Chapter 6

Pulmonary/Respiratory Systems

6.1 INTRODUCTION

Respiration is an act of breathing. Respiration is exchange of gases in biological process. In the human body, the respiratory system is the pneumatic system. A physiological air pump (called diaphragm), creates alternatively negative and positive pressures in a sealed chamber (called thoracic cavity) and causes air to be sucked into and out of a pair of lungs (elastic like bags) within the chamber. The lungs are connected to the surrounding air medium through nasal cavities. The tubing between lungs and nasal cavities has a common path way for carrying air to the lungs and food to the stomach. A special valve blocks the airway whenever food passes through the common region. Inhaling (inspiration) is a process of flowing of air into the lungs. In the inhaling process, the muscle will contract so that the ribs will lift and pull outward to increase lung volume. The increase in lung volume will allow air to rush into the lungs. The inspired air contains about 21% oxygen and may not contain carbon dioxide. Exhaling (expiration) is a reverse process of flowing of air out of lungs. In the exhaling process, the muscle will relax and decreases lung volume. The decrease in lung volume will exhaust the air out of lungs. The oxygen content in the expired air is about 16% and the content of carbon dioxide is about 5%. The respiratory system works on Hering–Breuner inspiratory reflex. That is, the expansion of the lungs stimulates nerve receptors (vagus nerve X) to signal the brain stem to turn off inspiration. Similarly, whenever the lungs collapse, the receptors give the turn on signal. Holding one's breath will affect respiration, but for short duration only. Holding one's breath will build-up carbon dioxide in the blood and forces a turn on signal.

The blood acts as a transport system to supply oxygen to the various parts of the body. It also transports the metabolic waste and carbon dioxide from the various parts of the body to the lungs and kidney. The function of respiratory system is to remove the carbon dioxide from the blood when it reaches lungs and in turn to enrich the blood with oxygen. The parameters of the respiration are rhythm, rate and depth. These parameters are controlled by the brain stem (pons and medulla). The respiratory parameters are adjusted depending upon the following situations:

(i) Whenever the concentration of carbon dioxide in the blood increases which increases the depth and rate of respiration.
(ii) Whenever lung tissue air pressure deviates from normal value.
(iii) Whenever increase in blood pressure, which slows down respiration.
(iv) Decrease in blood pressure, which increases respiration rate and depth and
(v) Drop in blood pH, which speeds up respiratory.

6.2 RESPIRATORY SYSTEM

The respiratory system consists of two tracts. One is the upper respiratory tract which includes the nose (nasal cavity, sinuses), mouth, larynx (voice box), and trachea (windpipe). Another is the lower respiratory tract which includes the lungs, bronchi, and alveoli. A human respiratory system is shown in Figure 6.1. The two lungs, one on the right and other on the left, are the body's major respiratory organs. Each lung is divided into upper and lower lobes. But a third subdivision is in the right lung, called right middle lobe. The right lung is larger and heavier than the left lung. Left lung is smaller in size because of the left side space occupied by the heart. A shiny, clear, thin coating called the pleura envelopes the lungs. The inner, visceral layer of pleura attaches to the lungs; the outer, parietal layer attaches to the chest wall (thorax). A wet surface between two glass slides sticks like the glass plates together. Similarly,

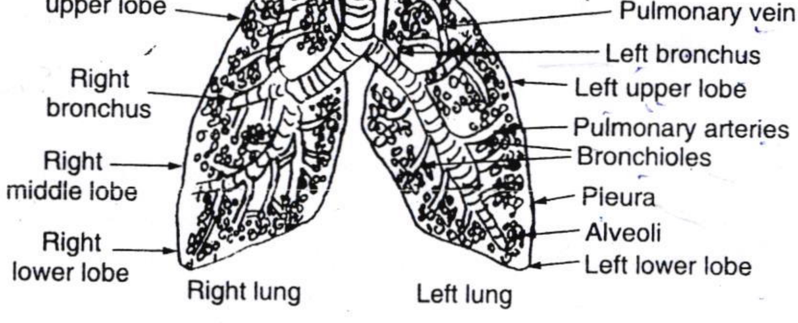

Figure 6.1 Respiratory system.

a pleural fluid between visceral layer and parietal layer keeps both layers in place. Mediastinum is an area that contains the heart and its large vessels, the trachea (windpipe), esophagus, thymus, and lymph nodes. The diaphragm made up of muscle separates the thoracic cavity from the abdominal cavity. The main function of the diaphragm is contracting and relaxing to perform breathing.

6.3 AIR DISTRIBUTION

On inspiration, air is entering the lungs through the upper respiratory tract called nose and the mouth. The dust particles and bacteria in air are filtered by nasal hairs and mucus. In addition to this filtering effect, the air is warmed and moisturized when inspired through nose. On the way to lungs, the larynx further warms and humidifies the air. Filtering, warming and moisturizing will not happen when air is inspired through the mouth. At the throat two openings exist, one is the esophagus for passage of food, and the other is the larynx for passage of air. When food is swallowed, the opening of the larynx closes to prevent from food entering the lungs. When air is inspired, the opening of the esophagus closes to prevent from air entering the stomach.

The trachea, through which the air flows, branches into the right and left bronchi. The main bronchi is divided into smaller bronchi, then into bronchioles. The bronchioles have hair-like, epithelial projections, called cilia. Cilia are beating rhythmically to sweep dust out of the lungs. The air in the bronchioles is at body temperature and 100% humidified and is herely completely filtered.

At the end of bronchioles a small, balloon like air sacs are there. These balloons are called alveoli and they are arranged in clusters. During inspiration, the chest cavity enlarges and a vacuum is created in each alveoli. Hence oxygen rich air is entered into the alveoli. Alveoli are covered by tiny blood vessels and capillaries. The higher concentration of dissolved oxygen is there in the trapped air in the alveoli. Similarly, higher concentration of dissolved carbon dioxide is in the capillaries filled with blood. Now, the oxygen diffuses across the alveolar walls into the blood plasma and carbon dioxide in the blood crosses from blood into the alveoli. On expiration, the alveoli relax and carbon dioxide rich air moves out of the lungs and breathed out.

Naturally haemoglobin has more affinity to oxygen than carbon dioxide. Haemoglobin can carry 70 times more oxygen than the plasma alone can hold. The oxygen carrying capacity of the blood depends on the following factors:

(i) The difference in oxygen concentrations of the blood in the capillaries of lungs and trapped air in the alveoli

(ii) The efficient and healthy functioning of the alveoli

(iii) The rhythm, rate and depth of respiration

6.4 PULMONARY CIRCULATION

The process of enriching the blood with oxygen and removal of carbon dioxide from the blood described through a pulmonary circulatory circuit is shown in Figure 6.2. Carbon dioxide rich (oxygen poor) blood travels to the right atrium and then to the right ventricle from the inferior

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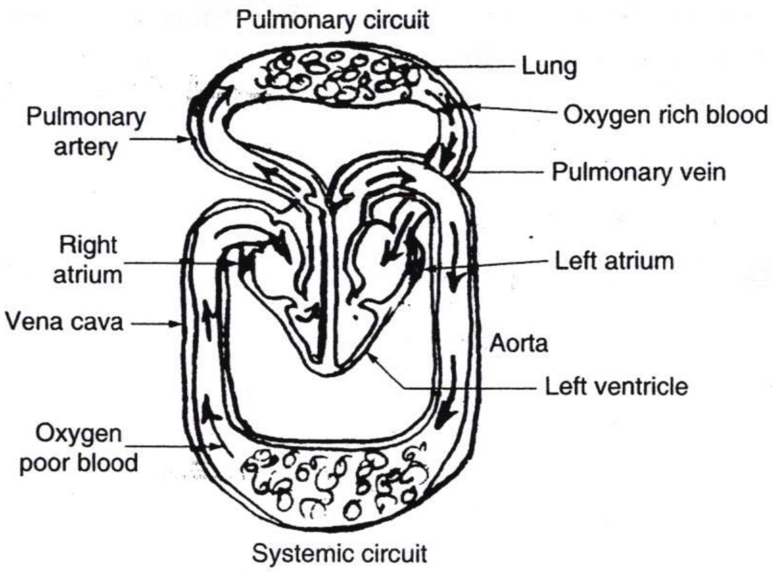
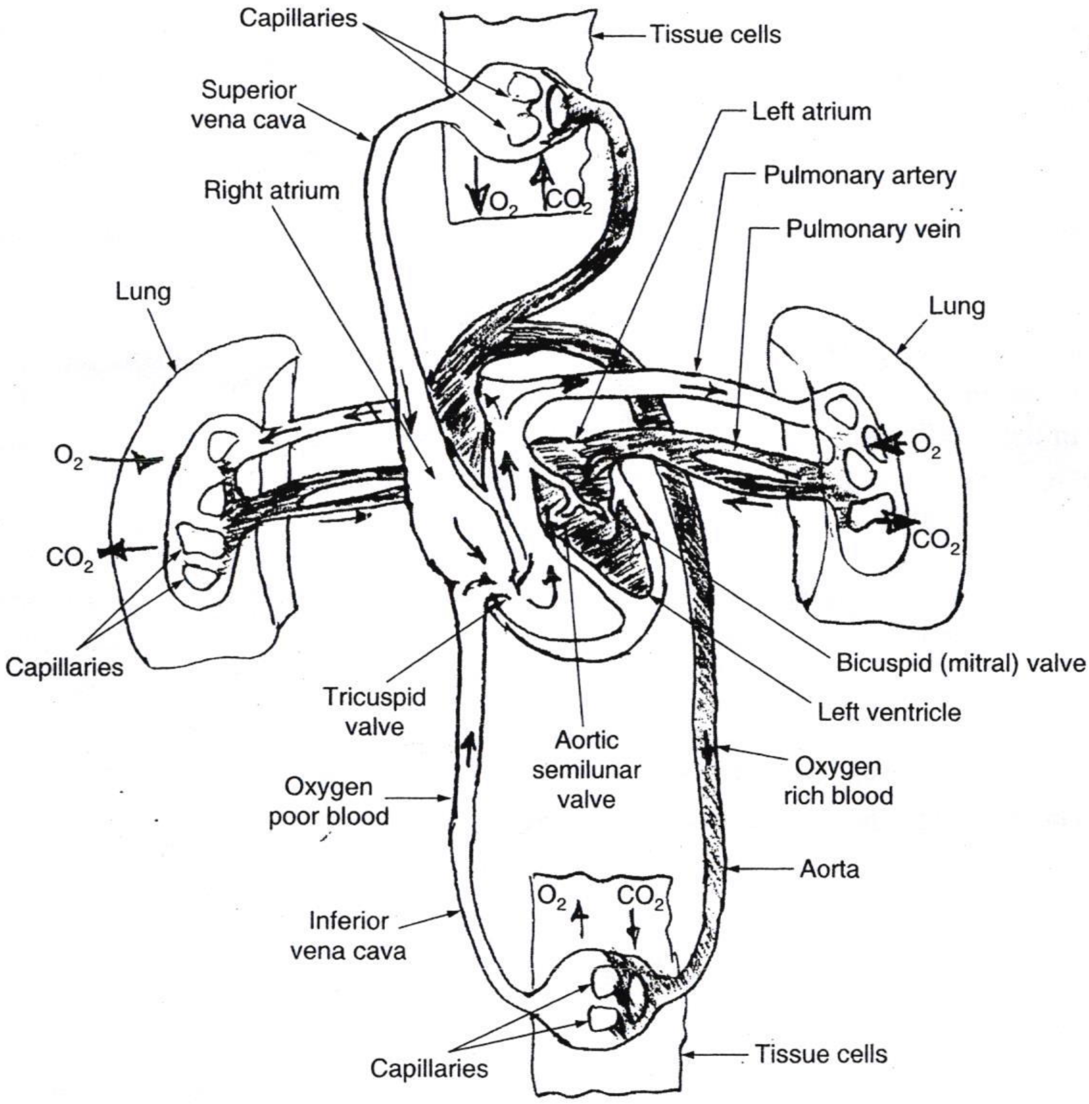


(a) Pulmonary and systemic blood circuit



(b) Blood circulating system

Figure 6.2 Pulmonary circuit.

and superior vena cava. From there, the blood is pumped into the pulmonary artery and branches to the right and left lungs until the carbon dioxide rich blood reaches the alveoli. In the alveoli, the exchange of carbon dioxide and oxygen takes place. Now, the blood becomes oxygen rich. The oxygen rich blood in the capillaries recombines to form venules and veins. Finally two veins in the right and two veins in the left carry oxygen rich blood to the left ventricle for distribution to the entire body.

Pulmonary and respiratory function analyzers are used to evaluate the state of the lungs or quality of the respiratory process. Clinically three basic parameters are measured to study the state of pulmonary and quality of respiratory function. The three basic parameters are ventilation, distribution and diffusion.

Ventilation: It is the ability of the body to displace air volume and the rate at which the displacement occurs. For ventilation measurements, spirometers are used.

Distribution: It is the degree of lung obstructions for the flow of air and residual volume of the lungs that can not be removed. Pneumo-tachometers are used to measure the instantaneous rate of volume flow of respired gases.

Diffusion: It is the ability of exchange of gas with circulatory system. In other words, it is the measure of rate at which the gas is exchanged with blood stream. Gas analyzers are used in the diffusion measurements.

Diffusion is transport of gases from higher pressure point to a lower pressure point to nullify the pressure difference. It consists of mixing of gases within the lungs, ventilation of alveoli and exchange of oxygen and carbon dioxide between air and blood in the lungs.

6.5 LUNG VOLUMES AND LUNG CAPACITIES

The amount of air that the lungs can hold, can be divided into smaller amounts called volumes. The amount of air a person breathes in and out at rest is called the tidal volume *TV* or V_t. Normally tidal volume is about 500 ml. A person breathing at rest, takes this normal amount of air in and out. On the other hand, when a person is doing maximum physical activity, the person will inhale additional amount of air. This additional amount is called the inspiratory reserve volume (IRV). A typical IRV is about 3000 ml. The additional amount of air a person could exhale is called the expiratory reserve volume (ERV). ERV is about 1000 ml. The amount of air that stays in the lung even after maximum expiration is called residual volume (RV). Combinations of two or more volumes are called capacities. They are total lung capacity (TLC), vital capacity (VC), and functional residual capacity (FRC). These capacities are defined as follows:

Total lung capacity (TLC): It is the total amount of air the lungs can contain.

$$TLC = RV + ERV + V_t + IRV$$

Vital capacity (VC): It is the total amount of air the person can breathe in and out.

$$VC = ERV + V_t + IRV$$

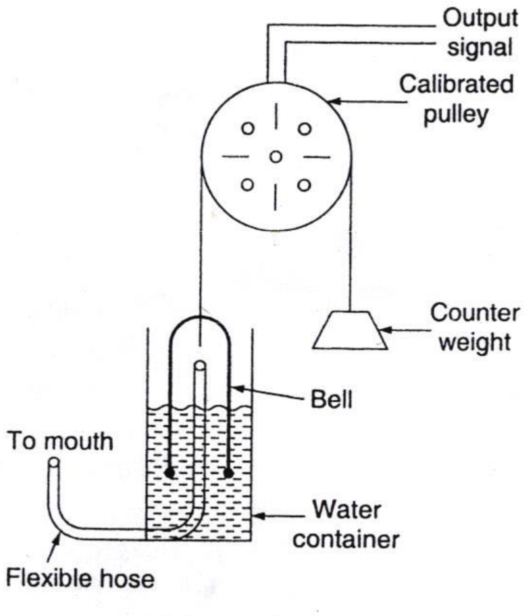
Functional residual capacity (FRC): It is the total amount of air left in the lungs at the end of a normal exhalation.

$$FRC = RV + ERV$$

Air flow volume in and out of the lungs is measured by a device called spirometer, and the recording of lung volume changes with time is known as the spirogram. Instruments that simply detect respiratory activity are referred to as pneumographs, and the resulting recording of respiratory–activity changes with respect to time are called pneumogram. A spirometer is in need to analyze the respiratory system and/or to find the malfunction of the system. A pneumogram can be used for routine monitoring and to indicate healthy breathing. Rate of breathing may be obtained either from spirogram or from pneumogram.

6.6 SPIROMETER

A typical spirometer is shown in Figure 6.3. A bell kept in a container full of water raises and lowers according to inspiration and expiration. Weight of the bell is nullified by a counter weight. The bell and counter weight are connected through a pulley. Pulley can be calibrated to read the volume of air inside the bell. A potentiometer may be connected to the pulley to transduce the volume of air in the bell proportional to change in the resistance of the potentiometer. This spirometer has heavy damping and hysteresis. Hence small and subtle changes in inspiration and expiration volumes are insensitive with this device.



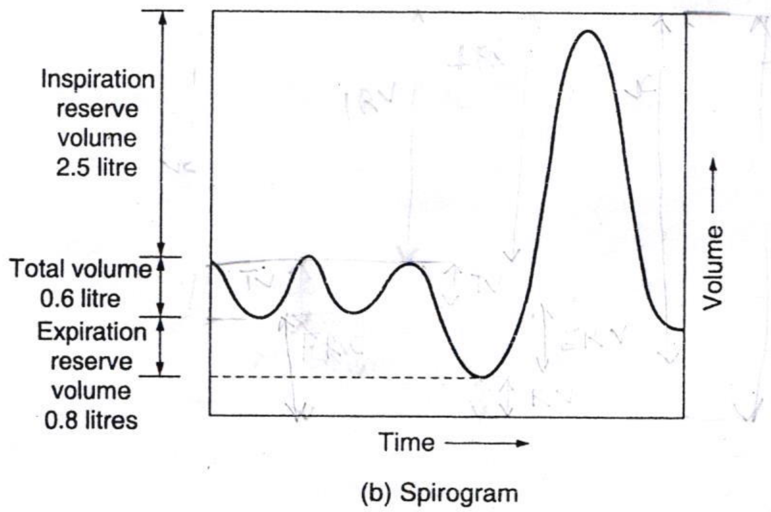


Figure 6.3 Spirometer and recording of lung volumes.

6.7 PNEUMOTACHOGRAPHY

This instrument can be used to measure either rate of air flow into the lungs or rate of tidal volume. This transducer generally used to find respiration rate. The transducers include thermistor placed in front of the nostril, displacement sensor put across the chest, impedance electrodes and signal from CO_2 transducer. The respiratory signal from any one of these transducers and time duration are used to find the respiratory rate. The following are the various methods used to find the respiratory rate:

(i) Differential pressure transmitter method
(ii) Thermistor method
(iii) Impedance pneumotachograph
(iv) CO_2 method of respiratory rate measurement

6.7.1 Differential Pressure Transmitter Method

This device consists of differential pressure transmitter (DPT) which can be used to find flow rate. A typical pneumotachograph is shown in Figure 6.4. One end of the DPT connected to the patient's nose and mouth by a face mask and the other end is left open to sense the atmospheric pressure. The pressure differential is found to be proportional to the velocity of air flow. A DPT transmitter calibrated proportional to velocity of air flow will directly display the rate of respiration. The integration of this value gives the rate of change of volume or rate of change of tidal volume.

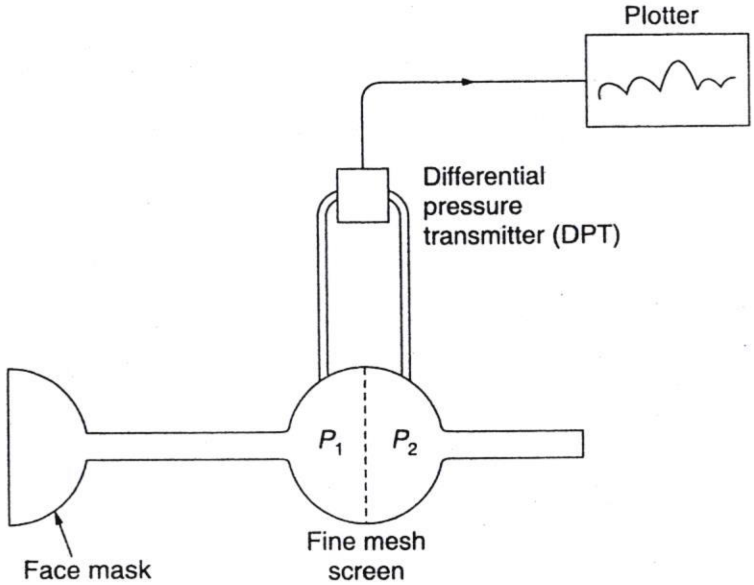


Figure 6.4 Pneumotachograph.

6.7.2 Thermistor Method

This method is useful in the post operation respiration rate measurement. A thermistor probe is placed in tracheal cannula to sense the change in air temperature during inspiration and expiration. Wheatstone bridge is used to transduce the change in resistance of the thermistor due to change in temperature. A differential amplifier cascaded with Wheatstone bride will amplify the signal. The signal can be suitably shaped to count the number of breaths per minute. The low frequency artifacts present in the signal has to be removed before shaping it to count the number of breaths per minute. If the temperature difference between the inspired and expired air does not have appreciable difference, then it is better to heat the thermistor so that to have appreciable magnitude of signal in the bridge output. This heating of thermistor can be achieved by increasing the dc voltage applied to the bridge. Even in the case of suffocated patients who do not have spontaneous respiration monitor inspires very small volumes of air alone can also be sensed using this thermistor method. Placing the themistor in tracheal cannula is not simple. Often the thermistor may be covered with excretions.

Some time this method does not work for the patients who are semiconscious and the tongue does not respond. The uncontrolled tongue may block the breathing system and the inspiration may be as low very small quantity. In such situations, the impedance pneumotachograph will solve the problem.

6.7.3 Impedance Pneumotachograph

It is an indirect method. It does not require any placement of mask on the face, fixing of tubes, flow meters and/or spirometers either in the nose or in the mouth. In this method, an electrode is placed externally over the thorax region and hence does not give any psychological effect on the patients. There is a change in the impedance of the skin of thoracic region as a function of depth and rate of respiration. A typical circuit is shown in Figure 6.5. The electrode used here is a self adhesive type. The motion artifacts can be minimized by having an electrode cream layer. The skin resistance will be in the range of 150–200 ohm. The change in resistance will be in the order of 1% of base resistance. A high frequency signal will be applied across the resistance and the potential drop across the resistance will be taken and applied across a high input impedance amplifier. A demodulator and filter will give a magnitude proportional to the change in resistance of the electrode. This magnitude can be calibrated to read the respiratory rate directly. This method gives faithful output and ease of use for quite patients. It gives more artifacts for moving patients. So, it is very difficult to implement on children.

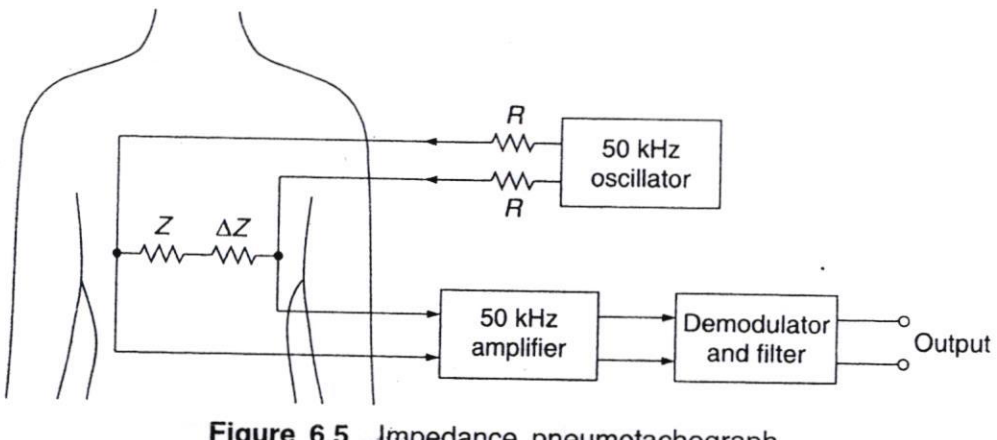


Figure 6.5 Impedance pneumotachograph.

6.7.4 CO_2 Method of Respiratory Rate Measurement

The respiration rate can be derived from the measurement of CO_2 content in the expired air. The measurement of CO_2 may be useful to set the respirator for the patients suffering from respiratory paralysis and other respiratory problems. The measurement can be made from the absorption property of infrared rays by certain gases. The infrared detector used here is PbSe. The amount of heat developed by PbSe is proportional to the intensity of the infrared rays. If the infrared rays are passed through expired air containing CO_2, then some amount of infrared radiations are absorbed by it. Hence there will be a decrease in heat energy produced by PbSe.

A typical infrared analyzer is shown in Figure 6.6. The chopper is rotated at a high speed of 3000 rpm. The infrared source is operated at a temperature of 815°C. Two beams of equal intensity are generated using the chopper assembly. One is passed through a reference cell consists of known quantity of CO_2. Another infrared ray of equal intensity is passed through a cell which contains the expiring air. The difference in absorption of infrared ray creates difference in temperature on either side of diaphragm in a sealed container. The difference in temperature made the diaphragm to deflect on one side. If the diaphragm is considered to be one of the plates of a transducer capacitor, then the amount of absorption of infrared by the CO_2 can be estimated from the change in the capacitance. The alternating signal available across the sensing capacitor can be amplified and wave shaped to give the CO_2 content in the expired air. The same signal can be suitably integrated to give respiratory rate.

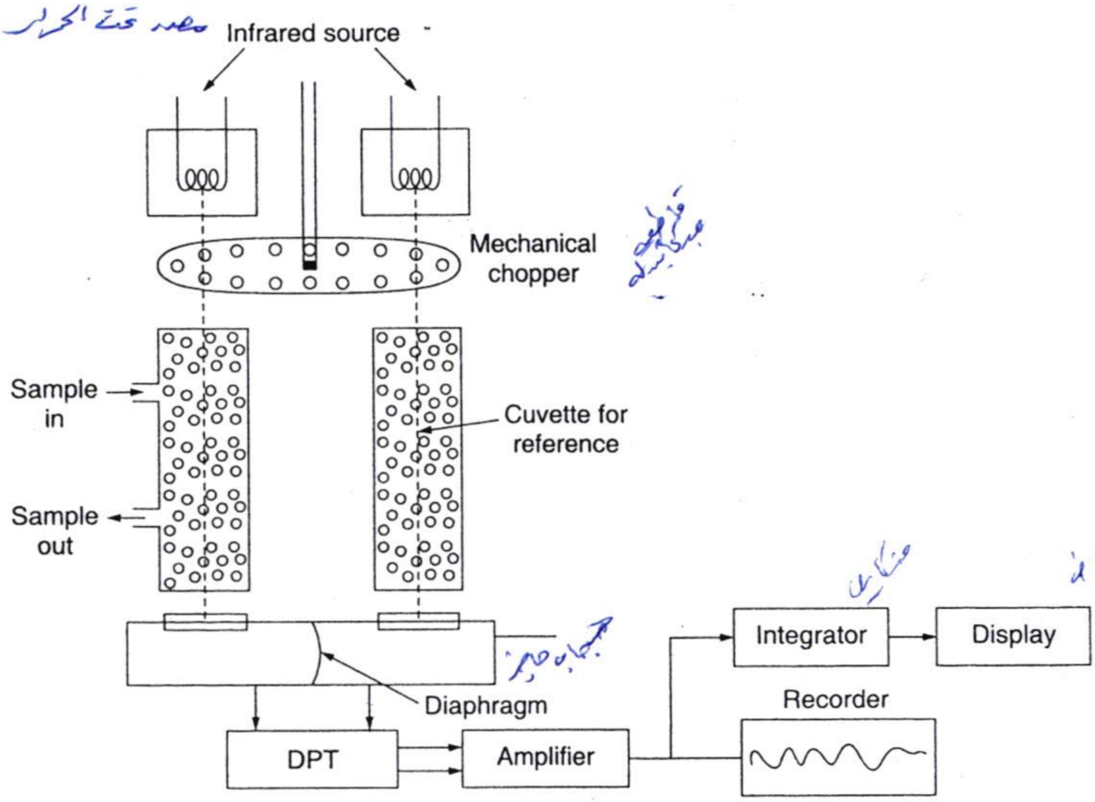


Figure 6.6 Infrared analyzer.

6.8 GAS EXCHANGE AND DISTRIBUTION

When the air is in the lungs, oxygen in the air will exchange with carbon dioxide in the blood. Again this blood carrier has to exchange the oxygen with carbon dioxide when it reaches body tissue. During this transaction, the blood has to transport the gases between lungs and tissues. There are many tests that have been devised to determine the effectiveness with which these processes are carried out. Some of these tests and instrumentation required will be discussed in this section. The tests related with exchange of gases will be discussed first and then the measurement of transport of oxygen and carbon dioxide will be discussed.

6.8.1 Measurement of Gaseous Exchange and Diffusion

Diffusion will occur whenever the gases are unequally distributed inside the chamber and may also occur whenever a membrane separates a permeable gas with a pressure difference. Measurements of partial pressure of oxygen (pO_2) partial pressure of carbon dioxide (pCO_2) are useful to determine the amount of diffusion. There are many methods available to estimate the amount of diffusion. Some of them are: (i) chemical gas analysis method (ii) Diffusion capacity using CO_2 infrared analyzer and (iii) Gas chromatograph. The first method is based on Haldane and Scholander gas analyzer. The second one is based on measuring the diffusing capacity of the lung when CO_2 is used as tracer gas. In the third method, the content of oxygen, nitrogen and CO_2 are measured in the expired air using gas chromatograph.

6.8.2 Measurement of Gas Distribution

Transport of oxygen from lungs to the tissues and carbon dioxide from the tissues to lungs takes place through blood. As we have seen earlier, the oxygen is transported by the haemoglobin of the red blood cells and the carbon dioxide is carried through carbonic acid which is formed by a chemical process of combination of water and CO_2. Carbonic acid is dissolved in the blood and affects the pH value of blood. Hence measurements of partial pressure of oxygen, partial pressure of carbon dioxide in the blood, percentage of oxygenation of haemoglobin and pH value of blood are useful to estimate the ability of distribution of respiratory gases.

6.9 RESPIRATORY THERAPY EQUIPMENTS

When a patient is not able to ventilate by natural processes to the required level, then clinical assistance has to be provided so that the sufficient oxygen will be supplied to the organs and tissues of the body. Hence excessive accumulation of carbon dioxide may be avoided. The process of providing clinical assistance through instrumentation is called respiratory therapy. The therapy includes inhalors, ventilators, respirators, resuscitators, positive pressure breathing apparatus, humidifiers, and nebulizers. The commercial instruments may have overlapping functions and the name of the instruments may vary from manufacturer to manufacturer.

6.9.1 Inhalors

Inhalors are used to supply oxygen or therapeutic gas to a patient who is able to breathe spontaneously without assistance. Inhalors are used whenever higher concentration oxygen than normal level is required. Inhalors consist of a gas source, pressure regulator to control the gas flow rate and a device to administer the gas. In addition to the above, nasal cannulae and catheters face masks, pediatrics and oxygen tents may be required for some cases. The oxygen concentration given to the patient is used to control by regulating the gas flow rate to the mask.

6.9.2 Ventilators and Respirators

Both ventilators and respirators terms are alternatively used to represent the same equipment. It is employed to improve ventilation of the lungs and to supply humidity or aerosol to the