11/Principles of Biomedical Measurement System

New techniques and method of measurement, using basic invention and discoveries in physical science, have resulted in convenience and accuracy with which biomedical measurements can be made.

The following parametres are frequently measured in bioscience and in current clinical medicine:

1. Electrical activity—electrocardiogram (ECG);
   —electroencephalogram (EEG);
   —nerve impulses.
2. Pressure—arterial and venous blood pressure;
   —cerebrospinal fluid pressure;
   —pressure in the lungs and thorax.
3. Flow—blood, respiratory gases.
4. Volume—blood, extracellular and body water.
5. Temperature—differentials.
6. Sound—heart sounds.
7. Physicochemical—blood and tissue pH and
   oxygen and carbon dioxide tensions.

In order to draw valid conclusions from the measurements it is important to assess the following factors:

(a) The technique should be specific for the function being measured and not be affected by other functions.

(b) The accuracy of the measuring device should be determined.

(c) The normal range of values of the function being measured must be known.

Transducer

A device which senses one sort of energy and changes (tranduces) it into another form of energy is known as a transducer. By the use of suitable trnasducers almost all measurements can be converted into electrical energy.

The electrical signal from the transducer may then be masured, displayed or recorded. The signal is usually small and is frequently associated with electrical interference from other sources. Therefore it is necessary to process (condition) it by means of an amplifier (signal conditioner) which increases the signal strength sufficiently to drive an oscilloscope or recorder and at the same time removes (filters) unwated interference.

Types of Amplifier

1. **Linear**—these are designed to faithfully reproduce, the input signal, but none are perfect and the range of input and output signals which

they function most accurately over is usually specified. Linear response should be better than 1%.

2. **High gain**—a small input signal is greatly amplified, e.g. 100× or 1000 or more.

3. **Low gain**—the input signal is amplified by a small factor, e.g. 5× or 10×.

4. **Integrating**—carries out the mathematical process of integration electronically e.g. gives a signal proportional to the area under a cardiac output dye dilution curve.

5. **Differentiating**—carries out the mathematical process of differentiation electronically, e.g. gives a signal which indicates the *rate* at which a pressure signal is changing with time.

6. **Frequency analyser**—these count impulses and can be used to display heart rate per minute.

Properties of Amplifiers

Stability—With continued use the response of electrical apparatus gradually changes and it is necessary to check the accuracy of the complete measuring system against known values.

Calibration of electrical devices should be carried out against known physical standards.

Pressure—Columns of water or mercury are connected to the transducer and the display scale adjusted accordingly. Zero is usually taken as the position when the transducer is open to atmosphere.

Volume—Electrical flow devices are checked against the time flow of fluid collected in a measuring cylinder—gas flow devices are checked by collecting gas over a known period in a reservoir and subsequently measuring the amount with a dry gas meter.

Temperature—electrical devices are checked against mercury thermometers.

Tension—is checked against known weights.

Gas tensions—O_2, CO_2 tensions are checked with a van Slyke apparatus.

Adjustments are available on transducers, amplifiers and recorders which enable the upper and lower points of the scale to be adjusted to correspond to the known physical standards.

Frequency response

The transducer, amplifier and recording system should respond to rapid changes in signal strength accurately. For practical purposes the system should be able to handle a frequency about 10× the frequency normally measured, e.g. pulse 100/minute —frequency response 0-1000/minute.

When measuring pressure, transducers and tubing which have large fluid volumes and heavy mechanical pen writers all have considerable inertia and cause damping of frequency response.

Recorders

Meters and direct writers

These are based on a moving coil galvanometer in which the signal passes through a coil suspended between the poles of a magnet. The coil develops a magnetic field which causes it to rotate by an amount proportional to the signal strength.

The degree of movement can be measured on a scale by means of a pointer attached to the coil.

A record of the movement may be obtained in two ways—

1. The coil is connected mechanically to a pen writer which traces the deflections on moving paper. The system is reliable and robust but the inertia of the moving parts makes it insensitive to rapid frequency change, e.g. ECG and EEG recorders.

2. A mirror is attached to the coil and a beam of reflected light traces the deflection on moving photographic paper, or indicates it on a scale. This system has a good high frequency response but is delicate.

Oscilloscope

This displays signals most accurately, and has the highest frequency response. A record of the signal may be obtained by photographing the image on the oscilloscope.

Both paper recording systems and oscilloscopes can have multiple channels which enable a number of signals to be displayed simultaneneously. The speed of the paper or sweep on the oscilloscope can be varied from a slow speed which compresses a number of signals into a small space, whilst faster speeds spread each signal out for detailed examination.

Finally, all electrical signals may be recorded on magnetic tape and displayed at a later time.

Computers

Computers have the ability to carry out mathematical processes at an extremely fast rate. They are therefore able to accept large quantities of information, and then display it in a way which would take an impossibly long time to acheive using mental arithmetic or desk calculators. The information to be analysed has to be processed in two electrical signals which the computer can respond to. There are two types of computer, analouge and digital.

Analouge Computers

These respond to variations in signal voltage, which represents the variation in a physical quantity, e.g. it will continuously analyse the varying electrical voltage produced by a blood pressure transducer.

The output voltage of the analouge computer represents the result of the calculations which the circuit has carried out on the input voltages. These may range from simple addition or substraction to integration and differention and many other mathematical processes.

Analouge computers are used in cardiac output monitors based on the dye dilution technique. The rise and fall of concentration of dye in the blood is fed into the computer in the form of a varying voltage. Since the computer has been calibrated against known dye concentrationt and voltages, it is able to calculate the average concentration of dye in a giaen time. If the original amount of dye injected is also known it can calculate the dilution and hence the cardiac output. This is carried out so rapidly that the cardiac output is displayed numerically as soon as the rise and fall of dye concentration is complete.

It is necessary to programme the analouge computer for the particular process which it is to analyse.

Simpler ones, such as the cardiac output calculator above are per set.

Larger computers have the facility for reprogramming and may be adapted for individual problems by incorporating the necessary sequence of mathematical equations.

Digital Computers

In this type of computer, information is dealt with in the form of impulses which represent the digits 0 to 9. Calculations are carried out in a manner similar to a desk calculator—multiply, divide, add, subtract. Information to be used by the computer must be coded usually in the form of holes purched into paper tape, which is then "read" by the computer and converted into electrical impulses. The sequence of impulses is stored either for immediate access in a 'magnetic block' or in slightly less accessible form on reels of magnetic tape. The instructions as to which calculation is to be applied to which set of digits are also stored in the form of a programme. A very simple programme might involve the sum 2+2. The instruction would say "Store the following: Store no. 100: 2, Store no. 101: 2. Begin calculation: add number in Store no. 100 to Number in Store 101. Place answer in Store 102. Print answer in Store 102. Stop."

The output from the computer can be used to drive a typewriter, or displayed on a television screen.

Since there an unlimited quantity of numbers it is possible to have a code system which represents all the letters of the alphabet. It is possible in this way to store patients hospital records including laboratory investigations in a digital computer.

Some examples of the use of computers in medicine are:

1. Calculation of cardiac output from dye dilution curves.
2. Analysis of each ECG complex to predict when cardiac arrhythmias are likely to develop.
3. Analysis of each arterial pressure trace as an indication of left ventricular contraction.
4. Analysis of frequency patterns of the EEG.
5. Patient monitoring, e.g. systolic and diastolic blood pressure, right and left artrial pressure, blood loss, intake and output of fluid and electrolytes and temperature. Results are stored and analysed continuously and any adverse trends are indicated.

Measurement of Intravascular Pressures

Pressure is force per unit area, and the simplest way of measuring it is to find the pressure which counterbalances a column of liquid. The pressure = height × density of liquid. This is usually expressed as mm mercury or cm water. (1 mm Hg = 13·6 cm H_2O).

Arterial pressure (Fig. 11.1)

(a) An aneroid blood pressure gauge may be connected directly to a needle inserted in an artery.

The whole system is filled with heparinised saline, and should be completely sterile. Because of inertia, only a mean arterial pressure will be indicated.

(b) Electrical pressure transducers.

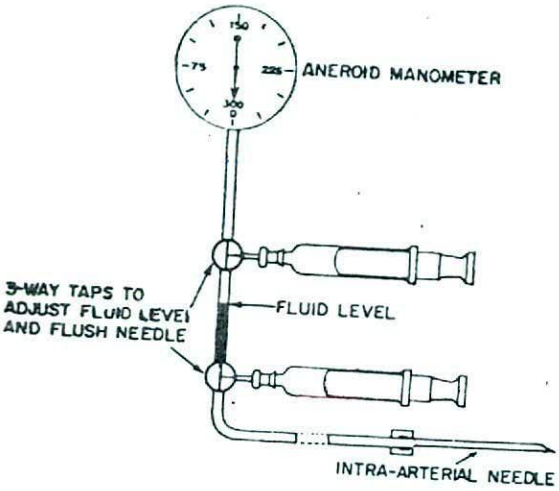


Fig. 11.1. Diagram showing direct measurement of arterial pressure.

(i) **Strain gauge**—modern ones incorporate a piezoelectric silicon crystal similar to a gramophone pick-up head (Figs. 11.2A & 11.2B).

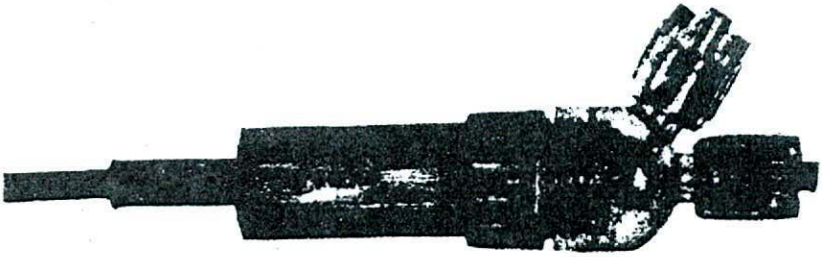


Fig. 11.2A.
Doppler blood pressure instrument.

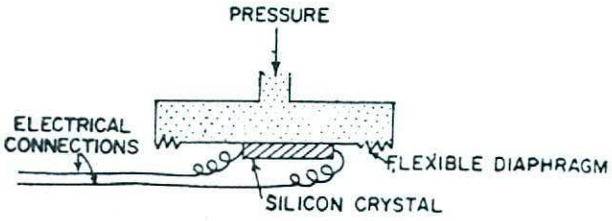


Fig. 11.2B.
Fig. 11.2A & 11.2B. Diagrams of silicon crystal strain gauge.

When this is distorted by the pressure acting on a diaphragm a voltage is produced which is proportional to the movement.

Silicon strain gauge transducers are robust reliable and small.

(ii) **Variable**—differential transformer pressure transducer. The metal core is adjusted so that it is symmetrical between the two coils on the output side. In this position the voltages in the two oppositely wound output coils balance. When the core is moved by the pressure on the diaphragm voltage variations are produced in the output coils proportional to the displacement from the zero point (Fig. 11.3).

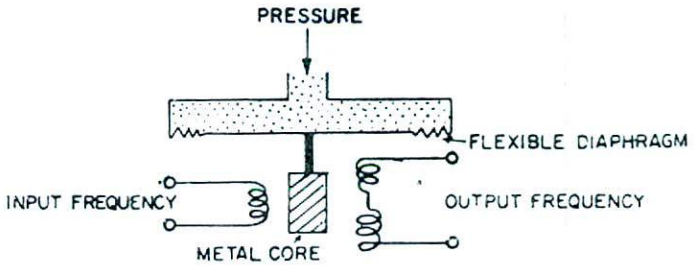


Fig. 11.3. Diagram of variable differential transformer pressure transducer.

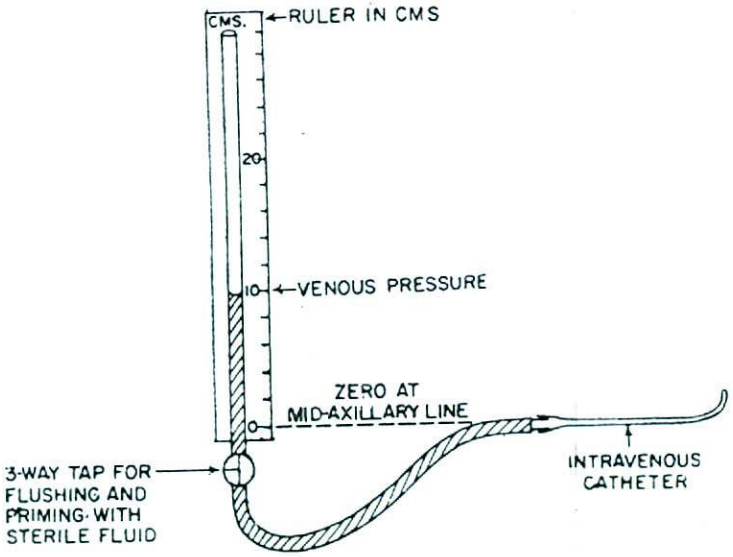


Fig. 11.4. Diagram of venous pressure measuring apparatus.

Venous pressure

This is usually taken to represent central venous pressure which is the pressure in the right atrium a position indicated by the mid axillary line when the patient is supine. A plastic intravenous catheter (Fig. 11.4) is inserted via an arm, neck or leg vein into the superior or inferior vena cava, and connected to a sterile saline filled manometer a plastic tube attached to a ruler marked in cms.

Normal venous pressure is 0—10 cm H_2O (0—8 mm Hg) and the meniscus in the manometer should swing gently with respiration.

An electrical transducer may also be used to measure venous pressure if it is designed to respond to low pressures.

Calibration of transducer systems (Fig. 11.5)

The transducer should be at the same level as the patient, otherwise artefacts due to hydrostatic pressure of the fluid in connecting tubing will occur. The zero point on the scale is adjusted when the transducer is open to atmosphere. The upper end of the scale is set against a column of saline or mercury.

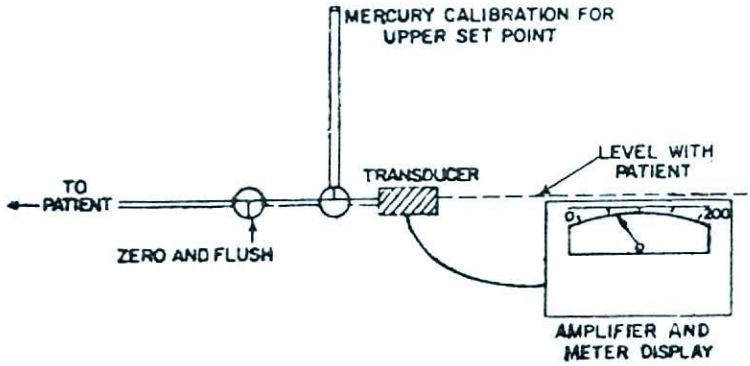


Fig. 11.5. Typical arrangement for measuring arterial blood pressure with an electric transducer.

Bubbles should be eliminated from all connecting tubing and the transducer, as they cause damping. If the trace is 'spiky' it is because the connecting fluid is vibrating at a similar frequency to the pressure change. Narrow connecting tubing and low volume transducers will help to minimise this.

Measurement of Flow

Flow is determined by measuring the volume of liquid or gas passing through a tube in a known time.

Liquids may be collected in measuring cylinders and gases in spirometers.

Gaseous flow

1. **Flow meters** (Fig. 11.6) are used to measure the instantaneous flow rates of a continuous stream of gas, the most useful type being the rotameter found on anaesthetic machines. This consists of a tapered glass tube with a needle valve at the bottom for adjusting the gas flow. A light bobbin floats in the gas stream as it passes up the tube and the position indicates the flow from calibrations on the tube. As the bobbin rises, the orifice surrounding it, through which gas flows, increases in area. This is a variable orifice flow meter, and the pressure drop at any flow is constant. Other types of flow meter are based on a constant orifice and the change in pressure across the orifice which occurs at different flow rates is proportional to the flow rate.

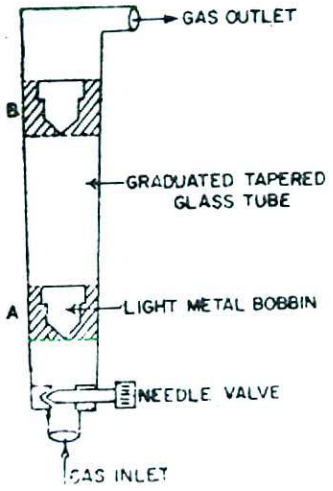


Fig. 11.6. Gas rotameter for measuring instantaneous gas flow.
Note: The shaded area at B is larger than A. Extra gas can pass bobbin for the same pressure gradiant-variable orifice, constant pressure gas flow meter.

2. **Pneumotachograph.** This device, based on the fixed orifice principle (Fig. 11.7) is used to measure the momentary high gas flow rates encountered during resuscitation. A flow meter would not respond quickly enough. The resistance consists of a cylinder containing a large number of parallel tubes. The pressure drops across the tubes is measured as the gas flows through it. The parallel tubes serve to keep gas flow laminar, since turbulent flow would invalidate the calculation. The pressures are usually measured by means of a differential pressure transducer which is designed in such a way that the electrical signal is proportional to the difference in pressure. The device is calibrated by-passing known flow rates through it. If the flow rate's signal is passed through a suitable integrating amplifier, the volume flow per minute can be obtained.

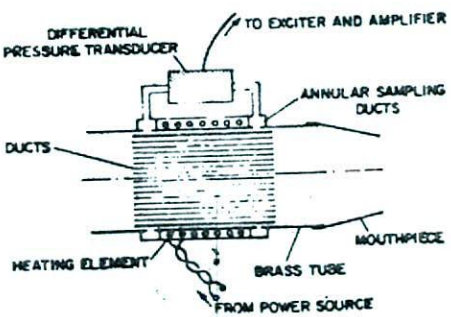


Fig. 11.7. Diagram shows pneumotachograph for in bereathing sudden changes in gas flow, as resuscitation. A constant orifice for resistance variable pressure flow meter.

Measurement of blood flow

Two types of instrument (Fig. 11.8.) are now being increasingly used to measure blood flow in vessels.

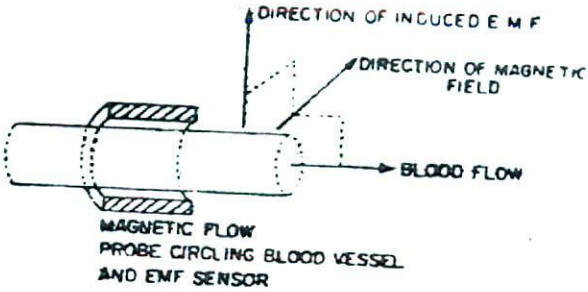


Fig. 11.8. Diagram illustrating principle of electromagnetic blood flow measurement.
N.B.—Flow, EMF, field are at right angles to each other.

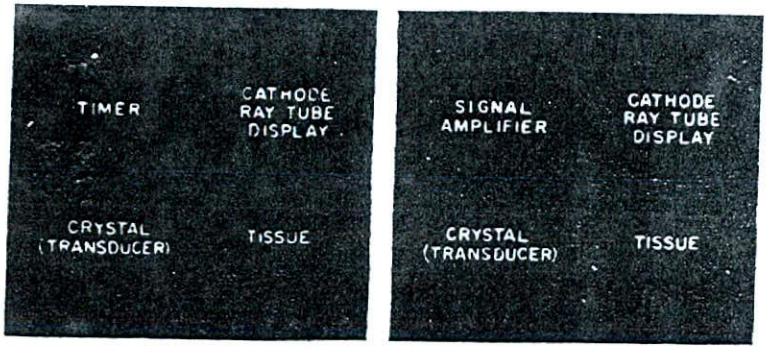
(a) **Electromagnetic blood flow meters**

These are based on the principle that blood is an electrically conducting medium; and that if it 'moves' or flows at right angles to a magnetic field then an e.m.f. will be induced in a plane at right angles to both the magnetic field and the direction of fluid flow. The magnitude of the induced EMF is proportional to the flow and by suitable electronic circuitry a direct readout of flow can be obtained. This method suffers from a number of disadvantages.

1. The probe head must be applied closely to the vessel, which must therefore be exposed surgically.
2. The vassel must be occluded for calibration.

Ultrasonic blood flow meters

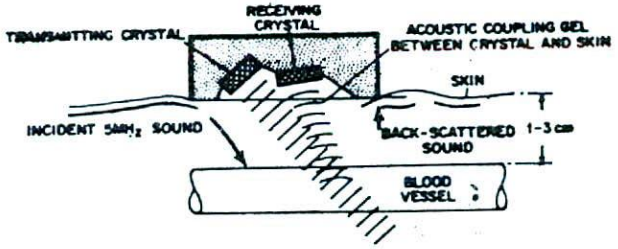
The basic principal of ultrasound process: the essential components are: a timer, a signal amplifier, a cathode ray display tube, a pulse generator, a transmitting and receiving crystal called a transducer (Fig. 11.9).



(a) Diagrm of ultrasound transmission. (b) Diagram of ultrasound echo reception.
Fig. 11.9.

The timer sends an electrical signal to the transmitting crystal which converts the electrical energy into a pulse of sonic energy and transmits it into the tissue being examined. At the same time this timing signal is displayed on the oscilloscope.

Ultrasound is transmitted in very brief pulses followed by a listening interval during which echoes are displayed in relationship to actual distances in soft tissue. When a pulse strikes a boundary between two substances with different acoustic impedance, some energy is reflected. The echoes are reflected to the crystal, which now acts as a receiver and converts the sonic energy back into electrical energy. This signal is then amplified and displayed on the oscilloscope. A small probe is placed near to a vessel, and electric crystal are used to transmit a beam of high frequency sound across the vessel. The beam is reflected back from tissue structures, and also the red blood corpuscles as they flow along the vessel. The frequency of the signal reflected from the moving corpuscles is altered due to the Doppler effect and is proportional to the velocity of flow. The reflected signals are detected and by analysing the Doppler shift an estimate of the flow rate of the blood can be obtained (Fig. 11.9A).



Doppler shift principle of blood velocity sensing.
Fig. 11.9A.

Thermodilution technique for measurement of cardiac output

An account of the method of measuring cardiac output by the dye dilution technique is given in another part of the book. It is possible to estimate cardiac output by rapidly injecting about 4 ml of water at 0·5°C into the right atrium or right ventricle via a catheter and measuring the temperature of the blood in the pulmonary artery by means of a thermometer probe catheter. The difference in temperature will be determined by the flow of blood between the injection point and the measuring point, i.e. the cardiac output. It is assumed that the water passes between the two points as a bolus. The calculations are based on the principle that in order to raise the temperature of a known volume of the water, a certain number of calories must be supplied by the blood, during the time in which the water passes from the site of injection to the site of temperature measurment. The temperature and specific heat of blood are known and hence the volume passing these sites in the time between injection and measurement can be calculated. The advantage of this method is that there is no recirculation of the bolus, as it rapidly equiliberates to body temperature. It is therefore possible to give up to 40 injections to one patient.

Gas analysis

The two gases whose concensration is most likely to be measured in medicine are CO_2 and oxygen. Chemical analysis of the concentrations of these gases is carried out by means of van Slyke's apparatus, which is accurate but difficult to use. Physical analysis of gas mixtures may be carried out more simply by a number of electromechanical devices, which should always be checked for accuracy against the more laborious chemical methods.

Nitrogen meter (Fig. 11.10).

This is used to measure the nitrogen concentration in expired air during respiratory function tests. It is based on the principle that all gases emit characteristic electromagnetic radiations when subjected to high voltage in a discharge tube. The gas sample is drawn through a gas

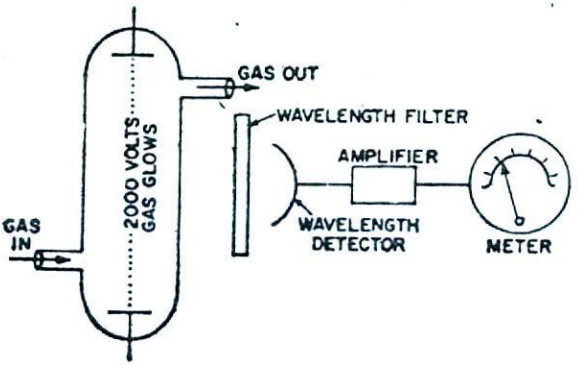


Fig. 11.10. Diagram showing nitrogen meter.

tube where it is subjected to a 2000 volt discharge. This ionises the gas which glows, emitting light of wavelengths of individual molecules, and the strength of signal is proportional to the concentration of that gas. This technique is normally used for measuring N_2 concentration in gas mixtures.

Chemical methods of gas analysis

The accuracy of all electronic techniques of gas analysis must ultimately be varified by means of techniques based on chemical or physical methods. The Haldane apparatus is used to measure oxygen and carbon dioxide either in gas mixtures or in blood. In the case of blood, the gases dissolved are first released by mixing the sample with acid to release CO_2, oxygen with potassium ferricyanide, and nitrogen by low vacuum. The principle of the apparatus is that the volume of the gas sample is measured in a gas burette, the CO_2 is absorbed in KOH solution and the shrinkage in volume measured; then the oxygen is absorbed by alkaline pyrogallate, and the further volume loss measured. The residual volume is nitrogen. The whole analysis is conducted at constant temperature and pressure.

Infra red CO_2 analyser

All gases also absorb electromagnetic radiations, the wavelength again being characteristic for each gas. By the use of suitable filters the

response of the instrument can be made specific for a particular gas, e.g. CO_2.

Infra red light is directed down two tubes each of which has a detector at the end. The gas for analysis is circulated through a chamber inserted

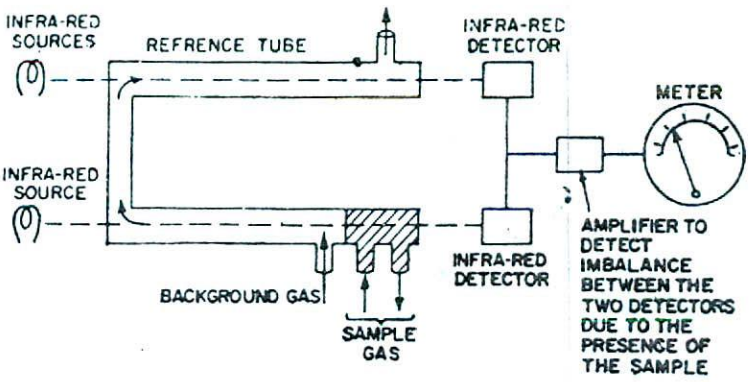


Fig. 11.11. Diagram showing infra red carbon dioxide analyser.

into one of the tubes and absorbes infra red light proportional to the gas concentration. The difference in radiation measured by the two detectors is proportional to the gas concentrate.

Unfortunately there is often ovrelap in the absorption wavelengths of different gases, e.g. nitrous oxide interferes with CO_2 absorption.

Paramagnetic oxygen analysis (Fig. 11.12)

Oxygen is strongly paramagnetic, i.e. it is attracted into a magnetic field. An instrument which makes use of this property to measure oxygen concentration in gases consists of a powerful magnetic with a fine glass

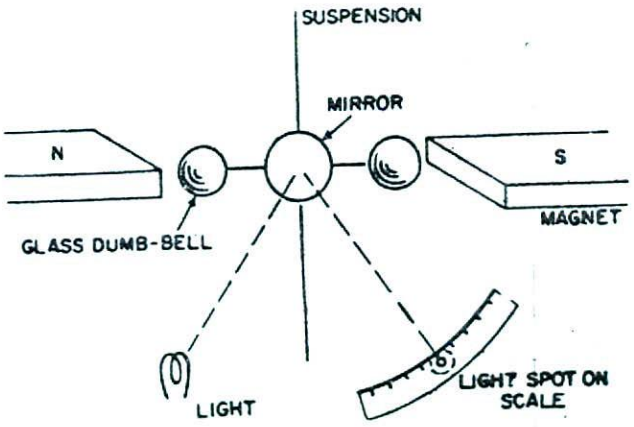


Fig. 11.12. Diagram showing principle of paramagnetic oxygen analyser.

dumbell, filled with nitrogen, suspended by a delicate quartaz thread between the poles of the magnet. Rotation of the dumbell is detected by movement of a light beam reflected in a mirror.

If oxygen is present in a gas sample introduced into the sample chamber which incorporates the spheres, it will concentrate between the poles of the magnet and displace the glass spheres.

Mass spectrometer (Fig. 11.13)

This instrument separates each gas in a mixture according to its molecular weight. The gas mixture is drawn into an ionisation chamber where it is ionised by bombarding it with electrons. A narrow beam of

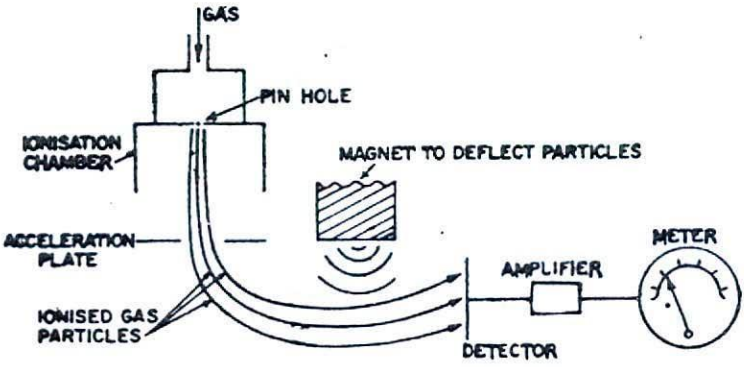


Fig. 11.13. Diagram showing principle of a gas mass spectrometer.

charged particles is accelerated out of the chamber by a high voltage, and then deflected by a different degree than lighter molecules. A detector is used to sample the beam and determine the deflection at each point.

Blood gas analysis

Measurement of hydrogen ion concentration is dealt with elsewhere, and this section will be confined to the description of apparatus used for measuring CO_2 and O_2 tension in blood or gases.

CO_2 electrode (Fig. 11.14)

This is basically a pH sensitive electrode separated from the sample by a membrane which is premeable to CO_2. As the CO_2 diffuses across the membrane it dissolves in the bicarbonate solution sorrounding the pH electrode causing a change in hydrogen ion concentration which can then be measured

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

The electrode is surrounded by a water jacket which maintains it at 37°C, i.e. body temperature.

Calibration is carried out with two gases containing known concentrations of CO_2. The electrode is reliable providing the membrane is not

allowed to dry out between use, when it is likely to develop holes and then requires replacing.

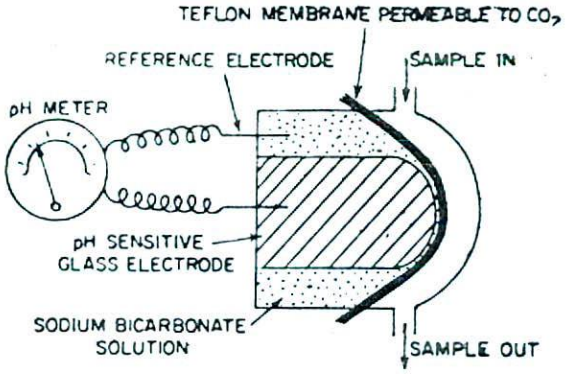


Fig. 11.14. Diagram showing principle of a CO_2 electrode.

Oxygen electrode (Fig. 11.15).

This is superficially similar to the CO_2 electrode in that it contains an electrode separated from the sample by a membrane.

The membrane is permeable to oxygen but not liquids. A small voltage 0·6 volts is applied between the platinum wire cathode sealed in the glass, and the anode in the surrounding electrolyte. This causes

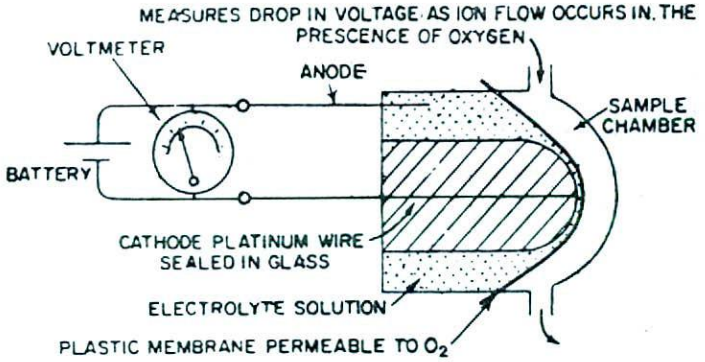


Fig. 11.15. Diagram showing principle of O_2 electrode.

electrons to pass from the cathode to combine with any oxygen molecules present reducing them to water, a process called polarisation. The area around the cathode is therefore at zero oxygen tension. If oxygen molecules diffuse into this area, more electrons pass from the cathode to reduce them. Since a flow of electrons is an electric current, a voltage drop occurs in the circuit which is indicated by a sensitive voltmeter. The voltmeter can be calibrated to represent oxygen tensions by putting gas samples of known oxygen tension into the sample chamber. Nitrogen

or deaerated water can be used to establish the zero point, and air, or oxygen for points higher up the scale.

Gas Chromatography

This technique of identifying chemical compounds is superficially similar to paper chromatography. In the latter, the substances in solution migrate across filter paper at a rate and distance depending on their individual molecular weight, and therefore accumulate at different places on the paper where they can be identified. Separation of different chemical substances in gas chromatography depends on the differing solubilities of the compounds in a solvent over which they pass. The solvent is absorbed onto inert powder in a metal column. The compounds under test are momentarily introduced into a carrier gas which is passing through the column. The substances will initially dissolve in the solvent on the powder according to their solubilities. Since the sample is only introduced momentarily, further flow of gas will results in compounds being progressively taken up and carried through the column. Highly soluble substances will be delayed longest, and least soluble substances will be carried through first. The column is a delaying device which makes use of the differing solubilities of the compounds under test. The gas from the column is passed through a detector which will indicate in sequence the concentration of each compound as it emerges. A chart recorder will show a series of peaks or waves indicating different substances. The machine is calibrated by injecting known compounds in known concretations so that the peaks on the recorder can be identified and calibrated. Gas chromatography is used to analyse anaesthetic and respiratory gases in mixtures, and for the determination of the contents of gases in blood samples.

Oximetry

Measurement of the degree of oxygen saturation of haemoglobin is determined by an oximeter which detects the light transmitted or reflected by red cells. This instrument consists of a light source, filters, a sample chamber, and a means for detecting the intensity of the reflected or transmitted radiation. The light and filters are selected to match the absorption characteristics of oxyhaemoglobin and reduced haemoglobin which incidentally differ widely at a wavelength of 650 nm (nanometers). At 650 nm HbO_2 absorbs far less light than reduced Hb. A control reading is taken at 800 nm at which point Hb and HbO_2 have equal absorption characteristics, and the difference between this and the sample level indicates the proportion of Hb and HbO_2

Oximeters are used to detect intracardiac shunts during cardiac catheterisation for the diagnosis of congenital heart lesions. By altering the filters they can also be made to detect the concentrations of dye injected into the circulation for estimation of the cardiac output.