

Physics & Measurement

PRESSURE

Def'n: Newton (N): the force that will accelerate a mass of 1 kg at 1.0 m.s^{-2}
Gravity (g): 9.81 m.s^{-2}
Pascal (Pa): $1 \text{ Pa} = 1 \text{ N acting over an area of } 1 \text{ m}^2$

- therefore, the force of gravity on 1 kg will be 9.81 N
- so, 1 newton is equivalent to $1/9.81 \text{ kg} = 102 \text{ gram weight}$
- 102 g acting over a square metre is small and cumbersome \rightarrow kPa
- atmospheric pressure at sea level = 101.325 kPa
= 760 mmHg

Def'n: 1 kPa = $10.2 \text{ cmH}_2\text{O}$
= 7.5 mmHg \rightarrow mercury is 13.6 times as dense as water

Def'n: 1 bar = 100 kPa
= 750 mmHg

FLUID FLOW

Laminar Flow

$$\dot{Q} = \frac{\pi r^4 \cdot \delta P}{8\eta l}$$

Hagen-Poiseuille Equation

but as $R = \delta P / Q$, so

$$R = \frac{8\eta l}{\pi r^4}$$

- where,
 1. *eta* (η) = the *viscosity* of the fluid in pascal seconds
 2. there are no eddies or turbulence
 3. flow
 - i. is greatest at the centre, being \sim twice the mean
 - ii. near the wall $\rightarrow 0$
 - iii. is directly proportional to the driving pressure

Turbulent Flow

- the velocity profile across the lumen is lost
- flow becomes directly proportional to the **square root** of the driving pressure

NB: therefore, as pressure flow is not linear, **resistance** is not constant, and the flow at which the resistance is measured must be specified

- other factors in turbulent flow may be summarized,

$$\dot{Q} = \frac{k \cdot r^2 \cdot \sqrt{\delta P}}{\rho l}$$

where, k = a constant
 r = **rho**, the density of the fluid in kg.m⁻³

- thus, radius has less of an effect on turbulent flow
- the likelihood of the onset of turbulent flow is predicted by,

$$\text{Reynold's number (Re)} = \frac{\rho v d}{\eta}$$

- where, d = the diameter of the tube
 v = the velocity of flow
 ρ = **rho**, the density of the fluid in kg.m⁻³
 η = **eta**, the viscosity of the fluid in pascal seconds

- empirical studies show that for cylindrical tubes, if Re > 2000 turbulent flow becomes more likely
- for a given set of conditions there is a **critical velocity** at which Re = 2000

■ Clinical Aspects

- thus the transition from laminar to turbulent flow depends on the mixture of gases present
- in the patient's airway the gases are humidified, contain CO₂ and are warmed
- the net effect is an increase in the critical velocity, due to a reduction in density due to warming of the gases
- for a typical anaesthetic mixture, critical flow (l/min) ~ airway diameter (mm)

- as breathing is cyclical, with peak flows > 50 l/min, turbulent flow usually predominates during peak flow, while laminar flow is present during other times in the respiratory cycle
- due to the great reduction in velocity in the bronchi and smaller airways, flow through them tends to be laminar
- in general, during quiet breathing flow tends to be laminar, while during speaking, coughing, or deep breathing flow becomes turbulent in the larger airways

Tension

▪ Laplace's Law

$$P = T.h.(1/r_1 + 1/r_2)$$

thus, for straight tubes,

$$P = T.h./r$$

and, for spheres,

$$P = \frac{2T.h}{r}$$

where, **T** = the tangential force in N/m, acting along a length of wall
 h = the thickness of the wall (usually small)

- thus, as the diameter of a vessel becomes smaller, the collapsing force becomes greater
- this can lead to vessel closure at low pressures, the **critical closing pressure**
- also seen in alveoli, leading to instability with small alveoli tending to fill larger ones
- however, due to the action of surfactant alveolar stability is maintained

Viscosity

- for a given set of conditions, flow is inversely proportional to viscosity
- blood viscosity increases with,
 - a. low temperatures
 - b. increasing age
 - c. cigarette smoking
 - d. increasing haematocrit
 - e. abnormal elevations of plasma proteins
- this may be reduced with low MW dextran
- the viscosity of blood is anomalous due to the presence of cells, and its behavior is non-newtonian

The Bernoulli Principal

- based on the principal of *conservation of energy*, the total energy of a fluid flow is given by,

$$E = PV + mgh + \frac{1}{2}mv^2$$

where,

PV	=	the potential energy of <i>pressure</i>
mgh	=	the potential energy due to <i>gravity</i>
$\frac{1}{2}mv^2$	=	the kinetic energy of <i>motion</i>

- thus, as the velocity of flow increases passing through a narrowing and the velocity increases, so the pressure decreases
- also, for a system to work efficiently, laminar flow is important as turbulence would allow flow energy to be lost as heat
- this is the principal of operation of a venturi, where the opening of a side tube leads to the entrainment of another fluid
- the *entrainment ratio* ER is defined as,

$$ER = \text{Entrained Flow} / \text{Driving Flow}$$

- when there is no opening on the side of a narrowing in a tube, a region of low pressure is established and the stream tends to adhere to the wall
- if the tube then diverges, the stream may adhere to either wall, diverting flow to one or other lumen, the Coanda effect
- valves can be constructed on this mechanism using fluid logic, a control nozzle being located just distal to the divergence of the lumen
- unfortunately these are wasteful and noisy

THE GAS LAWS

■ Boyle's Law

- at a constant temperature, the volume of a given mass of gas varies inversely with its absolute pressure, or,

$$PV = k_1$$

■ Charles's Law

- at a constant pressure, the volume of a given mass of gas varies proportionately to its absolute temperature, or,

$$V/T = k_2$$

■ The Third Perfect Gas Law

- at a constant volume, the absolute pressure of a given mass of gas varies proportionately to its absolute temperature, or,

$$P/T = k_3$$

■ Dalton's Law Of Partial Pressures

- in a mixture of gases, the pressure exerted by each gas is equal to the pressure which would be exerted if that gas alone were present

■ Avogadro's Hypothesis

- equal volumes of gases, at the same temperature and pressure contain equal numbers of molecules

■ Henry's Law

- at a constant temperature, the amount of a given gas dissolved in a given liquid is directly proportional to the partial pressure of that gas in equilibrium with that liquid

STP: $T = 273.15 \text{ K}$ (0°C)
 $P = 101.325 \text{ kPa}$ (760 mmHg)

■ A Mole (Mol)

- is the quantity of any substance containing the same number of particles as there are atoms in 0.012 kg of ^{12}C Carbon,

$$1 \text{ mol} \sim 6.022 \times 10^{23} \quad \text{Avogadro's number}$$

- for any gas at STP, $1 \text{ mol} \sim 22.4 \text{ litre}$

■ Universal Gas Constant (R)

- for 1 mol of any perfect gas, $R = PV/T$
- where n = number of mol of gas, $PV = nRT$

■ Critical Temperature

- is the temperature above which a gas cannot be liquified by pressure alone
 - i. $\text{N}_2\text{O} = 36.5\text{ }^\circ\text{C}$
 - ii. $\text{O}_2 = -119\text{ }^\circ\text{C}$

■ Critical Pressure

- is the pressure at which a gas liquifies at its critical T
 - i. $\text{N}_2\text{O} \sim 73\text{ bar @ } 36.5\text{ }^\circ\text{C}$
 - ii. $\text{N}_2\text{O} \sim 52\text{ bar @ } 20.0\text{ }^\circ\text{C}$

A Gas: a substance in the gaseous phase *above* its critical T

A Vapour: a substance in the gaseous phase *below* its critical T

■ Pseudo-Critical Temperature

- for a mixture of gases at a *specific pressure*, the *specific temperature* at which the individual gases may separate from the gaseous phase
 1. $\text{N}_2\text{O } 50\% / \text{O}_2\text{ } 50\% = -5.5\text{ }^\circ\text{C}$ for cylinders (most likely at 117 bar)
 2. $\text{N}_2\text{O } 50\% / \text{O}_2\text{ } 50\% = -30\text{ }^\circ\text{C}$ for piped gas

Filling Ratio: = $\frac{\text{the mass of the gas in the cylinder}}{\text{the mass of water which would fill the cylinder}}$

$$\text{N}_2\text{O} = 0.65 \quad (\text{UK})$$

■ Adiabatic Change

- the change of physical state of a gas, without the transfer of heat energy to or from the surrounding environment
- in rapid *expansion*, energy is required to overcome Van der Waal's forces of attraction, as this energy cannot be gained from the surroundings, it is taken from the kinetic energy of the molecules → basis of the *cryoprobe*
- in rapid *compression*, the energy level between molecules is reduced, as this energy cannot be dissipated to the surroundings, it is transferred to the kinetic energy of the molecules

SOLUBILITY

■ Bunsen Solubility Coefficient

Def'n: the volume of gas, corrected to **STP**, which dissolves in one unit volume of the liquid at the temperature concerned, where the partial pressure of the gas concerned is 1 atmosphere

■ Ostwald Solubility Coefficient

Def'n: the volume of gas which dissolves in one unit volume of the liquid at the temperature concerned

- i. the **temperature** must be specified
- ii. it is independent of **pressure**
 - as the pressure rises the number of molecules of gas in the liquid phase increases, however, when measured at the higher pressure the volume is the same

■ Partition Coefficient

Def'n: the ratio of the amount of a substance present in one phase as compared with than in another, the two phases being of **equal volume**, the **temperature** must be specified and the phases in **equilibrium**

DIFFUSION & OSMOSIS

■ Diffusion

- the spontaneous movement of molecules or other particles in *solution*, owing to their random *thermal motion*, to reach a uniform concentration throughout the solvent

■ Fick's Law

- the rate of diffusion of a substance across a unit area is proportional to the *concentration gradient* for that substance
- further, the diffusion of gas across a membrane, or into or out of a liquid, is proportional to the gases solubility in the liquid
- CO₂ being more soluble than O₂ diffuses far more rapidly across the alveolar membrane and into the RBC
- N₂O being far more soluble than N₂ may diffuse into and expand closed cavities during induction of anaesthesia

■ Graham's Law

- the rate of diffusion of a gas is inversely proportional to the square root of the *molecular weight*
- this only applies to simple models and is inaccurate when dealing with complex biological membranes

■ Osmosis

- the movement of *solvent* across a semipermeable membrane, down a *thermodynamic activity* gradient for that *solvent*

■ Osmotic Pressure

- the pressure which would be required to *prevent* the movement of *solvent* across a *semipermeable membrane*, down a thermodynamic activity gradient for than solvent
- 1 mol of any solute dissolved in 22.4 litres of solution at 0°C will generate an osmotic pressure of 1 atmosphere
- in mixed solutions the osmotic pressure is the sum of the individual molarities
- over 99% of the plasma osmolarity is due to *electrolytes*, the contribution of the plasma proteins being only ~ 1 mosmol/l
- normal rbc's lyse at osmolarities ≤ 200 mosmol/l
- as capillaries are relatively impermeable to protein, this generates an osmotic pressure difference between the plasma and the interstitial fluid, the plasma *oncotic pressure* ~ **26 mmHg**

■ Osmolality

- the number of osmotically active particles (osmoles) per kilogram of solvent
- the depression of the freezing point of a solution is directly proportional to the osmolality, 1 mol of a solute added to 1 kg of water depresses the freezing point by 1.86°C
- the presence of increased amounts of solute also lowers the vapour pressure of the solvent, viz.

■ Raoult's Law

- the depression or lowering of the *vapour pressure* of a *solvent* is proportional to the molar concentration of the *solute*
- as the presence of a solute decreases the vapour pressure, making the solvent less volatile, so the boiling point is raised

NB: these phenomena,

- i. depression of *freezing point*
- ii. depression of *vapour pressure*, and
- iii. elevation of *boiling point*

being related to osmolality are termed *colligative properties* of a solution

■ An Azeotrope

- is a *mixture*, from which the component liquids vaporise in the same proportions as the molar ratios in the mixture
- *ether & halothane* form an azeotrope when the volume and the molar concentration ratios are both **1:2**
- alcohol & water form an azeotrope when the volume % alcohol is ~ 96%
- this makes it impossible to prepare alcohol solutions over 96% by *fractional distillation*

WORK, ENERGY & POWER

Def'n: *work* is done when the point of application of a force moves in the direction of that force;

one joule of work is done when a force of *1 newton* moves its point of application *1 metre* in the direction of the force

- as most work in the body is performed by muscular contraction, the amount of work is the product of the distance of shortening and the mean force exerted
- for fluid flow this may be converted to pressure and volume, viz.

$$W = F.s$$

but $P = F/A$, therefore
and $V = A.s$, therefore
thus,

$$\begin{aligned} F &= P.A \\ s &= V/A \\ W &= P.A \times V/A \end{aligned}$$

or
$$W = P.V$$

Work of Breathing

- thus, for respiration the work performed is given by the area of a pressure-volume loop
- ie., the cumulative product of pressure-volume of air moved each instant,

$$W = \frac{\delta P . \delta V}{\delta t}$$

- this is required to overcome both *elastic* and *non-elastic* resistance to breathing,

- elastic resistance ~ 65%
- non-elastic resistance ~ 35% → 80% airway
20% viscous

- as airway resistance, or inspiratory flow rate increased, so would δP_{ip} , effectively sloping curve to right increasing total and viscous work

1. as respiratory *frequency* increases → flow rates & viscous drag increase
2. as *tidal volume* increases → elastic work area increases

NB: therefore, patients with stiff lungs → small shallow breaths
patients with airways obstruction → long deep breaths

as both of these patterns tend to *decrease* the work of breathing

Metabolic Work of Breathing (O₂ cost of breathing)

- expressed as ml of O₂ (additional O₂ consumption)/l ventilation
- this is low during quiet breathing
- increases with increasing ventilation, especially with pulmonary disease

O₂ cost of quiet breathing ~ 0.5 to 1.0 ml.O₂/l ventilation
or, ~ 1-2% of basal MRO₂ (250 ml/min)

■ Mechanical Efficiency

$$= \frac{\text{useful work}}{\text{total energy expended (O}_2 \text{ used)}} \times 100$$
$$\sim 5 \text{ to } 10\%$$

■ Power

- is the **rate of work**, measured in watts, 1 watt being 1 joule per second,

$$W = J.s^{-1}$$

- the power requirement of breathing depends upon the type of flow
- as work = P.V, so for
 - a. laminar flow, where $P \propto V$, then power $\propto V^2$
 - b. turbulent flow, where $P \propto V^2$, then power $\propto V^3$
- therefore, the power dissipation as fluid flows through a tube is proportional to the square and cube of the flow rate
- this does not allow for the **kinetic** component of fluid flow, however, for most physiological examples the kinetic energy component is negligible

Work of Myocardial Contraction

- similarly this is given by the area of a pressure-volume loop
- thus, work approximates 16 kPa (120 mmHg) x 60 ml,

$$\begin{aligned}\text{Work done} &\sim (16 \times 10^3) \text{ Pa} \times (60 \times 10^{-6}) \text{ m}^3 \\ &= 0.960 \text{ J} \\ &= \mathbf{960 \text{ mJ}}\end{aligned}$$

- therefore, each contraction requires just under 1 J of work

NB: if the HR = 60, the the power output of the LV = 1 J/s = **1 W**

- this can also be calculated from the mean pressure (12 kPa) and flow,

$$\begin{aligned}E' &= P \times V' \\ &= (12 \times 10^3) \text{ Pa} \times (5 \times 10^{-3}/60) \text{ m}^3/\text{s} \\ &= 1 \text{ W}\end{aligned}$$

- for the RV this would be,

$$\begin{aligned}E' &= (2.4 \times 10^3) \times (5 \times 10^{-3}/60) \\ &= 0.2 \text{ W}\end{aligned}$$

- thus, the total power of the heart ~ 1.2 W
- given the average efficiency of the heart ~ 15%, then the total energy requirement of the heart would be 8 W
- this approximates 10% of the basal MRO_2 , which ~ 80 W
- energy is also required to provide the *kinetic energy* of flow, however this is small at rest
- as power is the *product* of pressure and flow, increases in either the mean arterial pressure or the cardiac output will significantly raise the myocardial MRO_2

TEMPERATURE

■ Heat

Def'n: a form of energy, being the state of *thermal agitation* of the molecules of a substance, which may be transferred by,

- i. **conduction** through a substance
- ii. **convection** by a substance, and
- iii. **radiation** as electromagnetic waves

■ Temperature

Def'n: is the physical state of a substance which determines whether or not the substance is in *thermal equilibrium* with its surroundings, heat energy being transferred from a region of higher temperature to a region of lower temperature

- alterations in the temperature of a substance, through the addition or removal of heat energy, also leads to alterations of the physical properties of the substance
- thus, mercury expands when heated and this was used by Fahrenheit to construct the first temperature scale

■ Kelvin

- the SI unit of thermodynamic temperature
- equal to **1/273.16** of the absolute temperature of the *triple point* of water

→ the temperature at which ice, water and water vapour are all in *equilibrium*

■ Celsius Scale

- Temperature (K) = Temperature (°C) + 273.15
- therefore, on the Celsius scale the triple point of water is 0.01 °C

Measurement - Non-electrical

- a. mercury thermometers
 - accurate, reliable, cheap
 - readily made in maximum reading form
 - easily made into a thermostat
 - low coefficient of expansion and requires 2-3 mins to reach thermal equilibrium
 - unsuitable for insertion in certain orifices
- b. alcohol thermometers
 - cheaper than mercury
 - useful for very low temperatures, mercury \rightarrow solid at -39°C
 - unsuitable for high temperatures as alcohol boils at 78.5°C
 - expansion also tends to be less linear than mercury
- c. bimetallic strips
- d. Bourdon gauge \rightarrow pressure

Measurement - Electrical

- a. resistance thermometer
 - electrical resistance of a metal *increases* linearly with temperature
 - frequently use a platinum wire resistor, or similar
 - accuracy improved by incorporation in a Wheatstone bridge
- b. thermistor
 - made from a small bead of metal oxide
 - unlike normal metals, the resistance falls exponentially with temperature
 - may be made exceedingly small and introduced almost anywhere
 - rapid thermal equilibration
 - narrow reference range and require different thermistors for different scales
 - accuracy improved by incorporation in a Wheatstone bridge
 - calibration may be changed by exposure to severe temperatures, eg. sterilization
- c. thermocouple
 - based on the Seebeck effect
 - at the junction of two dissimilar metals a small voltage is produced, the magnitude of which is determined by the temperature
 - metals such as copper and constantan (Cu+Ni)
 - requires a constant reference temperature at the second junction of the electrical circuit
 - may be made exceedingly small and introduced almost anywhere

Body Temperature

- humans, like all mammals and birds are *homeothermic* and control their body temperature within a narrow range = $37 \pm 0.5 \text{ }^\circ\text{C}$
- normal circadian rhythm varies temperature by $0.4 \text{ }^\circ\text{C}$, being lowest in the early am. and highest in the evening
- also varied with the menstrual cycle, basal temperature increasing in the second half of the cycle after ovulation
- body is divided into zones,
 - a. central core $\sim 37 \text{ }^\circ\text{C}$
 - b. intermediate zone
 - c. shell $\sim 2.5 \text{ cm}$ $\sim 32\text{-}53 \text{ }^\circ\text{C}$

■ Heat Production

- in the average male under resting conditions $\sim 50 \text{ W.m}^{-2}$, or 80 W total
- increases of the BMR occur after food, with exercise etc.
- also, the BMR rises when there is an increase in the core temperature
- there is no mechanism for a reduction in heat production to compensate for overheating
- increased heat production can be achieved by shivering and voluntary muscular activity

■ Heat Loss

- there are four routes of heat loss from the body,
 - a. radiation $\sim 40\%$
 - b. convection $\sim 30\%$
 - c. evaporation $\sim 20\%$
 - d. respiration $\sim 10\%$
 - humidification 8%
 - heating of air 2%
- **conduction** is not an important means of heat loss in humans as gases are poor conductors
- radiation is predominantly in the *infrared* spectrum and is determined by the temperature difference between the body and surrounding objects
- the amount of heat loss by evaporation may be increased up to 10 fold by sweating
- all of these mechanisms depend upon the surface area of skin exposed to the environment
- thus, if this area is reduced heat loss is minimized

■ Specific Heat Capacity

- the heat required to raise the temperature of 1 kg of a substance by 1 K (J/kg/K)
 - i. water SHC = 4.18 kJ/kg/K or, 1 kcal/kg/K
 - ii. blood SHC = 3.6 kJ/kg/K
- infusion of 2000 ml of blood at 5°C, requiring warming to 35°C, would therefore require,
$$2 \text{ kg} \times 3.6 \text{ kJ/kg/}^\circ\text{C} \times (35-5)^\circ\text{C} = 216 \text{ kJ}$$
- this would result in the person's temperature falling by ~ 1°C

■ Heat Capacity

- the heat required to raise the temperature of a given object by 1 K (J/kg/K)
- for a human the individual SHC's can be approximated to a mean value ~ 3.5 kJ/kg/K
- thus, the heat capacity for a 70 kg person would ~ 245 kJ

■ Specific Heat Capacity - Gases

- gases have very low SHC's which are usually expressed per unit *volume* rather than per kg,
 - Air ~ 1.01 kJ/kg/K
 - Air ~ 1.20 J/l/K (ie. ~ 1/1000th)
- therefore, only very small amounts of heat are gained or lost when the temperature of a small volume of gas is altered
- for an intubated patient with a tracheal temperature of 34°C, a minute ventilation of 7.0 l/min and a room temperature of 20°C, the heat lost from the patient would be,

$$\begin{aligned}\text{Heat Loss} &\sim 7.0 \text{ l/min} \times 1.2 \text{ J/l/}^\circ\text{C} \times 14^\circ\text{C} \\ &= 118 \text{ J/min} \\ &= 1.96 \text{ W}\end{aligned}$$

- this is insignificant compared with the basal heat production of 80 W
- however, greater losses are encountered if the air must be humidified due to the latent heat of vaporisation of water

■ Specific Latent Heat

- the heat required to convert 1 kg of a substance from one phase to another at a given temperature = *latent heat of vapourization*
= *latent heat of fusion*
- the LHV of water at 100°C = 2.26 MJ/kg
- at body temperature, the LHV of water = 2.42 MJ/kg
- therefore, the lower the temperature the greater the latent heat required
- as temperature rises, the latent heat falls until ultimately it reaches zero at a point which corresponds with the *critical temperature*

■ Latent Heat In Anaesthesia

- vaporisation of ethyl chloride → skin cooling and local anaesthesia
- vaporisation of volatile anaesthetics results in cooling & lowering of saturated vapour pressure
- compensatory mechanisms are then required to ensure a constant vapour pressure
- rapid emptying of a N₂O cylinder results in cooling and a steady decrease in the cylinder pressure
- this returns to 52 bar if the cylinder is closed and allowed to reheat
- carbon dioxide and cyclopropane are also stored as liquids but the rate of use is too slow to significantly reduce the liquid temperature
- liquid oxygen is stored in containers at about -160°C as its critical temperature is -119°C
- the pressure inside the vessel is set at ~ 7 bar which is the vapour pressure of oxygen at -160°C
- this is then passed through a superheating coil and regulated to a pipeline pressure of ~ 4.1 bar
- no refrigeration is needed as the contents are kept cool by the LHV of the oxygen
- if no oxygen is used the temperature and pressure rise above the setting of a safety valve, oxygen is then blown off, cooling the remaining contents
- if the usage rate is greater than the rate of vaporisation, a low pressure valve allows liquid oxygen to flow directly into the superheating coil, increasing the rate of vaporisation

■ Heat Lost From The Patient

- for a person breathing dry gas at a minute ventilation of 7 l/min with an upper airway humidity of 34 mg/l, then

$$\begin{aligned}\text{Total water vapourized} &= 7.0 \text{ l/min} \times 34 \text{ mg} \\ &= 0.238 \text{ g/min}\end{aligned}$$

$$\begin{aligned}\text{Total LHV required} &= 2.42 \text{ MJ/kg} \times 0.000238 \text{ kg/min} \\ &= 576 \text{ J/min} \\ &= 9.6 \text{ W}\end{aligned}$$

- therefore, the total heat loss from respiration ~ 11.6 W, or ~ 15% of the basal heat production
- the losses from humidifying air being 5 times those to warm the air

Vaporisers

- the saturated vapour pressures of the volatile anaesthetics are many fold greater than their respective MAC's

Agent	Sat. Vapour P _{20°C}		MAC
Halothane	243 mmHg	32%	0.75 %
Enflurane	175 mmHg	23%	1.68 %
Isoflurane	251 mmHg	33%	1.15 %

- reduction in the vapour pressure is achieved by dividing the gas flow from the meter into two streams, one bypassing the vapour chamber
- gas can flow through a vapourizer by two means,
 - a. plenum vapourizers → gas is driven proximally
 - b. draw-over vapourizers → distal "negative" pressure
- in the later the pressure is decreased either by the patient's respiratory efforts, or by mechanical means

Boyle's Bottle

- early, simple type of plenum vapourizer
- bypass and vapour streams determined by a rotatory valve
- the degree of saturation of vapour is highly dependent upon the flow rate
- with vaporisation, the temperature and saturated vapour pressure of the bottle fall
- output varies with both temperature and flow rate, making the device unsuited for calibration

■ Flow Dependence

- this is abolished if all vapour passing through the chamber is fully saturated at all flow rates
 - concentration can be adjusted by the splitting ratio, and is independent of flow
- this requires a large surface area in the chamber, which may be achieved by,
 - a. wicks → Floutec, Dräger, Abingdon
 - b. scintered discs
- the *splitting ratio* depends on the relative resistances to flow through the two paths, and thus is affected by,
 - a. laminar vs. turbulent flow
 - b. physical properties of gases - viscosity and density
- problems are usually worse at low flow rates (<1 l/min)
- calibration will depend upon which carrier gas is used, and this should be undertaken to represent the clinical conditions of use

■ Temperature Control

- the glass used in the walls of Boyle's bottle is a poor conductor and little heat exchange occurs with the surroundings
- most modern vapourizers use metal cases with good thermal conductivity
- also, a heat reservoir of either metal or water may be used to delay temperature fluctuations
- these changes are however not eliminated and some form of compensation is required,
 - a. temperature measurement and concentration scales
 - b. temperature measurement and manual adjustment
 - c. temperature controlled valves
 - i. bimetallic strips (Fluotec, PAC)
 - ii. bellows valve (EMO, Abingdon, Ohio)
 - iii. metallic rod valve
 - d. direct addition of the volatile liquid to the gas stream
- due to the high saturated pressures of the volatile agents, regular calibration is essential to prevent inadvertent overdosage

■ IPPV

- due to an intermittent fall in back pressure from the ventilator, gas from the vapour chamber may expand into the bypass channel, thereby increasing the concentration of agent delivered
- this is more likely to occur when the volume of the chamber is significantly larger than the bypass channel
- this may be solved by,
 - a. a pressurizing valve, ensuring the vaporiser pressure is always ~ the ventilator pressure
 - b. the volume of the vapour chamber = the bypass channel
 - c. increasing the length of the chamber inlet tube so no retrograde flow reaches the bypass channel

■ Hyperbaric Conditions

- the saturated vapour pressure is unaffected by the ambient temperature
- thus, for halothane, is still 32 kPa at 200 kPa ambient pressure
- since the splitting ratio is unchanged, the vapourizer will deliver 1/2 of the dialled percentage
- however, as the depth of anaesthesia is dependent upon the partial pressure of the agent, not the percentage, most vapourizers may be used with the usual settings at different ambient pressures

■ Vapourizer Position

- should be positioned between the flow meter block and the oxygen emergency flush control
- if there is an emergency gas flow cut-out actuated by failure of the oxygen supply then this should be down-stream of the vapourizer
- the control should be off in the clockwise position and both inlet and outlet to the chamber should be occluded

Draw-Over Vapourizers

- similar problems exist but in addition the internal resistance of the circuit must be low, so not as to add undue resistance to the patients breathing
- because they do not require gas supplies, they are ideal for "field" work
- the "EMO" is well established and has a bellows thermal compensatory device and a water reservoir for thermal stability
- it is designed for use with ether as this produces less cardiorespiratory depression than the modern volatile agents

4. Other Methods
 - i. electrical transducers - both resistance & capacitance
 - ii. mass spectrometry
 - iii. UV absorption spectroscopy

Types of Nebulizers

- a. cold water bubble through
- b. condenser
- c. hot water bath
- d. heated Bernoulli nebulizer and anvil
- e. ultrasonic nebulizer

NB: * these are in order of increasing efficiency

OXYGEN MEASUREMENT

- under normal conditions, the oxygen cascade results in an interstitial P_{O_2} between 20-40 mmHg and an intracellular $P_{O_2} \sim 20$ mmHg
- mitochondrial enzyme systems are designed to function at a $P_{O_2} \sim 3$ mmHg, therefore there is usually an excess of oxygen
- **hypoxia** could therefore be defined as a **mitochondrial $P_{O_2} < 3$ mmHg**
- in the classic study of Comroe & Botelho (1947), after 7,204 observations, it was found that trained observers were unable to detect any degree of cyanosis until the arterial $SaO_2 < 85\%$
- for the detection of cyanosis ~ 5 gm of reduced Hb must be present
- with a normal haematocrit this corresponds to a **$SaO_2 \sim 60-70\%$**
- in the presence of anaemia, the saturation must be considerably lower

Arterial Oxygen Content

Def'n: volume of oxygen, in ml, contained in 100 ml of blood at 1 atmosphere, at 37°C
= volume percent

$$CaO_2 \sim (1.37 \times [Hb] \times SaO_2) + (0.0034 \times P_{aO_2})$$
$$\sim 20 \text{ vol\%}$$

- the ideal value for the carriage of oxygen by Hb of 1.39 ml/g is not reached in vitro due to the presence of dyshaemoglobins
- thus, for the measurement of content three variables must be known, SaO_2 , P_{aO_2} and $[Hb]$
- however, SaO_2 is a function of P_{aO_2} as expressed by the Hb- O_2 dissociation curve
- three key points on this standard curve are,
 - i. 90% \rightarrow 60 mmHg
 - ii. 75% \rightarrow 40 mmHg
 - iii. 50% \rightarrow 26.2 mmHg = P_{50}
- the curve is displaced to the **right** by 4 factors,
 1. increasing $[H^+]$ (decreasing pH)
 2. increasing temperature
 3. increasing CO_2
 4. increasing 2,3-DPG
- it is displaced to the **left** by Hb-F, metHb and CO-Hb

Oxygen Delivery - Flux

Def'n: $O_2 \text{ Flux} = CO \times CaO_2 \times 10 \text{ ml } O_2/\text{min}$

- the normal CO is taken from the cardiac index, $CI = CO/BSA$
 $\sim 3.0\text{-}3.4 \text{ l/min/m}^2$
- this gives an average O_2 flux $\sim 640 \text{ ml/m}^2/\text{min}$
- the average BSA for a 70 kg male = 1.8 m^2 $\rightarrow CO \sim 5.75 \text{ l/min}$
 $\rightarrow O_2 \text{ flux} \sim 1150 \text{ ml/min}$
- the normal MRO_2 is stable for a given individual at rest and ranges from $115\text{-}165 \text{ ml/m}^2/\text{min}$
- the mixed venous oxygen roughly reflects global tissue oxygenation
- the normal value corresponds with
 - i. $Cv'O_2 = 12\text{-}15 \text{ vol.}\%$
 - ii. $Pv'O_2 = 40\text{-}46 \text{ mmHg}$
 - iii. $Sv'O_2 = 72\text{-}78 \%$
- however, different vascular beds have different extraction ratios and the mixed venous P_{O_2} does not reflect regional ischaemia

Hypoxia

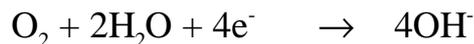
- hypoxia is defined as inadequate tissue oxygenation
- therefore this may result from either,
 - a. ischaemia - inadequate CO
 - b. hypoxaemia - decreased CaO_2
 - i. hypoxaemic hypoxaemia - decreased P_{aO_2} & SaO_2
 - ii. anaemic hypoxaemia - decreased [Hb]
 - iii. toxic hypoxaemia - decreased SaO_2
- P_{aO_2} & [Hb] normal

Measurement of P_{O₂}

- in 1956, Leyland Clarke developed the *polarographic* oxygen electrode for measuring the partial pressure of oxygen
- prior to this the P_{O₂} had not been measured
- the Severinghaus CO₂ electrode was developed in 1958 and arterial blood gas analysis was revolutionized
- P_{O₂} may also be measured by,
 - i. fuel cell
 - ii. paramagnetic analysis
 - iii. the optode
 - iv. mass spectrometry

■ Clarke Electrode

- the circuit consists of,
 - a. DC voltage source (0.6 V)
 - b. ammeter
 - c. platinum cathode
 - d. silver/silver chloride anode
 - e. electrolyte solution (KCl) and O₂-permeable membrane
- as for any resistive circuit as the voltage is increased the current will increase proportionately
- in the above circuit there exists a *plateau voltage* range over which the current does not increase with increasing voltage, however does increase with an increasing P_{O₂} in the cell
- the following reaction takes place at the platinum cathode,



- the current flow being in direct proportion to the consumption of oxygen
- the platinum electrode cannot be inserted directly into the blood stream as protein deposits form an affect its accuracy

■ Oxygen Fuel Cell

- circuit consists of,
 - a. ammeter
 - b. gold mesh cathode
 - c. lead anode
 - d. compensating thermistor
 - e. electrolyte solution (KCl) and O₂-permeable membrane

- the same reaction takes place at the *cathode*,



- current flow depends upon the uptake of oxygen at the cathode
- the reaction at the *anode* is as follows,



- unlike the Clarke electrode, the fuel cells requires no external power source, acting as an oxygen dependent battery
- like other batteries, the fuel cell will eventually expire
- the output is affected by *temperature*, as is that of the Clarke electrode, however compensation may be achieved by means of a parallel thermistor
- the typical response time is ~ 20-30 s

■ Paramagnetic Oxygen Analysis

- oxygen is paramagnetic and is therefore attracted into a magnetic field
- this is due to the unpaired outer shell electrons of the oxygen molecule
- most other gases, such as N₂, are weakly diamagnetic and are repelled from a magnetic field
- actually measures oxygen *concentration*
- most common systems use deflection of nitrogen containing glass spheres, arranged in a dumbbell or similar
- these indicate either by direct rotation of a pointer or deflection of light, or may be arranged in a null deflection system
- they require calibration before use with 100% N₂ and 100% O₂
- the presence of water vapour biases the result, therefore gases should be dried through silica gel before analysis

■ P_{O2} Optode

- based on the principle of **photoluminescence quenching**
- when light shines on luminescent material, electrons are excited to higher energy states and on their return emit light at characteristic wavelengths
- this excited electron can also return to its original energy state by interacting with an oxygen molecule, increasing the vibrational and rotational energy of the later
- for such photoluminescent quenching dyes, the amount of oxygen present can be related to the luminescent intensity by the **Stern-Volmer equation**,

$$I_{P_{O_2}} = \frac{I_0}{1+(k.P_{O_2})}$$

where, I = the luminescent intensity at a P_{O2}
 I₀ = the intensity in the absence of O₂
 k = the **quenching constant** for the dye

- the advantages of this system are its simplicity and size, which allow intra-arterial insertion and measurement
- pH-sensitive dyes are also available, therefore , a three optode sensor can measure P_{O2}, P_{CO2} and pH simultaneously

Measurement of Hb-Saturation

- CaO₂ was originally measured **volumetrically** by the method of Van Slyke and Neill
- oxygen saturation is defined as the CaO₂ / the oxygen capacity, expressed as a percentage
- this includes contributions from Hb-O₂ and dissolved O₂
- normal adult blood contains four species of Hb,
 1. O₂-Hb
 2. Hb
 3. met-Hb
 4. CO-Hb

- the later two are normally found only in low concentrations, except in disease states, and are ineffective in the transport of oxygen
- functional haemoglobin saturation is defined,

$$\text{Functional SaO}_2 = \frac{\text{O}_2\text{-Hb} \times 100 \%}{(\text{O}_2\text{-Hb} + \text{Hb})}$$

- similarly the **fractional SaO₂** includes both met-Hb and CO-Hb in the denominator

■ Beer's Law

- spectrophotometry was first used to determine the [Hb] of blood in the 1930's, by application of the *Lambert-Beer Law*

$$I_t = I_i \times e^{-DC\alpha}$$

where,

I_i	=	the incident light
I_t	=	the transmitted light
D	=	the distance through the medium
C	=	the concentration of the solute
α	=	the extinction coefficient of the solute

- the extinction coefficient is specific for a given solute at a given wavelength of light
- therefore, for each wavelength of light used an independent Lambert-Beer equation can be written, and if the number of equations = the number of solute, then the concentration for each one can be solved

Invasive P_{O₂} Monitoring

- by strict definition a monitor should be *continuous*, otherwise it is a test
- Clark Electrode
 - the main problem with continuous invasive P_{aO₂} monitoring is miniaturization of the electrode to fit through an arterial cannula
 - there are two approaches to this problem,
 - a. insert only the platinum cathode with the anode on the skin
 - b. miniaturization of the entire electrode
 - umbilical Clark electrodes in neonates have been associated with a number of complications,
 - a. thrombosis
 - b. sepsis
 - c. embolization
 - d. vascular perforation
 - e. lower extremity ischaemia and infarction
 - the size of the electrode also causes problems with blood pressure measurement and arterial blood sampling
 - similar problems have been encountered with electrodes for radial artery monitoring
 - recently electrodes have been developed which will fit through an 18 or 20 gauge cannula
 - problems encountered which may relate to the formation of clot around the cannula tip include,
 1. calibration drift
 2. systematic under estimation of P_{aO₂}
 - due to the requirement for the glass components in CO₂ and pH electrodes, it is unlikely that such a combined electrode could be developed for intra-arterial use
- Optode
 - these fibreoptic sensors can easily be made to fit through a 22-gauge cannula, though, most reported data comes from use with 20-gauge sets
 - these tend to be most accurate at low P_{aO₂}'s, which is desirable in a clinical setting
 - due to the smaller diameter, problems with BP measurement and arterial blood sampling have been reduced
 - large amounts of data are not available but it is anticipated that these will suffer similar problems to Clark electrodes, ie. thrombus formation and underestimation of P_{aO₂}

Non-invasive P_{O_2} Monitoring

■ Transcutaneous P_{O_2}

- first application of heated Clark electrodes being used to measure P_{aO_2} was in Europe in 1972
- after a decade of use in the neonatal field it was established that P_{tcO_2} values were significantly lower than the P_{aO_2} during periods of haemodynamic instability
- this flow dependence of P_{tcO_2} makes this a useful assessment of peripheral oxygenation, analagous to an alveolar-arterial P_{O_2} gradient
- the skin must be heated to over 43°C , this has two effects,
 - a. the stratum corneum becomes permeable to O_2
 - b. the vasodilatation "arterializes" the capillary blood
- a large amount of data has been analyzed and it has been established that the P_{tcO_2} index ($= P_{tcO_2}/P_{aO_2}$) decreases steadily with age
- for the premature infant this is ~ 1.14 , in the adult ~ 0.8 and over the age of 65 it falls to 0.7
- in addition to being sensitive to hypoxia, the P_{tcO_2} is also sensitive to dyshaemoglobins (CO-Hb & Met-Hb), being able to detect tissue hypoxia in the presence of a normal P_{aO_2} and CO
- problems and limitations with this technique include,
 - a. skin burns
 - b. sensor calibration and drift
 - c. sensitivity to halothane (reduced at the cathode)
 - d. location of the sensor on the trunk
 - e. equilibration times of ~ 15 mins

■ Conjunctival P_{O_2}

- when the eyes are closed the cornea receives its blood supply from the palpebral conjunctiva
- thus, this inner layer of cells is well vascularized, deriving its blood supply from the ophthalmic and ipsilateral carotid arteries
- Clarke electrodes have been incorporated into polymethylmethacrylate ocular conformer rings, which fit inside the eyelid
- these are not heated and measure P_{O_2} directly from the tissues
- therefore, the equilibration time is much shorter ~ 60 secs
- as for P_{tcO_2} , since this measures tissue oxygenation, the value will be affected by both P_{O_2} and CO
- as the blood supply is via the carotid, these are particularly well situated to detect alterations in carotid blood flow
- the P_{cjO_2} index has similar values to P_{tcO_2} , $\sim 0.7-0.8$ in the adult
- the limitations are similar to transcutaneous measurement,
 - a. electrode maintenance
 - b. calibration
 - c. anaesthetic (halothane) interference

Invasive SaO₂ Monitoring

- the mixed venous P_{O₂} (P_{vO₂}) and the Hb saturation reflect global tissue oxygenation and the ability of the CVS to transport adequate oxygen for the bodies needs
- in 1973 a fiberoptic pulmonary artery catheter system was used to continuously monitor Sv'O₂ by spectroscopy
- this method was short lived due to the technical difficulties in inserting the catheter which was made relatively rigid by the optical fibres
- newer, more flexible systems have been developed, and most of these operate on three wavelengths of light
- therefore these are only accurate in the absence of significant dyshaemoglobins
- this type of monitoring can follow changes in the relationship of O₂ delivery and consumption, though, it gives no indication of the source of any imbalance, nor will it detect regional ischaemia

Non-Invasive SaO₂ Monitoring - Pulse Oximetry

- the term oximeter was coined by Millikan et al. in the 1940's
 - they developed a lightweight oximeter which measured SaO₂ by transillumination of the earlobe with 2 wavelengths of light, red & IR
 - there were two technical problems with this approach,
 - a. there are many non-Hb light absorbers in tissue
 - b. the tissues contain capillary & venous blood in addition to arterial blood
 - these were overcome by first measuring the absorbance of the ear while it was compressed to remove all blood
 - after this blood-less "baseline" measurement the ear was heated to "arterialize" the blood
 - this device was shown to accurately predict intra-operative desaturations, however, due to the technical difficulties was never adopted on mass
 - in the mid 1970's, the Japanese engineer Takuo Aoyagi noted that the pulsatile components of the red & IR absorbances were related to the Sv'O₂
 - he used 2 wavelengths of light,
 - a. red = 660 nm
 - b. IR = 940 nm
 - the signal was divided into two components,
 - a. ac = pulsatile arterial blood
 - b. dc = tissue + capillary blood + venous blood + non-pulsatile arterial blood
- NB:** all pulse oximeters assume that only the pulsatile absorbance is arterial blood

Physics & Measurement

- for each wavelength, the oximeter determines the ac/dc fraction, which is independent of the incident light intensity = *pulse added absorbance*
- then the ratio (R) of these is calculated,

$$R = \frac{(\text{ac absorbance/dc absorbance})_{\text{red}}}{(\text{ac absorbance/dc absorbance})_{\text{IR}}}$$

$$= A_{660\text{nm}} / A_{940\text{nm}}$$

- this value varies from,

- SaO₂ = 100% R = 0.4
- SaO₂ = 85% R = 1.0
- SaO₂ = 0% R = 3.4

- being a 2 wavelength device, the pulse oximeter assumes that there are only two light absorbing Hb species in arterial blood
- if met-Hb or CO-Hb are present then they will contribute to the pulse added absorbance
- CO absorbs very little light at 940 nm (IR) but about the same as O₂-Hb at 660 nm (red), therefore,

$$\text{High [CO-Hb]} \quad \rightarrow \quad \text{SaO}_2 \sim P_{\text{aO}_2} + (0.9 \times \text{CO-Hb})$$

- met-Hb absorbance is high at both wavelengths, thus increasing both A_{660nm} & A_{940nm} and forcing R → 1.0,

$$\text{High [met-Hb]} \quad \rightarrow \quad \text{SaO}_2 \sim 85\%$$

- foetal Hb has a greater affinity for O₂ than HbA, however, the absorbance coefficient is identical and the presence of HbF should not affect the SaO₂ reading
- the presence of HbF is only important if the aim of therapy is to maintain a specific P_{aO2}, as opposed to a specific SaO₂
- the photo-detector diodes of the sensor will also register ambient light
- this interference is reduced by cycling the light signal from red only → infrared only → both off
- this is repeated at 480 Hz in an attempt to subtract the ambient light signal, even when this is oscillating
- despite this filtering, ambient light can produce erroneous readings so the sensor is usually covered with an opaque material
- in order to assess the ac component of the absorbance, pulse oximeters have automatic gain controls
- amplification of low signal strengths → low signal to noise ratio
- newer meters give "low signal strength" warnings to alleviate this problem
- laser-Doppler flow studies show that these oximeters will estimate saturation down to ~ 8% of the control pulse strength
- thus they will estimate SaO₂ over a wide range of CO values, so long as an adequate pulse is detected

- another serious signal-noise problem is patient motion artifact
- most oximeters employ signal averaging circuitry to prevent this, however, by increasing the signal averaging time, so the response time of the device is increased
- the final source of error is LED wavelength variability, which can be up to 10 nm from the specified value
- this produces a probe-probe variation in accuracy
- manufacturers claim accuracies around,
 - a. $\text{SaO}_2 \sim 100\% \text{ to } 70\% \rightarrow \pm 2\%$
 - b. $\text{SaO}_2 \sim 70\% \text{ to } 50\% \rightarrow \pm 3\%$
 - c. $\text{SaO}_2 < 50\% \rightarrow \text{unspecified}$

■ Limitations Of Pulse Oximetry

- a. SaO_2 does not indicate oxygenation unless [Hb] is known
- b. insensitive to directional changes in P_{aO_2} above 80 mmHg
- c. due to automatic gain, oximetry is insensitive to perfusion
- d. errors of saturation estimation
 - i. signal to noise ratio
 - ii. intravenous dyes
 - iii. dyshaemoglobins
 - iv. motion artifact
 - v. light artifact
 - vi. probe variability errors

■ Cytochrome aa3 Saturation Monitoring

- this enzyme is distal in the cytochrome oxidase chain and contains copper
- when oxidized this enzyme has an absorbance peak $\sim 830 \text{ nm}$ in the near infrared range
- as this wavelength is absorbed by both Hb & $\text{O}_2\text{-Hb}$, simultaneous estimation of these must be carried out and three wavelengths must be used
- the device for measuring this, the *Niros scope* = near infrared oxygen sufficiency scope
- uses powerful laser diodes with sufficient light intensity to penetrate the skull

MEASUREMENT OF CO₂ AND pH

Measurement of pH

- pH is defined as the negative logarithm to the base 10 of the hydrogen ion **activity** ($\sim [H^+]$)
- at 37°C, the normal blood pH = 7.4 ± 0.04
- the circuit consists of,
 - a. a capillary tube of pH sensitive glass $\rightarrow \delta V$
 - b. a reference buffer solution the other side of the glass
+ a silver/silver chloride electrode
 - c. an electrolyte solution (KCl) in contact with blood
+ mercury/mercury chloride electrode
 - d. a surrounding water jacket at 37°C
 - e. a voltmeter
- the electrodes are metal/metal chloride, which are then in contact with electrolyte containing Cl⁻ to maintain their stability
- the pH difference across the glass produces a potential in proportion to the [H⁺] difference
- temperature control is important as acids/bases dissociate at higher temperatures altering the pH
- this is described approximately by the formula by **Rosenthal**,

$$\delta pH \sim \delta T^{\circ}C \times -0.015$$

- before use pH meters should be calibrated with two buffer solutions

Measurement of P_{CO₂}

- the normal P_{aCO₂} = 40 mmHg (5.3 kPa)
- measurements are based on pH, due to the dissociation of carbonic acid
- the P_{CO₂} is therefore related to the [H⁺]
- the **Severinghaus CO₂ Electrode** provides a direct measure of P_{CO₂} from the change in pH
- the circuit consists of,
 - a. a closed cylinder of pH sensitive glass in the centre
 - b. 2 electrodes, 1 inside, the other outside the cylinder
 - c. a surrounding solution of sodium bicarbonate
 - d. a thin film of bicarbonate impregnated nylon mesh covering the end of the cylinder
 - e. a thin, CO₂ permeable membrane covering the end of the electrode
- at the end of the electrode CO₂ diffuses from the blood sample through the membrane into the nylon mesh and by the formation of carbonic acid lowers the pH of the bicarbonate solution
- this change in pH alters the δV across the glass

- as pH changes such that,

$$\delta\text{pH} \sim \delta\log_{10} P_{\text{CO}_2}$$

- the output of the voltmeter can be calibrated in terms of P_{CO_2}
- should the end membrane be perforated, then it ceases to be a semipermeable membrane to CO_2 and the reading will be erroneous
- the electrode has an accuracy ~ 1 mmHg
- the response time ~ 2 -3 mins
- as for the pH electrode, the CO_2 electrode must be kept at 37°C and regularly calibrated with known concentrations of CO_2
- transcutaneous electrodes, similar to the Clark electrode have been used for continuous PCO_2 monitoring

Infrared Analysis

- gases which have two or more molecules absorb IR radiation
- the absorbance peak is characteristic for a given gas and for $\text{CO}_2 \sim 4.28\mu\text{m}$
- the Beer-Lambert law applies, as for Hb absorbance
- as glass absorbs IR radiation, the chamber windows must be made of a crystal of sodium chloride or sodium bromide
- calibration may be achieved by filling the chamber with a CO_2 free gas, or by splitting the incident beam and passing this through a reference chamber
- the use of a reference beam also allow compensation for variations in the output of the IR source
- the sample chamber is made small, so that continuous analysis is possible
- the response time is ~ 100 ms, enabling end-tidal CO_2 estimations

Ultra-Violet Analysis

- halothane absorb light in the UV spectrum
- therefore the concentration of halothane may be measured in accordance with Beer's law, as for end-tidal CO_2
- a reference is obtained with a beam splitter and a second chamber
- the sample and reference cells have quartz windows as glass absorbs UV light

GAS CHROMATOGRAPHY

- chromatography is now used as a general term for analytical procedures that separate a mixture into its components as the mixture passes through a column
- the system has a stationary phase and a mobile phase
- for gaseous mixtures, the stationary phase of the column is frequently a material such as fine silica-alumina coated with polyethylene glycol or silicone oil
- through this column a flow of carrier gas is passed, such as argon or helium
- sample gases are then entered into the stream, and the speed with which they pass through the column is determined by their differential solubility between the two phases
- as solubility is temperature dependent, the apparatus is maintained at a constant temperature
- this system is often termed gas liquid chromatography

- as the gases leave the column they pass through some form of detector, which may be either a,
 - a. flame ionization detector - organic vapour
 - b. thermal conductivity detector - inorganic vapour
 - c. electron capture detector - halogenated vapours

- in a flame ionization detector, the gas is introduced into a hydrogen/air flame
- as the constituents of flames are ionized particles, the resistance of the flame will decrease in the presence of organic gas vapour
- if a constant potential (150V) is generated across the flame, then the current flow will show peaks as the individual components of the gas mixture enter the flame
- the thermal conductivity detector, also called a *katharometer*, has a heated electrical resistance wire in the main stream of the gas flow
- as different gases have different thermal conductivities, as each component of the sample passes over the wire the temperature will fluctuate
- this system is more suited for the measurement of inorganic gases
- halogenated compounds can be detected with greater sensitivity by an electron capture detector
- a polarizing voltage is applied across an ionizing chamber, in which electrons are released by a radioactive cathode
- halogenated compounds capture these electrons and decrease the current flow reaching the anode

- NB:** ** none of these detectors allows absolute identification of the component gasses, and some knowledge of the substituents is necessary prior to analysis

- the time between entry of the sample and the appearance of the component is the *retention time*
- most samples will have numerous peaks with varying retention times
- with appropriate calibration the area of a peak can be used to calculate the quantity of the gas present in the mixture
- if the portal of entry of the sample is heated then injected liquids will be vapourized and these can also be analyzed

■ Clinical Uses - Gas Chromatography

- a. volatile anaesthetic agents
- b. barbiturates
- c. benzodiazepines
- d. phenothiazines
- e. steroids
- f. catecholamines

- it is useful for measuring very low concentrations of either gases or liquids
- however, continuous analysis is not possible and some knowledge of the sample must be available

MASS SPECTROMETER

- the sample is passed through a molecular leak into an ionizing chamber
- the ionized particles are then accelerated and focussed into a beam which directed through a strong magnetic field
- depending upon their *charge/mass ratio*, different molecules describe different arcs of travel
- these separated beams are then detected depending upon their position
- by varying the accelerating voltage, molecules of different masses can be made to describe the same arc → one detector
- alternatively, multiple detectors can be used
- an alternative means of manipulating the accelerated beam is the quadrupole
- here, 4 electrically charged rods are positioned around the beam such that only a molecule of a given charge/mass ratio will remain undeflected
- some compounds fragment on ionization and analysis of the fragments can allow differentiation between molecules of the same charge/mass ratio
- this occurs with N_2O and CO_2 , both of which have a MW = 44, however the nitrous oxide fragments into nitric oxide which allows differentiation

Piezoelectric Gas Analysis - "Emma"

- a quartz crystal is coated with oil
- gasses are absorbed into the oil in proportion to their gas:oil partition coefficients and in accordance with Henry's law
- the presence of the gas alters the resonant frequency of the crystal which can be measured electronically
- these analyzers are not agent specific and will respond partially to water vapour