Chapter 3

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PHYSIOLOGY*

A basic understanding of the bodies' processes is needed to grasp the physiological effects of diving and the application of diving medicine. The cardiovascular and respiratory systems are described here while the physiology of some other organs, such as the ear, are considered in specific chapters.

METABOLISM

The Need for Energy

Energy is a fundamental requirement for all life processes. It is needed for growth, repair, movement and all the active functions of the body. The fuel for this energy comes from **carbon compounds**, which are incorporated in complex molecules in the food we eat. This is biochemically dismantled in the digestive tract into simple chemical compounds which are absorbed and carried by the blood stream to the cells. Here they undergo further biochemical processing until ultimately the carbon is combined with oxygen (O_2), forming carbon dioxide (CO_2) and releasing energy.

This is similar to the energy formation which takes place in an automobile engine or a fire, where carbon in fuel or wood is combined with O_2 to produce energy. The body processes will only function under strict conditions of O_2 availability, temperature and acidity.

The body needs a means of transferring food products to the cells, together with delivery of O_2 and removal of CO_2. This is performed by the blood, in the vascular system. It comprises **arteries** which take blood to the tissues, a vast network of microscopic **capillaries** that bring the blood into contact with all the cells of the body, and **veins** which return blood to the heart.

The blood is circulated through the blood vessels by a muscular pump – the heart, and the whole system is called the **cardiovascular** system. It brings O_2 from the lungs to the cells and eliminates CO_2 through the respiratory system.

*** Reading this chapter can be delayed if time does not permit, and the reader is in a hurry to commence diving**

RESPIRATION

Anatomical Structure

The respiratory tract begins at the mouth and nose and ends in the microscopic air sacs called the **alveoli**, in the lungs.

The **nose**, apart from its decorative function, warms and humidifies the air that we breathe. It also filters large particles which might otherwise be inhaled. If the nose is bypassed by breathing through the mouth, a snorkel or scuba regulator, the lung then has to cope with drier, colder, unfiltered air.

After passing through the mouth or nose, the air then enters the throat where the **larynx** (or voice box) is situated. This is recognised as the "Adams Apple". The larynx produces the sounds of speech as well as helping to protect the lungs from inhalation of foreign material.

When sea-water from a flooded snorkel or scuba regulator enters the larynx, a trap-door like structure called the epiglottis closes over the opening and the vocal cords shut to prevent the foreign material from entering the lungs. If any material passes these structures, the cough reflex, activated by foreign material touching the inside of the air passages, may cause a **coughing** reaction which tends to expel whatever has been inhaled.

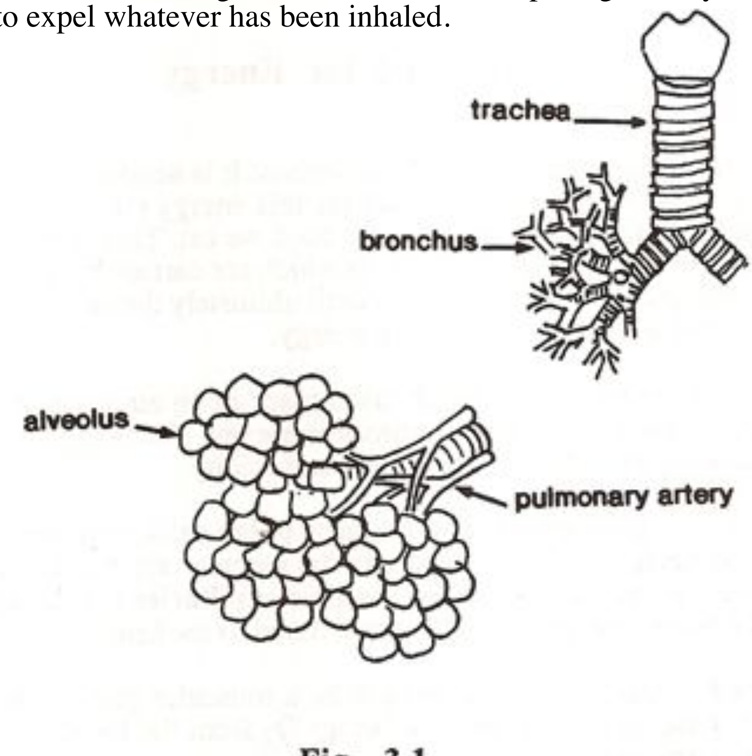

Fig. 3.1
Diagram showing the trachea and bronchial tree, terminating in the alveoli. The relationship between the bronchus, alveoli and branches of the pulmonary artery can be seen.

Below the larynx the air passes through a tube called the **trachea**. This is about as thick as the average snorkel and branches inside the chest into two tubes, the **bronchi**, which lead to the lungs. Those air passages are lined with cells covered with microscopic hairs (cilia) which move a sheet of secreted mucous slowly upwards towards the larynx. Small pieces of foreign material such as dust eventually find their way to the larynx, along with this mucous sheet. It is then either coughed-up or swallowed. The cilia may be damaged by smoking or infection, causing retention of mucous and inhaled material which may eventually obstruct the air passages.

The bronchi divide repeatedly into progressively smaller passages rather like the branches of a tree. These passages have encircling muscles in their walls which, by contraction or relaxation, can vary the diameter of the air passage.

In **asthma** the muscles of the small bronchi become oversensitive and overactive, causing excessive narrowing and obstruction of these air passages. This can occur in response to exercise, allergy, cold, infection, anxiety, smoking or other inhalants such as sea water. At the same time, the cells lining these passages produce excessive and thickened mucous. The combination of these factors causes airway narrowing which has serious repercussions for a diver.

The smallest branches of the bronchi end in bunches of microscopic air sacs called **alveoli**. The vast number of alveoli are packed together into the two sponge like organs, the **lungs**. There are about 300 million alveoli in the lungs and the combined surface area of all the alveoli in the lungs is equal to about half a tennis court. The alveoli are lined by a thin layer of fluid containing a detergent-like substance called **surfactant**. This acts as a wetting agent to prevent the alveoli from collapsing from surface tension.

The surfactant lining of the alveoli can be damaged in disease or by inhalation of water, leading to collapse of the lungs and serious respiratory difficulty.

Each alveolus is surrounded by a network of blood capillaries. These bring the blood into close contact with the air in the alveolus, with only the microscopically thin walls of the alveolus and capillary separating the two.

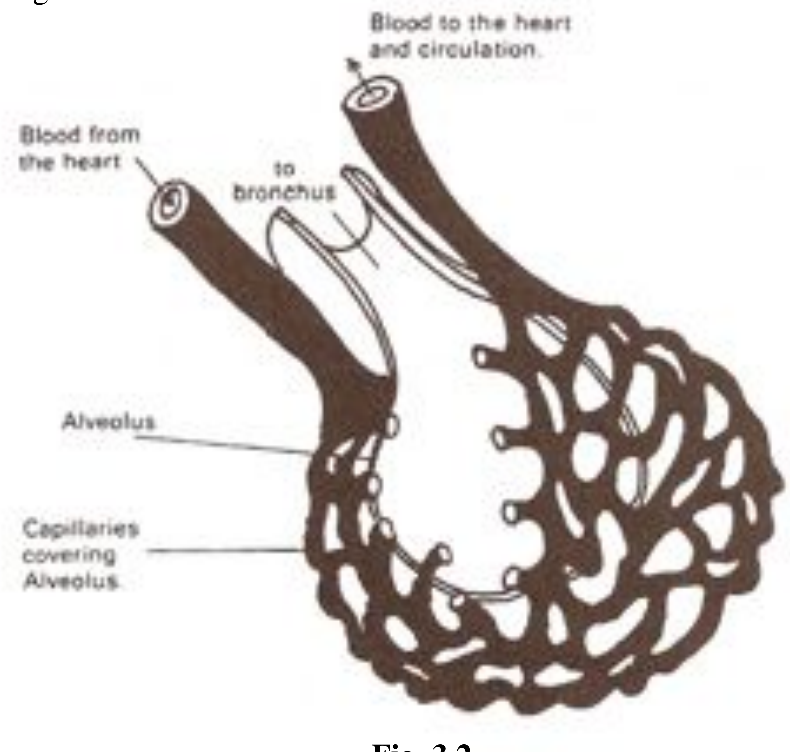

Fig. 3.2
This diagram illustrates an alveolus with its surrounding meshwork of capillaries.

If the wall of an alveolus is ruptured, as it may be in **pulmonary barotrauma** ("burst lung"), then air from the alveolus is able to enter the blood stream where it may cause blockage of distant vessels such as those in the brain. This is called an **air embolism**.

The lungs occupy a cavity about the size of a football on each side of the chest. The lung is covered by a thin membrane coating, called the **pleura,** and the inside of the chest wall is lined by a similar membrane. Between the two pleural layers is a narrow space which contains a small amount of lubricating fluid to minimise friction as the lungs expand and contract during breathing. If the outer surface of the lung tears, as it may in pulmonary barotrauma, then air can enter this pleural space causing the lung to collapse. This disorder is called **pneumothorax**.

The chest wall which encloses the lungs is made up of ribs with muscles between them - known as intercostal muscles. At the base of the chest cavity lies a large thin dome shaped muscle called the **diaphragm**. When the diaphragm contracts, it flattens and has a piston like effect, reducing the pressure in the chest cavity and increasing the volume of the lungs. The reduced pressure draws air into the lungs through the air passages.

Contraction of the diaphragm is the main method of **inhalation** in the resting state. It is assisted by contraction of the muscles between the ribs which rotate the rib cage upwards and outwards, enlarging the chest cavity and reducing the pressure in the chest. A group of neck muscles which are attached to the rib cage can also assist respiration when maximal breathing is required.

At the end of inhalation the elasticity of lungs and rib cage causes the lungs and chest wall to contract and **exhalation** takes place. With quiet breathing, this does nor require muscular effort. With heavy breathing, exhalation can be assisted by the abdominal and chest muscles.

Respiratory Function

During quiet respiration in adult males, about 500 ml of air is moved in and out of the respiratory tract with each breath. The volume per breath is termed "**tidal volume**". During extremely heavy exercise, the tidal volume can increase 10 fold, up to about 5 litres.

The total amount of air that can be held in the lungs (**total lung capacity** or **TLC**) in adult males is approximately 6 litres. Only about 10% of the air in the chest is exchanged with each breath during quiet respiration. The **vital capacity** (**VC**) is the maximum volume that can be exhaled in one breath, and the **forced expiratory volume** (**$FEV_{1.0}$**) is the maximum volume that can be exhaled in one second.

The **flow of air** through the respiratory passages varies at different stages of respiration. It reaches a peak about midway through inspiration — and during quiet breathing this peak flow rate is approximates 30 litres per minute. This value increases during exercise to 600–700 litres per minute.

Any breathing system (such as a snorkel or demand valve) which the diver is using, should be capable of handling these large air flows without significant resistance. If this does not occur, then the diver must exert extra effort during respiration in order to overcome this resistance. This problem is compounded when the diver is breathing compressed air at depth because the increased density of the gas will further increase the resistance to airflow in both the equipment and the lungs.

Gas Uptake and Loss

Air, which contains approximately 21% oxygen (O_2) and 78% nitrogen (N_2), is inhaled into the alveoli where it is brought into contact with the blood in the capillaries. This blood contains a lower partial pressure of O_2 than the air in the alveolus and a higher partial pressure of CO_2, since it has just returned from the body, which has been using O_2 and generating CO_2. Consequently, there is a pressure gradient causing O_2 to diffuse from the alveoli to the blood, and CO_2 to diffuse from the blood to the alveoli, where it is then exhaled. There is no net movement of N_2 since the N_2 in the alveoli and in the blood is in equilibrium, except when diving, altitude exposure or breathing different gases.

If the diver breathes air (78% N_2) or another inert gas such as helium, while descending or remaining underwater, this inert gas will pass from the alveoli to the blood because the partial pressure of the gas in the lungs is increasing as the diver goes deeper.

On ascent, the partial pressure of inert gas in the lungs will reduce, and this allows inert gas to move from the blood (returning from the tissues) to the alveoli, and be exhaled.

Respiratory Control

The partial pressures of CO_2 and O_2 in the blood are kept within very strict limits by a sensitive control system. There are sensors in the brain which detect small changes in the blood CO_2. If this increases, then the sensor causes stimulation of the **respiratory centre** within the brain, leading to faster and deeper respiration to eliminate more CO_2.

When a snorkel diver holds his breath, the CO_2 level in his blood increases. This produces respiratory stimulation which compels the diver to take a breath — hopefully after he has had time to return to the surface.

The sensors for blood O_2 pressure are in the carotid arteries which supply the brain. A reduction in the blood O_2 level also leads to respiratory stimulation, but this effect is not as powerful as that caused by CO_2 changes.

Smoking

The ingenious habit of rolling tobacco into a tube of paper, setting fire to it and inhaling the smoke, sabotages the complex respiratory and circulatory process at several points.

As well as predisposing to lung cancer and emphysema, noxious tars in the smoke precipitate out in the bronchi producing chronic irritation, narrowing of the bronchi and cause a persistent outpouring of mucous. This ultimately results in chronic bronchitis. The tar also poisons the cilia, which conduct the mucous up the airway to the larynx, resulting in retention of old mucous in the lungs (smell the breath!).

Various toxins in the smoke ultimately cause destruction of the alveolar walls producing cavities in the lungs and destruction of the lung architecture, resulting in the disease called **emphysema**. This, combined with obstruction of the air passages, makes the smoking diver less physically fit and more liable to air trapping in the lungs and pulmonary barotrauma (see Chapter 11).

The carbon monoxide content of the smoke reduces the capacity of the blood to carry O_2, thereby reducing oxygenation of the tissues.

Some of the chemical constituents of the smoke are absorbed into the blood stream producing changes in the walls of the blood vessels supplying the heart, brain and limbs. Ultimately these become obstructed. In later life this can cause heart attacks, strokes and peripheral vascular disease (gangrene).

CARDIOVASCULAR SYSTEM

Blood

Arteries take blood from the heart. **Veins** return blood to the heart. Arterial blood (which has absorbed O_2 as it passed through the lungs), is then pumped to the periphery by the heart and is brought close to all the cells in the body by the capillary system. Here the O_2 diffuses into the cells and the CO_2 diffuses out of the cells into the blood.

The blood transports O_2 and CO_2. The O_2 is mainly carried by an iron containing compound called **haemoglobin (Hb)** contained in the red cells. 100 ml of blood will transport approximately 20 ml of O_2. If the red blood cells are removed, blood plasma (the liquid part of blood) will transport only 0.3 ml of O_2 per 100 ml blood. A drop of blood contains approximately 300 million red cells.

In arterial blood, the haemoglobin is almost 100% oxygenated when the blood leaves the heart to go to the tissues. It is bright red in colour. If for any reason the arterial blood is not adequately oxygenated, it causes the blue colour of the skin and tongue (cyanosis) seen in **hypoxia** (see Chapter 20).

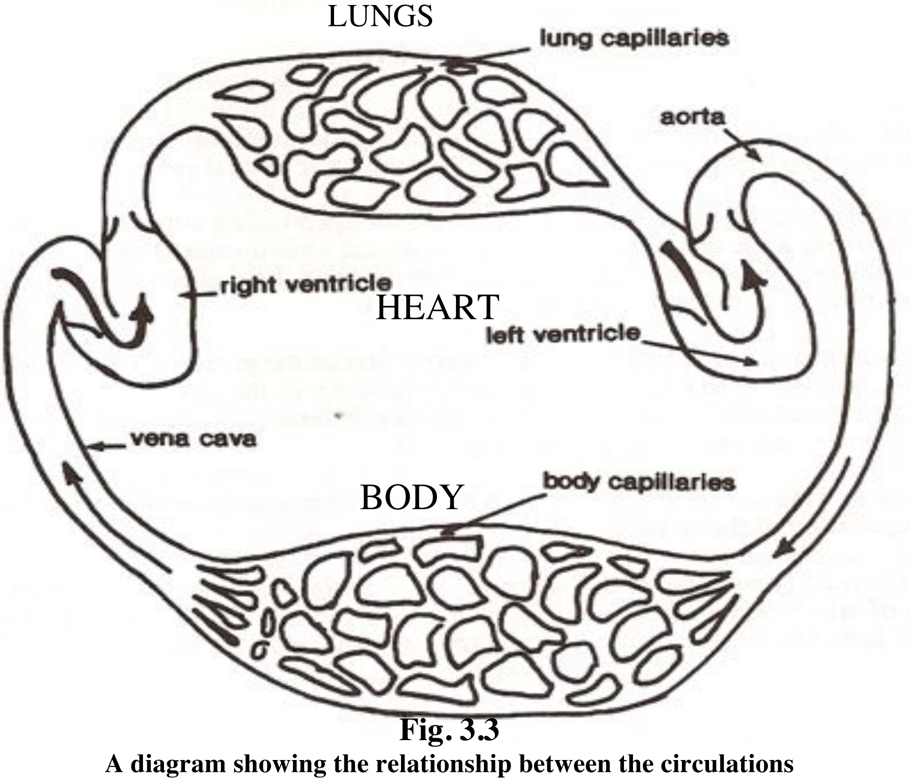

Fig. 3.3

A diagram showing the relationship between the circulations produced by the right and left sides (ventricles) of the heart.

In venous blood, the haemoglobin in red blood cells returns to the heart with 75% of its O_2 load still attached. It is then a more bluish colour.

The tissues need only 25% of the O_2 carried in arterial blood. This allows a reserve supply of O_2 which can be used during exercise or breath holding.

CO_2 is carried from the tissues by the blood in the veins, back to the lungs. Some of it is dissolved in blood plasma and some bound to the protein of the haemoglobin molecules. Although the CO_2 dissolved in the blood forms carbonic acid, the acidity of the blood is prevented from rising to excessive levels by a system of buffering compounds.

It is possible to increase the O_2 carrying capacity of blood by the use of **hyperbaric oxygen**. In recompression chambers, increased amounts of O_2 can be physically dissolved in the plasma, even though the haemoglobin is fully saturated with O_2.

Heart

The heart is a large muscular pump (about the size of a man's fist) located in the centre of the chest. See fig 3.4. It is composed of two functionally separate pumps which maintain two distinct circulations. The **right side** of the heart receives venous blood from the body and pumps this blood through the lungs where it picks up O_2 and eliminates CO_2. The **left side** of the heart receives this oxygenated arterial blood from the lungs and pumps it through the body.

Each side of the heart is essentially a two-stage pump which is not unlike a two-stage compressor. The **atrium** is the first or low pressure stage of the pump and it has a thin muscular wall. It receives blood from the veins at low pressure. When it contracts, it propels this blood into the second or high pressure stage – the more thickly walled and stronger ventricle.

The **ventricle** has two "one-way" valves, one valve preventing blood from flowing back into the atrium, and the other valve preventing blood flowing back into it from the arteries. When it contracts, it pumps blood into the arteries.

Occasionally there may be openings between left and right sides of the heart (patent foramen ovale, septal defects). In divers this allows bubbles to pass from the venous system to the arterial, causing serious manifestations of decompression sickness from dives that should otherwise be safe. People with significant heart abnormalities should not undertake scuba diving.

The heart, being a muscle, requires its own blood supply. This is provided by the **coronary arteries** which originate in the aorta, the main artery of the body. Any obstruction of these coronary arteries will cause damage to the heart muscle – a heart attack.

Partial obstruction of the coronary arteries may produce **angina** (which is pain or discomfort arising from insufficient O_2 in cardiac muscle), because it is receiving insufficient blood supply. Since a heart attack can take some of the fun out of a diving expedition, it is important for divers to have skilled medical examinations to exclude this problem or to help predict which divers will be susceptible to such heart conditions (coronary artery disease).

The resting output of the heart is about 5 litres of blood per minute. The heart has considerable reserve and if the tissues require it, can increase this output several fold by increasing its rate and strength of contraction.

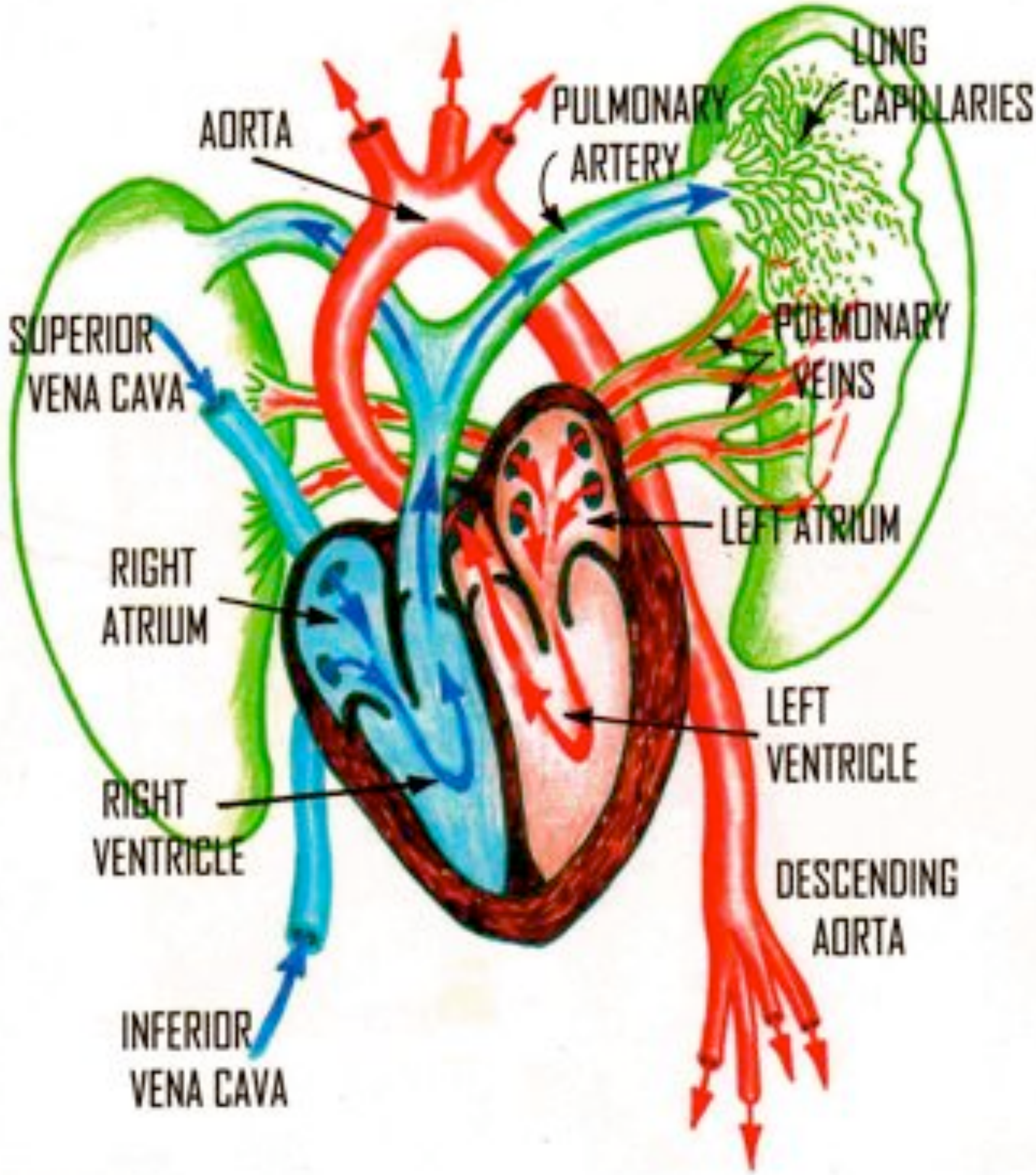

Fig. 3.4
This diagram shows a cutaway drawing of the heart to illustrate the flow of blood from the vena cava through the chambers of the heart and the lungs to the aorta.

Circulation

The blood flow from the heart is pulsatile and the **blood pressure** varies depending on the stage of heart contraction. The higher blood pressure during the heart's contraction is called the **systolic blood pressure** and has a normal value of around 100–140mm mercury (mm Hg). The pressure when the heart is not contracting is the **diastolic blood pressure** which has a normal value of around 60–90mm Hg. Blood pressure is normally recorded as Systolic / Diastolic – e.g. $^{130}/_{90}$.

Blood vessels can change their internal diameter under the control of the nervous system. This allows for some variation in blood flow to parts of the body depending on specific circumstances. For instance, during exercise the blood vessels dilate allowing more blood flow to the muscles, while under cold conditions the blood vessels to the skin constrict, reducing the blood flow to the skin (appearing pale) and so minimising heat loss.

The constriction or dilatation of the blood vessels also influences blood pressure. Excessively high blood pressure **(hypertension)** can ultimately cause damage to the blood vessels and an excessive strain on the heart. High blood pressure requires treatment, often with drugs which dilate the blood vessels but which may interfere with safe diving.

Blood pressure is constantly maintained by a sophisticated sensing and feedback mechanism. Variations in blood pressure caused by physical activity or standing from a reclining position are quickly compensated for by changes in the diameter of the blood vessel walls.

When a person is in a reclining position, blood pressure is maintained easily and the effect of gravity does not have to be opposed by the contraction of blood vessels. When standing up quickly from this position, blood pressure in the upper part of the body may fall. Occasionally, even in normal people, the heart and blood vessels cannot compensate rapidly enough and fainting or light-headedness can result. This is known as **syncope** or **postural hypotension**.

The cardiovascular system is able to compensate for changes in blood volume, such as those associated with severe bleeding (**haemorrhage**), by constricting the blood vessels and diverting blood from non-essential organs to essential organs such as the brain and heart.

In **pulmonary barotrauma,** air can gain access to the blood as it passes through the lungs. Air bubbles may be carried to vital organs such as the brain and heart, obstructing their blood flow and leading to serious consequences **(air embolism)**. In **decompression sickness,** gas bubbles may also be transported by the blood stream.

COMPRESSED-AIR DIVING

Scuba allows the diver considerable freedom but has its own limitations. It has all the potential problems of free diving, but adds special physiological problems of its own.

Resistance to Breathing

A major limitation to diving with scuba is resistance to breathing. During maximal exertion, a diver can consume over 70 litres of air per minute at the surface – but the peak flow rate during inspiration is about three times this value. Some regulators may have difficulty delivering gas at this rate, adding considerable resistance to breathing.

This problem is magnified at depth because the greater pressure increases the density of the inhaled gas, especially at depths in excess of 30 metres when air is breathed. The same effect is seen at about 200 metres depth when helium /O_2 (heliox) mixture is breathed, because heliox is less dense than air. It is likely that resistance to breathing will ultimately limit the depth to which divers can reach.

An idea of the respiratory loads which the diver faces can be gained from the following table :

SCUBA SWIM	SPEED*	OXYGEN CONSUMPTION	RESPIRATORY MINUTE VOLUME
Slow scuba swim	0.5 knots	0.8 litres / minute	18 litres / minute
Average scuba swim	0.8 knots	1.5 litres / minute	28 litres / minute
Fast scuba swim	1.0 knots	1.8 litres / minute	40 litres / minute
Maximum scuba swim	1.3 knots	3–4 litres / minute	70–100 litres / minute

*. a knot is equal to 1 nautical mile per hour, or 1.85 km / hr

Table 3.1

Air Consumption

O_2 consumption is virtually the same for a given amount of exercise whether it is performed at the surface or deep under water. Because compressed air is being breathed at depth, more O_2 will be supplied than is needed by the diver. The actual volume of gas breathed at any depth will be the same as that which would be breathed at the surface. However, since the gas being breathed at depth is at greater pressure, the volume breathed, if converted to atmospheric (surface) pressure, will also be greater.

For example, during maximal effort a diver may consume 70 litres of air per minute at the surface. If he is performing an equivalent amount of effort at 20 metres depth (3ATA), he will still be breathing 70 litres per minute from his scuba regulator at 20 metres, but this will be equivalent to :

70 (litres) x 3 (atmospheres)
= 210 litres per minute at surface or atmospheric pressure.

So, the endurance of an air supply decreases with depth.

The regulator may not be able to meet the respiratory demands of a diver when certain conditions apply (see Chapter 5). Under these conditions, the diver may be aware of an inadequate air supply and either panic or take other dangerous action, such as a rapid ascent or omission of decompression requirements.

Skip Breathing

It is possible for a scuba diver to minimize his air consumption by deliberately slowing his breathing rate. This type of breathing pattern obviously limits the reserve of O_2 which will be stored in the divers lungs and haemoglobin, and may lead to retention of CO_2 and acidosis. It reduces the safety margin in the event of air supply failure as well as increasing the likelihood of pulmonary barotrauma, and is recommended only for those with suicidal tendencies. Excess. CO_2 also acts as a narcotic, so the diver may make less sound decisions

Other Effects on a Scuba Diver

The physiological effects of scuba diving may parallel those of breath-hold diving (see Chapter 4). Hyperventilation, breath holding, the diving reflexes and the effects of immersion, may all be provoked. The dehydration effect of immersion is of importance in aggravating decompression sickness.

The many pathological problems developing from scuba diving are referred to later in this text. They include pulmonary barotraumas (see Chapter 11), respiratory decompression sickness (see Chapter 15), oxygen toxicity (see Chapter 21), breathing gas contamination (see Chapter 24), the drowning syndromes (see Chapters 25 and 26) and scuba divers' pulmonary oedema (see Chapter 32).

Gas Pressures

Because of the increased pressures on the diver, high nitrogen partial pressures cause nitrogen narcosis (or "narks"). Similarly, higher O_2 partial pressures may produce O_2 toxicity in very special circumstances. Gas coming out of solution in the divers body may cause decompression sickness and/or dysbaric osteonecrosis (or "bone rot").