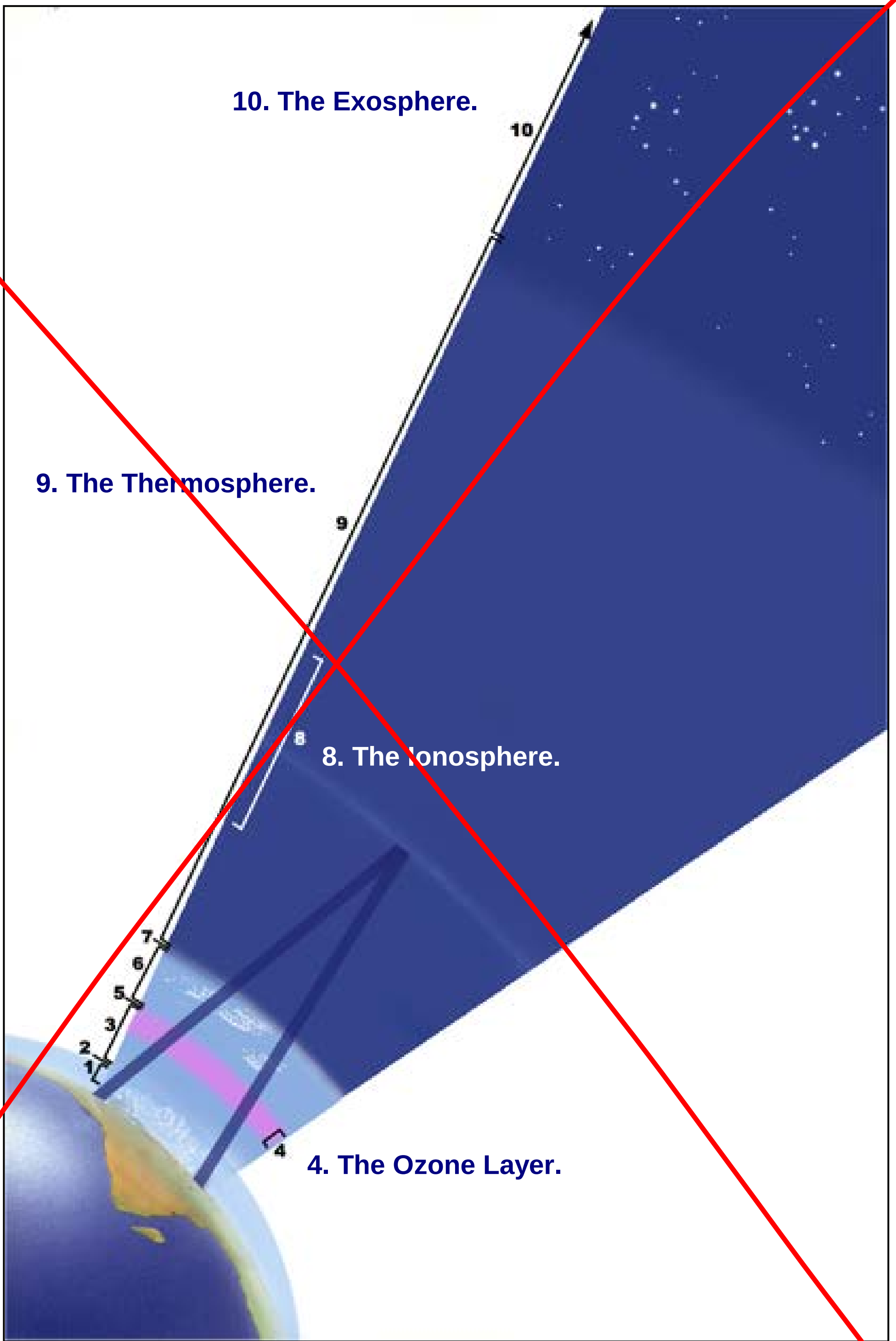
If a pilot fully understands the basic principles of aviation physiology, he/she will be able to better manage the environmental and working conditions encountered in aviation. These principles include the composition and structure of the atmosphere, gas laws and the oxygen requirements of human tissue.

8.1.2 Structure of the Atmosphere

The Earth's atmosphere forms a gaseous covering around the planet about 700 km deep. It is composed of layers or spheres, each having different temperature ranges and different mixture of gases.

There is no clear dividing line between these layers. Therefore an intermediate region exists between the layers, which are known as "-pause", e.g. the region between the Troposphere and the Stratosphere is known as the "Tropopause".

These layers are:



7. Mesopause
6. Mesosphere
5. Stratopause
3. Stratosphere
2. Tropopause
1. Troposphere

8.1.3 Composition of the Atmosphere

Most of the Earth's atmosphere is so lacking in air (rarefied) that humans could not survive in it. Lighter gas molecules such as hydrogen and helium constantly float away into space from its upper fringes. Only the thin layer next to the ground, called the troposphere (meaning the changing sphere) contains enough oxygen for living beings to breathe.

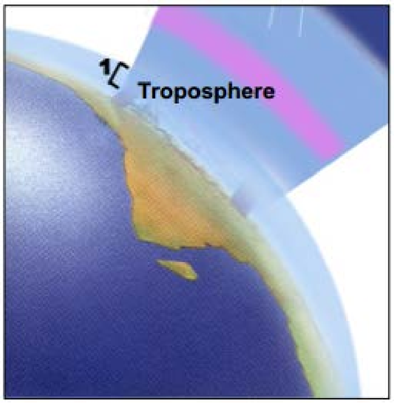
Conventional aviation takes place within the troposphere and the stratosphere, while the Space Shuttle operates to the upper limits of the thermosphere. Satellites are found even higher within the exosphere, which forms the barrier about 200 km deep between the rest of the atmosphere and outer space.

The troposphere extends barely 12 km above the ground, yet it contains 75% of all the gas in the atmosphere, as well as enormous quantities of water drops and fine dust. The constant movement and churning of this thick mixture within the troposphere is called weather, which has a significant influence on aviation.

Above the troposphere we find the stratosphere (meaning layered sphere), which extends up to 50 km above the ground. Its air is calm and clear.

Commercial air traffic operates in the upper regions of the troposphere and the lower parts of the stratosphere in an attempt to fly “above the weather” that buffets them in the stratosphere. The air at these levels is so thin that the aircraft cabins must be pressurised to allow the crew and passengers to breathe normally.

For the purpose of basic physiology one should focus on the following characteristics of the **troposphere**:



- There is a relatively constant decrease in temperature with an increase in altitude (1.98°C/1 000 ft)
- Density (and therefore atmospheric pressure) decreases with an increase in altitude
- Small increases in height at low altitude causes a much greater change in pressure than the same change in height at high altitude

Also remember that the air, through which an aircraft flies, consists of a mixture of gases of remarkably constant composition, i.e:

- Oxygen: 21%
- Nitrogen: 78%
- Other gases: 1%

8.1.3.1 Oxygen

Oxygen is essential for the sustenance of life and the combustion of materials. In the context of aviation, oxygen is required for the combustion of fuel, and also for life support of the passengers and crew. A deficiency of oxygen results in incomplete burning and reduced engine efficiency.

A deficiency of oxygen in the human body can have serious implications for the pilot's performance and therefore the safety of flight.

8.1.3.2 Nitrogen

The most plentiful of all gasses in the atmosphere is nitrogen. It is an essential building block of amino acids and nucleic acids. Without nitrogen life on earth would not be possible. Excess nitrogen in the body can also cause problems commonly referred to as "the bends".

8.1.3.3 Carbon Dioxide

Carbon dioxide is a product produced during the combustion process. Its quantity in the atmosphere has drastically increased since the industrialisation of the world economy. Carbon dioxide is also produced by humans and animals and breathed out into the atmosphere. Carbon dioxide contributes towards the warming of the atmosphere and the changing of the world climate.

8.1.3.4 Water Vapour

The presence of water vapour in the atmosphere plays a role in how comfortable humans are. Very dry air or very moist (humid) air may affect the performance of pilots.

8.2 Gas Laws and Respiration

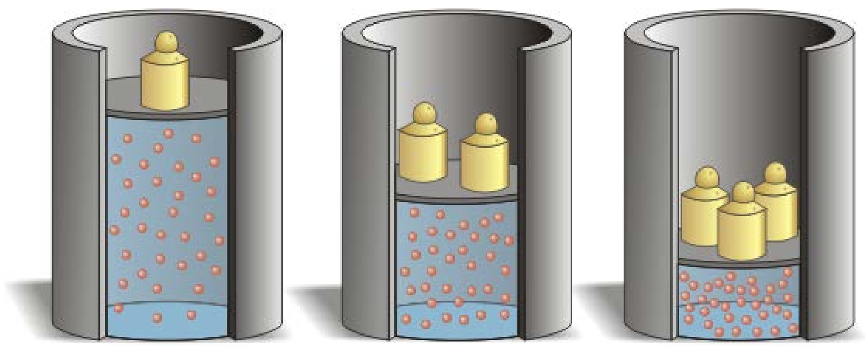
8.2.1 Gas Laws

The gas laws of particular relevance in aviation medicine are Boyle's law, Henry's law, Dalton's law, Charles law and Grahams Law.

8.2.1.1 Boyle's Law

Boyle's Law states that under conditions of constant temperature and quantity, there is an inverse relationship between the volume and pressure for an ideal gas.

In other words, as the pressure reduces the gas expands.



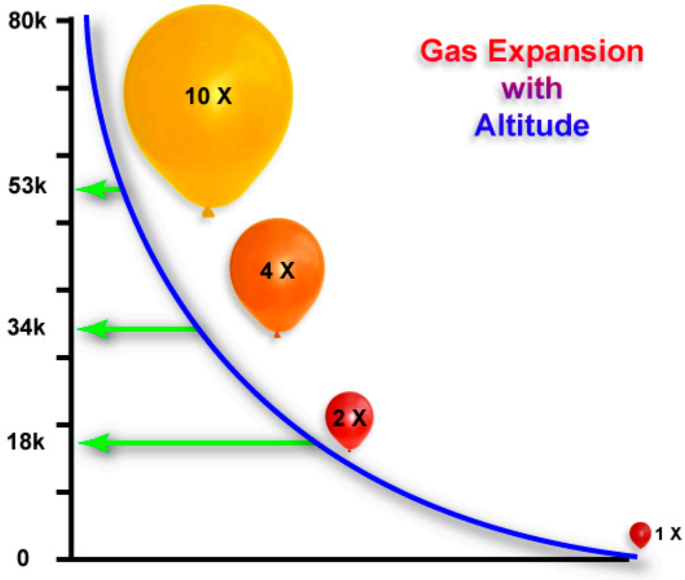
For a given Mass, at a constant Temperature, the pressure times the volume is a constant

Mathematically Boyle's law can be given as:

$P_1V_1 = P_2V_2$

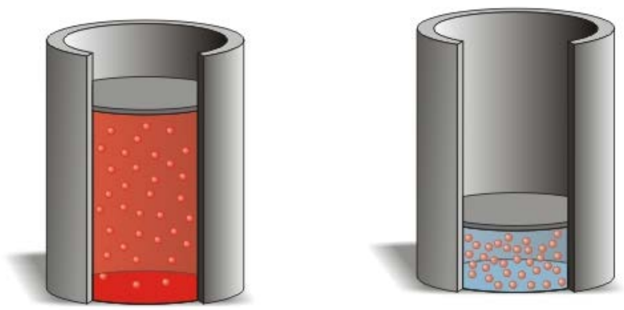
V = Volume
P = Pressure

When a human body is exposed to a sudden drop in pressure, for example during explosive decompression, the gasses in the body (lungs, tissues, etc) will expand according to Boyle's Law. If gas gets trapped in the body it might lead to severe pain and damage to organs.



8.2.1.2 Charles's Law

Charles's Law states that under conditions of constant pressure, volume is directly proportional to temperature. When a pocket of gas is heated, the volume will increase, and when cooled the volume will decrease, under the condition that the pressure remains constant.

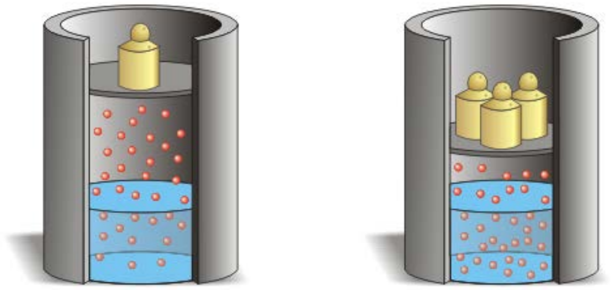


8.2.1.3 Henry's Law

Henry's law states "the mass of a gas that dissolves in a definite volume of liquid is directly proportional to the pressure of the gas provided the gas does not react with the solvent."

Gas solubility is always limited by the equilibrium between the gas and a saturated solution of the gas. The dissolved gas will always follow Henry's law. The concentration of dissolved gas depends on the partial pressure of the gas.

The partial pressure controls the number of gas molecule collisions with the surface of the solution. If the partial pressure is doubled the number of collisions with the surface will double. The increased number of collisions produce more dissolved gas.

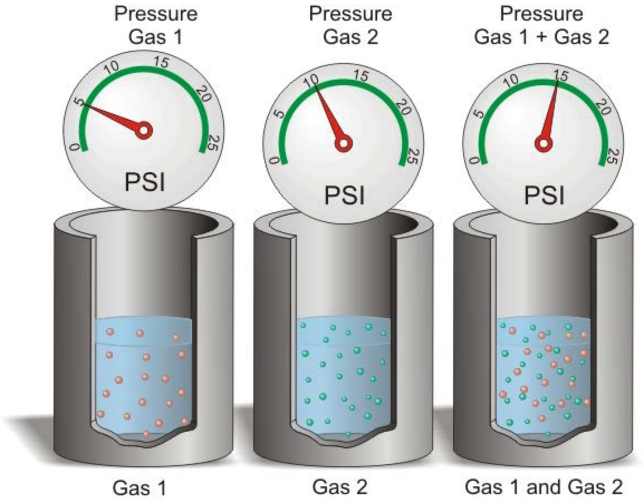


The illustration shows that if the pressure is tripled then the concentration of dissolved gas will triple.

Henry's Law describes why more nitrogen is absorbed into human tissues while under increased pressure, for example during scuba diving. The result of pressure decreases is the cause of decompression sickness.

8.2.1.4 Dalton's Law

Dalton's law states "the pressure of a mixture of gases is equal to the sum of the pressures of all of the constituent gases alone."



Mathematically Dalton's law can be represented as:

$$Pressure_{Total} = Pressure_1 + Pressure_2 \ldots Pressure_n$$

From this, the partial pressure of oxygen in the atmosphere can be derived for any altitude since the pressure at that altitude can be measured and the concentration of oxygen in atmospheric air is constant. This is of great significance to man in his ascent through the atmosphere.

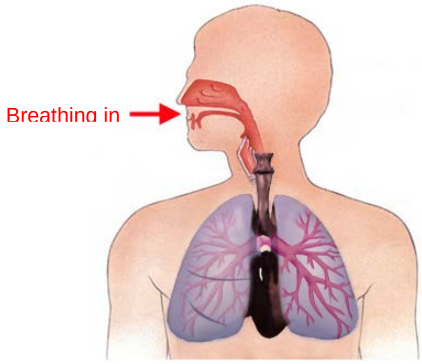
8.2.1.5 Universal gas equation

PV α T

P: pressure, V: Volume, T: temperature in Kelvin

8.2.1.6 Graham's Law

Graham's Law states that gas will diffuse through a membrane from high to low pressure. This is the principle that allows the exchange of O_2 and CO_2 across the alveoli membranes in the lungs.

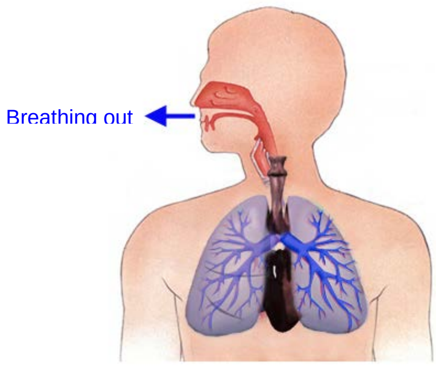


8.2.2 Oxygen Requirements for Human Tissue

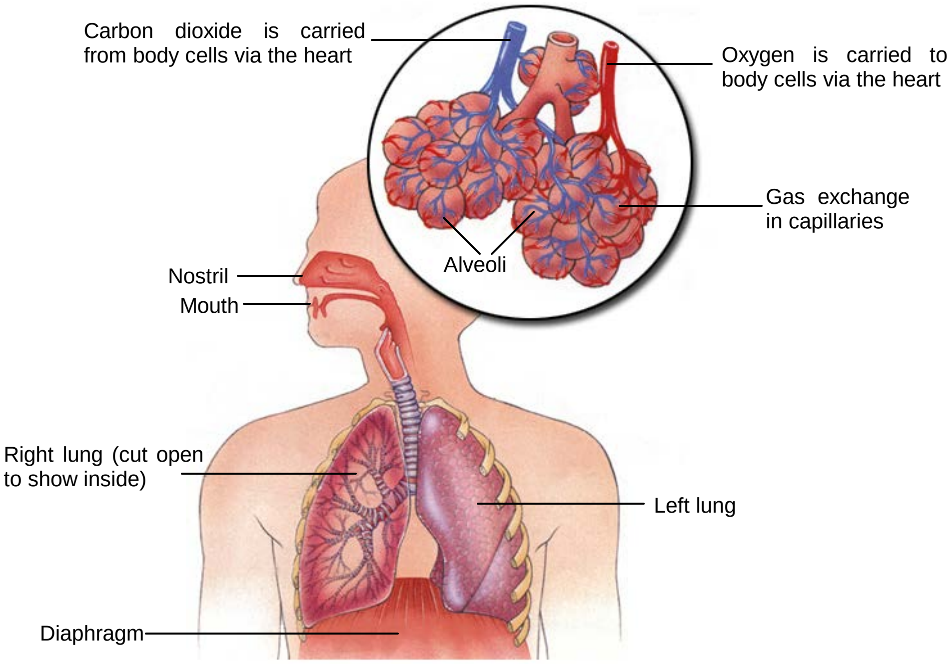
All living tissues need a constant source of energy in order to survive and this energy comes from burning fuel (carbohydrate, fat or protein). The fuel burns when it is combined with oxygen, which is carried from the air that is breathed to the cells via the bloodstream.

After the oxygen has been burned (oxidised), there are three end products:

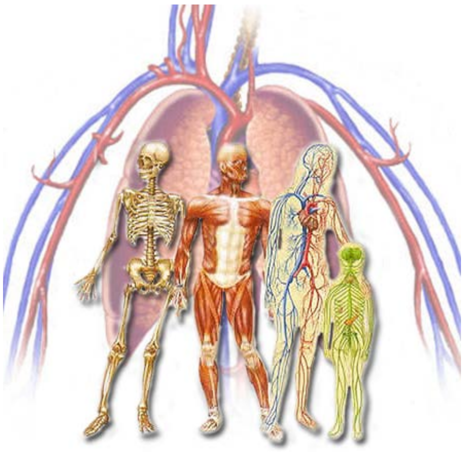
- Energy
- Water
- Carbon dioxide.



Getting rid of the carbon dioxide, which the body does not need, is where the exchange comes in. Carbon dioxide is carried by the blood to the lungs, where it is breathed out and more oxygen taken in.



8.3 Cardio Respiratory System



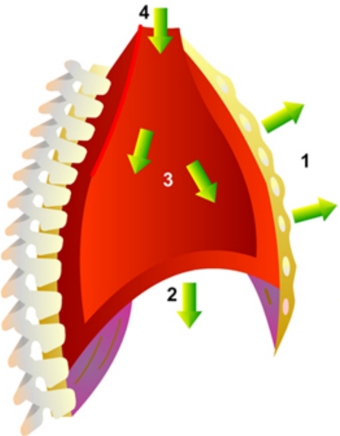
8.3.1 Introduction

The cardiovascular and respiratory systems can be considered as a dynamic closed system, integrated with other body systems, for the primary purpose of delivering oxygen and other nutrients to the tissues of the body.

8.3.2 The Lungs and Transport of Oxygen

Inspiration

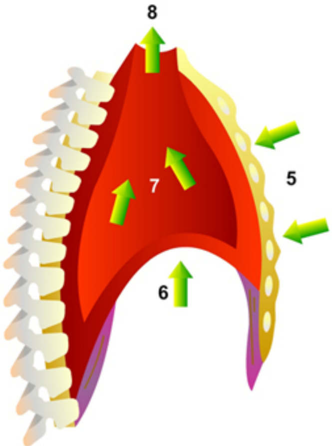
1. Ribs Raised
2. Diaphragm Depressed
3. Lungs Expand
4. Air drawn in



When you inhale, air is drawn into the lungs by the outward movement of the chest wall and the downward movement of the diaphragm, resulting in a fall of pressure inside the chest.

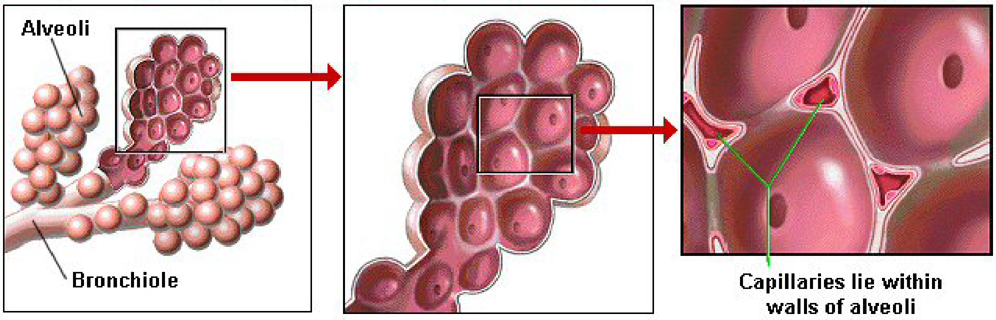
Exspiration

5. Ribs Return
6. Diaphragm Relaxes
7. Lungs Return to Original
8. Air Expelled



When exhaling, air is expelled from the lungs by the generally passive process of muscular relaxation, allowing the chest wall to fall and the diaphragm to relax.

The ever-dividing passageways in your lungs terminate at the alveoli (very fine, sac-like structures) where the blood in the alveolar capillaries is brought into very close proximity with oxygen molecules.



Under the influence of a pressure-gradient (Graham's Law), oxygen diffuses across the capillary membrane from the alveolar sac into the blood. From here the oxygen is taken up by the protein-molecule, haemoglobin, for transport around the body.

Note:

Breathing provides an exchange of respiratory gases between the environment and the blood. The rate and depth of breathing are adjusted to meet the enormous changes in the consumption of oxygen and the elimination of carbon dioxide.

When breathing normally the nervous system primarily controls the depth and frequency of breath to maintain the correct amount of carbon dioxide (CO^2) as well as sufficient oxygen to the body's tissues. Carbon dioxide (CO^2) is a by-product from combustion (fuel + oxygen). The nervous system measures the amount of CO^2 in the blood and adjusts the breathing accordingly high concentration levels of CO^2 equals to low oxygen and vice versa.

If CO^2 levels are high, the oxygen levels in the body are low, causing the brain's blood vessels to dilate, this assures sufficient blood flow and supply of oxygen. Conversely, low carbon dioxide levels cause the brain's blood vessels to constrict, resulting in reduced blood flow to the brain and light headedness (during hyperventilation).

Hyperventilation effectively means over-breathing, or breathing at a rate greater than that required to remove excess carbon dioxide (CO^2) in the lungs. Our rate and depth of breathing is controlled by our brain, which reacts not to the level of oxygen in the blood, but the level of CO^2. If the brain detects a rise in CO^2 in the blood, it interprets this as exertion and commands the body to increase the breathing rate and so reduce the level of CO^2 in the blood. If we suffer some psychological distress such as fear or anxiety, we may start to breath too quickly; the result will be the removal of too much CO^2 and the blood will become too alkaline. The person is then said to be suffering from alkalosis.

8.3.2.1 Factors Affecting Alveolar gas pressures

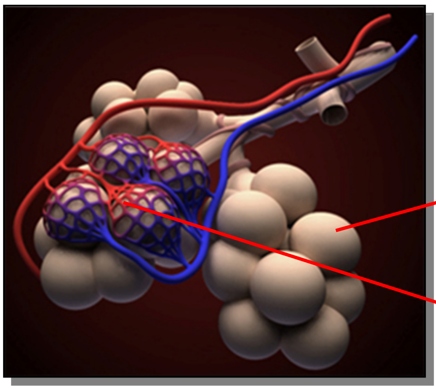
With ascent (i.e. commencing a climb) the partial pressure of oxygen (ppO_2) falls in parallel with atmospheric pressure thus reducing the movement of oxygen into the blood.

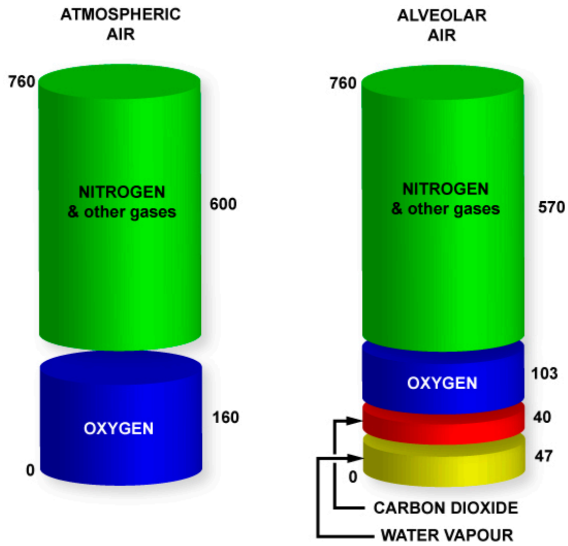
The ppO_2 (partial pressure oxygen) in the alveoli is about 103 mm Hg.

This is lower than the ppO_2 (partial pressure oxygen) in the atmosphere of 160 mm, for two reasons:

a. As the air enters the lungs, it is humidified by the upper airway and thus the increased water vapour displaces some of the oxygen in the air. The partial pressure of water vapour (47 mmHg) reduces the oxygen partial pressure to about 150 mmHg.

b. The rest of the difference is due to the continual uptake of oxygen by the pulmonary capillaries, and the continual diffusion of CO_2 out of the capillaries into the alveoli.

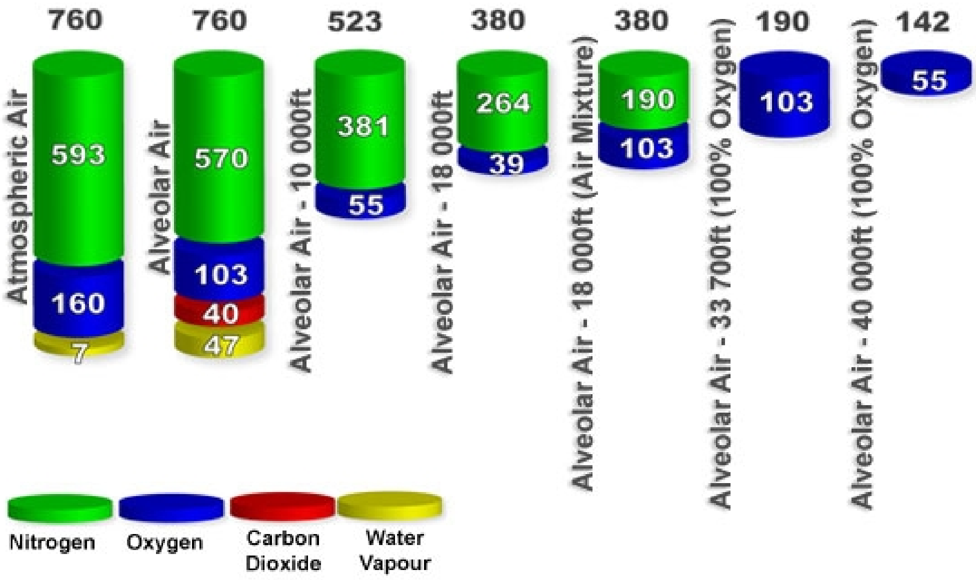




Pressure of the gas components (in millimetres of mercury) in the atmosphere and the lungs at sea level

The amount of oxygen being diffused through the alveoli membranes depends upon the partial pressure of oxygen in the alveoli. If the Partial pressure of O_2 falls to too low a level, not enough oxygen will pass into the blood and therefore be transported to the body tissues.

Our bodies are obviously happy at sea level, where the ppO_2 in the lungs is 103 mm Hg. Our lungs will continue to provide enough oxygen into the blood (provided we are not too physically active, such as sitting in an aeroplane) down to a ppO_2 of 55 mm Hg. This partial pressure occurs at 10,000'.



As we climb above 10,000', we must either maintain (or increase) the air pressure in the cabin, (for example, by cabin pressurisation) or increase the **proportion** of oxygen in the atmosphere we are breathing. We must maintain the ppO_2 at somewhere between 55 and 103 mm Hg, ideally close to 103 mm Hg. As we climb higher, we would need to progressively increase the proportion of oxygen that we are breathing, until we are eventually breathing pure oxygen.

To maintain a ppO_2 in the lungs of 103 mm Hg, by 33,700' we will need to be breathing 100% O_2.

Breathing pure oxygen, we can continue to climb until the ppO_2 falls again to 55 mm Hg. This will occur at 40,000'. If we want to continue to climb, we must increase the pressure of the oxygen in our lungs by some form of pressure breathing apparatus, which forces the oxygen into our lungs under pressure.

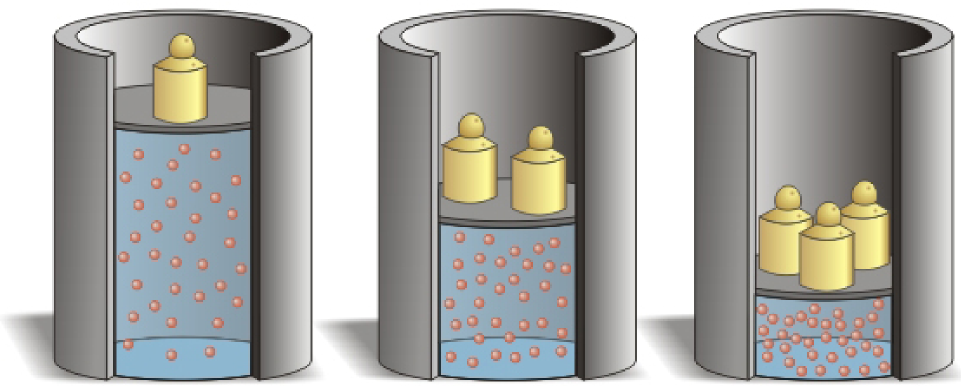
In summary:

- Partial pressure of O_2 in the lungs is:
  - 103mm Hg at sea level
  - 55mm Hg at 10,000 ft
  - 103mm Hg at 33,700 ft breathing pure oxygen
  - 55mm Hg at 40,000 ft breathing pure oxygen.
- From MSL to 10,000’ we can breathe normal air
- Over 10,000’ we commence breathing an O2 / air mix,
- As we climb above 10,000 the O2 percentage is gradually increased to maintain alveolar pp O2 at 103 mm hg
- At 33,700’ O2 = 100%, air 0 %. Alveolar pp O2 = 103 mm hg
- At 40,000’ breathing 100% O2 alveolar pp O2 = 55 mm hg
- Above 40,000 ft oxygen must be pushed in under pressure.

8.3.3 Pressure and Decompression

In your career as a pilot you will still become very familiar with the terms Pressurisation and Decompression. In order to understand the effect that these two concepts have on the body, we need to revise the gas laws again.

<u>Illustration of Boyle's</u>



Boyle's Law states "…when the temperature remains constant, the volume of a given mass of gas varies inversely to its pressure…" In other words, as the pressure reduces the gas expands.

In order to explain the effects that this has on the human body we will concentrate on **Barotrauma** and **Decompression Sickness**.

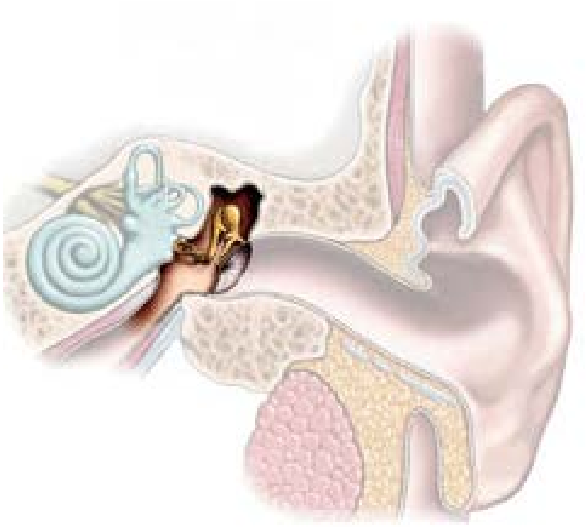
8.3.3.1 Barotrauma

Barotrauma is the tissue damage that results from the expansion or contraction of gas in enclosed spaces, and is a direct effect of the gas volume changes (Boyle's Law).

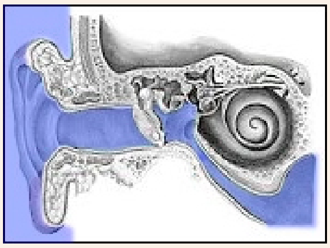
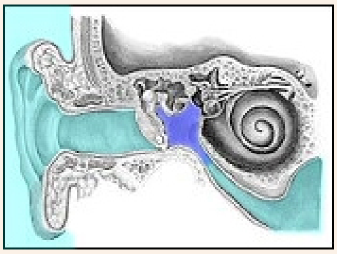
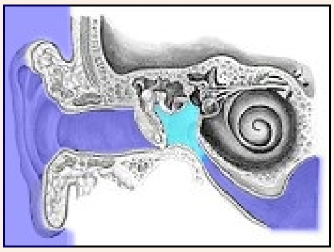
Barotrauma can occur in several places in the human body and these places are:

a. **The middle ear**

The middle ear is an air-filled cavity connected with the nose and throat via the Eustachian tube. The walls of this Eustachian tube are soft and the nasal end (lower end) can sometimes act as a one-way valve. This tube allows expanding/contracting gas to vent on ascent/ descent but if this tube becomes blocked (e.g. by a cold or allergy) the air pressure in the middle ear cannot equalise.



b. **Otic Barotrauma**

Atmosphere	**Ascent**	**Descent**
		
Pressure in middle ear, throat and atmosphere is equal.	On ascent expanding air in middle ear has to escape through Eustachian tube to equalise pressure on either side of eardrum.	On descent air is sucked into the middle ear through Eustachian tube to equalise lower pressure in middle ear with higher atmospheric pressure.
If air is prevented from entering or leaving the middle ear cavity, the eardrum is distorted by the difference in pressure causing pain and possible damage. This is called Otic barotrauma or Barotitis media.		

This failure to restore the correct pressure inside the middle ear results in a distortion of the eardrum, giving rise to pain and injury known as Otic Barotrauma.

Note: Opening the Eustachian tube can be achieved by yawning or chewing movements or the Valsalva manoeuvre

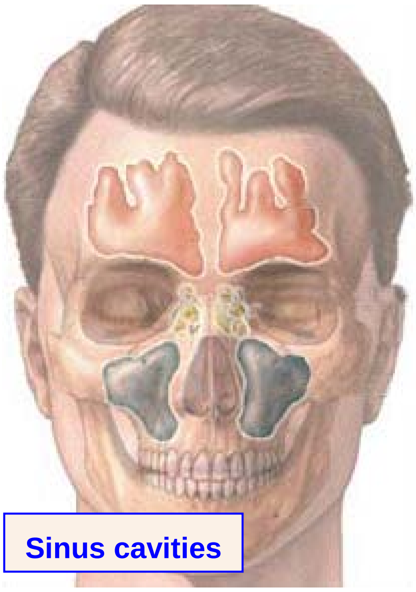
c. **Pressure Vertigo**

A condition caused during descent when one ear equalises pressure, but the other one does not. The feeling is a leaning sensation, or heaviness on one side of the head. It can be very distracting. Flying with a head cold can often be the cause, and it is wise to NOT fly, if you have a head cold.

d. **The Valsalva Manoeuvre**

To help clear the ears on descent, swallowing, yawning and chewing are useful. If none of these works, then the Valsalva Manoeuvre can be used. Close the mouth and pinch the nose, then **gently** exhale into the pharynx and nasal region. This will help to open the eustachian tubes and equalise pressure in the middle ear.

e. **Sinuses**

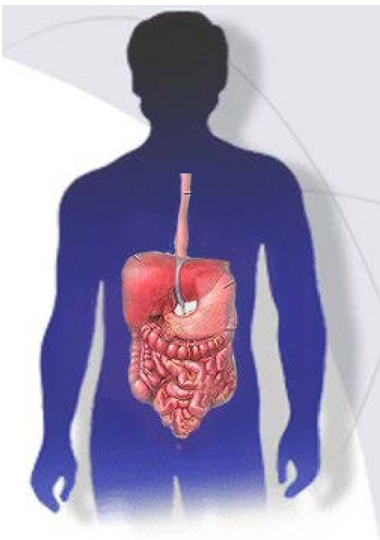


The sinuses are cavities within the skull that help to make the voice resonant and in addition make the skull lighter than it would otherwise be. In a very similar manner to the ears, the sinus opening can become blocked (on ascent or descent) causing sinus barotrauma. Sinus barotrauma causes facial pain. The most common cause is once again a cold/flu and allergies. For this reason aircrew with a cold or flu must avoid flying whilst symptoms persist.

f. **Teeth (Aerodontalgia)**

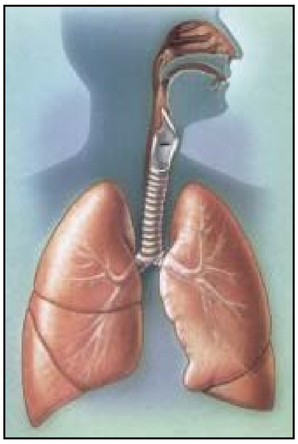
Tiny pockets of air in the teeth behind fillings may expand during ascent, causing severe pain. This is called Aerodontalgia. A tooth with a badly inserted filling may even "explode" causing considerable pain. Gas can also form in the roots of infected teeth also causing Aerodontalgia. Annual dental checkups and x-rays are done to repair defects and prevent this condition.

g. **Digestive canal**



Normally the human stomach and intestines contain between 0 and 400 ml of air. This is mostly swallowed, but fermentation and rotting of food also produce gas. During ascent the gas contained in the stomach expands and usually escapes upwards as "burps". Gas in the large bowel also expands and is vented through the anus. Symptoms of trapped expanded air vary from mild discomfort to severe pain. However, it usually only becomes a problem above 25 000 ft. (No perforation or bursting has ever been recorded in a healthy person due to flying.)

h. **Lungs**



The lungs contain a very large volume of gas but are generally in easy communication with the outside. Therefore, ambient pressure changes can readily be accommodated and no pressure differential develops, except in people with lung disease (e.g. asthma). The only potential risk arises from very rapid decompression but, provided the individual breathes out during the decompression, lung damage is extremely rare.

8.3.3.2 Decompression Sickness

Decompression sickness (DCS) occurs in association with the exposure to reduced atmospheric pressure and is characterised by the formation of Nitrogen bubbles in the bloodstream and tissues. The body is normally saturated with nitrogen. When ambient pressure is abruptly reduced on ascent some of this nitrogen comes out of solution as bubbles. (Henry's Law)

Although nitrogen is poorly soluble, there is enough present to give rise to problems under very particular circumstances. Ascents to altitude above 18 000 ft and especially over 25000ft in unpressurised aircraft are associated with a significant incidence (35-55%) of decompression sickness unless certain steps are taken to avoid it.

DCS is more commonly associated with scuba diving than with flying. However, in aviation it may result due to the following:

- Loss of cabin pressure at high altitude
- Prolonged flight at high cabin altitudes above 18 000 ft
- Flying shortly after scuba diving.

DCS can occur in different parts of the body and it has some symptoms that will indicate its presence. These are:

- **Joint and Limb Pains:** "The Bends". Bubbles forming in muscle, joints or ligaments give rise to usually ill-localised, deep-seated pain.
- **Skin Disturbances:** "The Creeps". Symptoms of itching, tingling and a crawling sensation under the skin occurs at altitudes and is usually transient and of little importance.

- **Chest Pain and Dry Cough:** "The Chokes". This is a sore, burning feeling in the chest with pain on inhaling. This is an indication of serious DCS, requiring definitive treatment.
- **Neurological Symptoms:** "The Staggers". Bubbles that form in the brain or spinal canal cause neurological symptoms that are usually short lasting. Loss of motor control or Vestibular function causes the "staggers". Visual disturbances, such as a temporary defect in the visual field, also occur. All neurological symptoms should be regarded as serious.

Other factors increasing the risk of DCS are age, obesity, exercise, alcohol etc.

To a great extent the risk of DCS can be avoided by pre-oxygenation in which the pilot breathes 100% oxygen for a period prior to high altitude exposure, reducing the body store of nitrogen as much as possible.

If DCS does occur in flight immediate descent must be instituted and the aircraft should land as soon as possible. The patient should be put on 100% oxygen and kept warm and rested. On landing the patient may need recompression to depth and other supportive medical treatment.

As a pilot you should always be aware of the danger involved in **flying after diving**.

DCS is relatively uncommon, but the incidence is greatly increased for individuals who have been diving shortly before a flight. In SCUBA diving air under pressure is used as a source of breathing gas and this increases the body's store of nitrogen. On subsequent ascent this may come out of solution, giving rise to DCS.

Therefore strict guidelines are set down concerning diving and flying, i.e:

CASA Regulation

Do not fly within 4 hours after diving at a depth not more than 10m (33').

At depths greater than 10 m:

- If the dive was for less than 4 hours, no flying for 12 hours
- If the dive was for more than 4 hours, no flying for 48 hours

Requires decompression stops on ascent.

Other countries have different standards. A common standard being used by many countries, including the EASA is:

EASA Regulation

Do not fly within 12 hours after diving to a depth not more than 30'.

Do not fly within 24 hours after diving to a depth more than 30'.

At the surface, pressure is 1 atmosphere—at 10 metres below the surface the pressure is 2 atmospheres and increases by 1 atmosphere for every 10 metres increase in depth.