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 Pa = 1 N acting over 1 m^2
Pa = $N.m^{-2}$

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

Def'n: **1 kPa** ? 10.2 cmH_2O
? 7.5 mmHg → mercury is **13.6x** water density

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

FLUID FLOW

Laminar Flow

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

Hagen-Poiseuille Equation

but as R = δP/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 ~ 2x mean
   ii. near the wall → 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,

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

where, k = a constant
ρ = ***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 CO_2 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. increasing haematocrit
d. abnormal elevations of plasma proteins
e. cigarette smoking

- 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,

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

where,
- PV = the potential energy of ***pressure***
- mgh = the potential energy due to ***gravity***
- $\tfrac{1}{2}mv^2$ = the kinetic energy of ***motion***

- thus, as the velocity of flow increases passing though 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 K (0°C)
P = 101.325 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}Carbon,

  1 mol ? 6.022×10^{23} ***Avogadro's number***
- for any gas at STP, 1 mol ? 22.4 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. N_2O = 36.5 °C
  ii. O_2 = -119 °C

■ *Critical Pressure*

- is the pressure at which a gas liquifies at its critical T
  i. N_2O ? 73 bar @ 36.4 °C
  ii. N_2O ~ 52 bar @ 20.0 °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. N_2O 50% / O_2 50% = - 5.5 °C for cylinders (most likely at 117 bar)
2. N_2O 50% / O_2 50% = - 30 °C for piped gas

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

N_2O = 0.65 (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*

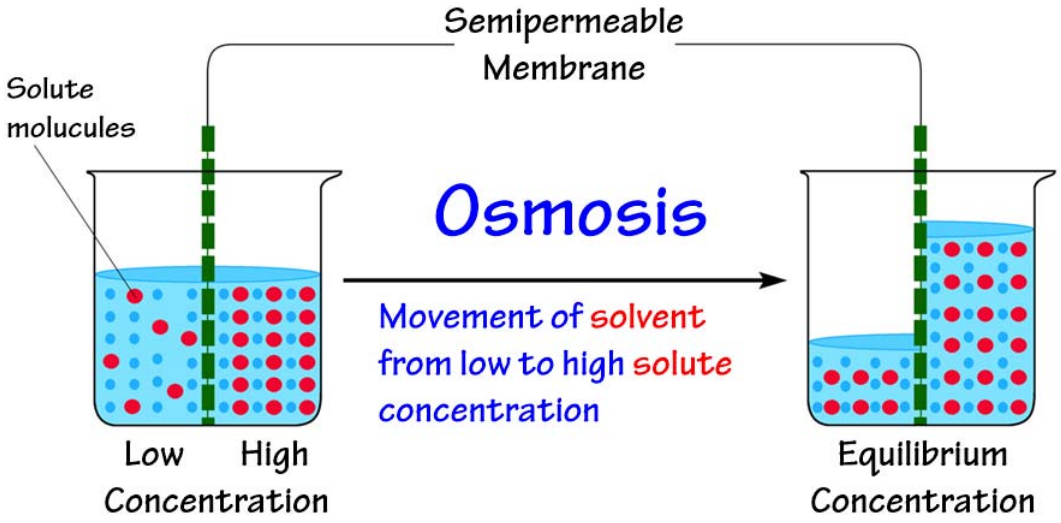
- the rate of diffusion of a substance across a unit area is proportional to the ***concentration gradient*** for that substance
- further, the diffusion of gas across a membrane, or into or out of a liquid, is proportional to the gases solubility in the liquid
- CO_2 being more soluble than O_2 diffuses far more rapidly across the alveolar membrane and into the RBC
- N_2O being far more soluble than N_2 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

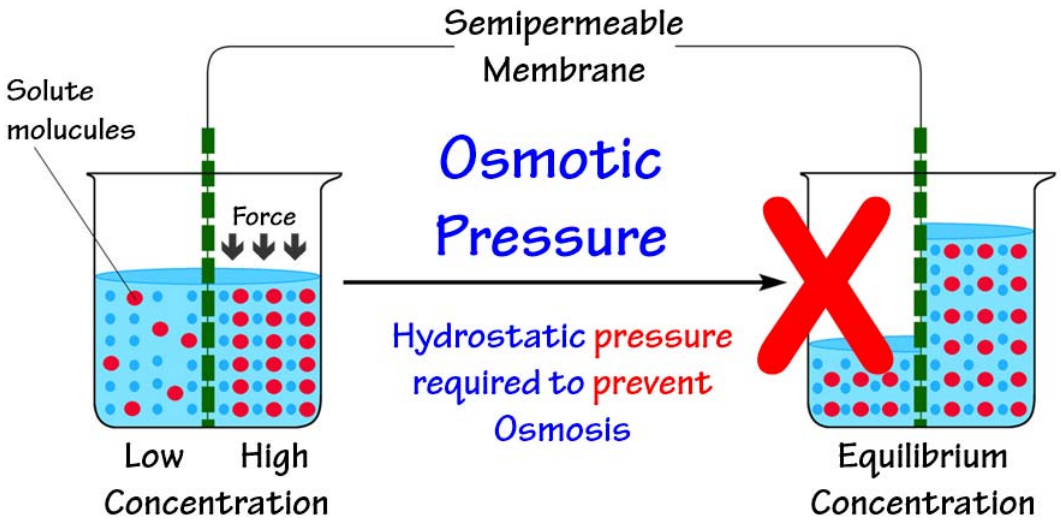
■ *Osmosis*

- 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, *or*
- 1 mol in 1 L will produce an osmotic pressure of 22.4 atmospheres
- plasma osmotic pressure: 280 msom/L $\rightarrow$ 0.28 x 22.4 x 760 ≈ 4,770 mmHg
- actual values are higher > 5,000 mmHg
    - T = 37°C
    - Gibbs-Donnan

- 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 osmolarity 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.

$$W = F \cdot \vec{s}$$

but P = F/A	→	F	= P.A
and V = A.s	→	s	= V/A
thus,		W	= P.A x V/A
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,

a.	elastic resistance	~ 65%		
b.	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 (O_2 cost of breathing)

- expressed as ml of O_2 (additional O_2 consumption)/l ventilation
- this is low during quiet breathing
- increases with increasing ventilation, especially with pulmonary disease

O_2 cost of quiet breathing	~ 0.5 to 1.0 ml.O_2/l ventilation
or,	~ 1-2% of basal MRO_2 (250 ml/min)

▪ *mechanical efficiency*

$$= \frac{\text{useful work}}{\text{total energy expended } (O_2 \text{ used})} \times 100$$

~ 5 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,

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

- 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,

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

- for the RV this would be,

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

- 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 → 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 guage → 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 exceeding 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 exceeding 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 ± 0.5 °C**
- normal circadian rhythm varies temperature by 0.4 °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	~ 37 °C
b.	intermediate zone	
c.	shell ~ 2.5 cm	~ 32-53 °C

▪ *Heat Production*

- in the average male under resting conditions ~ 50 $W.m^{-2}$, 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	~ 40%	
b.	convection	~ 30%	
c.	evaporation	~ 20%	
d.	respiration	~ 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 kg x 3.6 kJ/kg/°C x (35-5)°C = 216 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 ahuman 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,

Heat Loss ~ 7.0 l/min x 1.2 J/l/°C x 14°C
= 118 J/min
= 1.96 W

- 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 N_2O 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

Total water vapourized	= 7.0 l/min x 34 mg
	= 0.238 g/min
Total LHV required	= 2.42 MJ/kg x 0.000238 kg/min
	= 576 J/min
	= 9.6 W

- 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 is produces less cardiorespiratory depression than the modern volatile agents

HUMIDFICATION

■ *Absolute Humidity*

- the ***mass*** of water vapour (g) present in a given volume of air (m^3), numerically = mg/l

■ *Relative Humidity*

- the ratio of the mass of water vapour in a given volume of air to the mass required to fully saturate that volume of air at a given temperature (%)

NB: fully saturated air at 20°C contains ~ 17 mg/l
37°C contains ~ 44 mg/l

- although relative humidity is expressed in terms of mass, as mass is directly proportional to the number of moles present, then by the ideal gas equation it becomes evident that,

$$\text{Relative humidity} = \frac{\text{actual vapour pressure}}{\text{saturated vapour pressure}}$$

Measurement of Humidity

1. Hair Hygrometer
   - based on the principle that hair elongates as the humidity rises
   - very simple and cheap
   - only really accurate over the range 30-90%

2. Wet & Dry Bulb Hygrometer
   - the temperature of the wet bulb is reduced due to evaporation
   - the lower the humidity the greater the evaporative cooling and the greater the temperature difference $\rightarrow$ tables relating δT to % humidity
   - air must be flowing over the wet bulb to prevent a local rise in the humidity

3. Regnault's Hygrometer
   - uses the principle that condensation occurs when the air is fully saturated at a given temperature = the ***dew point***
   - air is blown through a silver test tube containing ether, reducing the temperature by evaporation
   - the dew point is noted and from tables both the relative and absolute humidity can be established,

$$\text{Relative humidity} = \frac{\text{s.v.p. at dew point}}{\text{s.v.p. at ambient temp.}}$$

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_{O2} between 20-40 mmHg and an intracellular P_{O2} ~ 20 mmHg
- mitochondrial enzyme systems are designed to function at a P_{O2} ~ 3 mmHg, therefore there is usually an excess of oxygen
- ***hypoxia*** could therefore be defined as a ***mitochondrial*** **$P_{O2} < 3$ 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 ~ 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

$$CaO_2 \sim (1.37 \times [Hb] \times SaO_2) + (0.0034 \times P_{aO2})$$
$$\sim 20 \text{ vol}\%$$

- the ideal value for the carriage of oxygen by Hb of 1.39 ml/g is not reach in vitro due to the presence of dyshaemoglobins
- thus, for the measurement of content three variables must be known, SaO_2, P_{aO2} and [Hb]
- however, SaO_2 is a function of P_{aO2} as expressed by the Hb-O_2 dissociation curve
- three key points on this standard curve are,

i. 90% → 60 mmHg
ii. 75% → 40 mmHg
iii. 50% → 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 Flux = CO x CaO_2 x 10 ml O_2/min

- the normal CO is taken from the cardiac index, CI = CO/BSA
  ~ 3.0-3.4 l/min/m^2
- this gives an average O_2 flux ~ 640 ml/m^2/min
- the average BSA for a 70 kg male = 1.8 m^2 → CO ~ 5.75 l/min
  → O_2 flux ~ 1150 ml/min

- the normal MRO_2 is stable for a given individual at rest and ranges from 115-165 ml/m^2/min
- the mixed venous oxygen roughly reflects global tissue oxygenation
- the normal value corresponds with
  i. $Cv'O_2$ = 12-15 vol.%
  ii. $Pv'O_2$ = 40-46 mmHg
  iii. $Sv'O_2$ = 72-78 %

- however, different vascular beds have different extraction ratios and the mixed venous P_{O2} 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_{aO2} & SaO_2
   ii. anaemic hypoxaemia - decreased [Hb]
   iii. toxic hypoxaemia - decreased SaO_2
   - P_{aO2} & [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 CO_2 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 O_2-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,

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$$

- 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 O_2-permeable membrane

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

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$$

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

$$Pb + 2(OH^-) \rightarrow PbO + H_2O + 2e^-$$

- 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 N_2, 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% N_2 and 100% O_2
- 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***,

$$I_{P_{O2}} = \frac{I_0}{1+(k.P_{O2})}$$

where, I = the luminescent intensity at a P_{O2}
I_0 = the intensity in the absence of O_2
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

- CaO_2 was originally measured ***volumetrically*** by the method of Van Slyke and Neill
- oxygen saturation is defined as the CaO_2 / the oxygen capacity, expressed as a percentage
- this includes contributions from Hb-O_2 and dissolved O_2
- normal adult blood contains four species of Hb,

1. O_2-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,

$$\text{Functional } SaO_2 = \frac{O_2\text{-Hb} \times 100\ \%}{(O_2\text{-Hb} + \text{Hb})}$$

- similarly the ***fractional*** $\mathbf{SaO_2}$ 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 CO_2 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_{O2} Monitoring

■ *Transcutaneous P_{O2}*

- first application of heated Clark electrodes being used to measure P_{aO2} was in Europe in 1972
- after a decade of use in the neonatal field it was established that P_{tcO2} values were significantly lower than the P_{aO2} during periods of haemodynamic instability
- this flow dependence of P_{tcO2} makes this a useful assessment of peripheral oxygenation, analagous to an alveolar-arterial P_{O2} 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_{tcO2} index (= P_{tcO2}/P_{aO2}) 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_{tcO2} is also sensitive to dyshaemoglobins (CO-Hb & Met-Hb), being able to detect tissue hypoxia in the presence of a normal P_{aO2} 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_{O2}*

- 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_{O2} directly from the tissues
- therefore, the equilibration time is much shorter ~ 60 secs
- as for P_{tcO2}, since this measures tissue oxygenation, the value will be affected by both P_{O2} and CO
- as the blood supply is via the carotid, these are particularly well situated to detect alterations in carotid blood flow
- the P_{cjO2} index has similar values to P_{tcO2}, ~ 0.7-0.8 in the adult
- the limitations are similar to transcutaneous measurement,

    a. electrode maintenance

    b. calibration

    c. anaesthetic (halothane) interference

Invasive SaO_2 Monitoring

- the mixed venous P_{O2} ($P_{v'O2}$) 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 $Sv'O_2$ 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 O_2 delivery and consumption, though, it gives no indication of the source of any imbalance, nor will it detect regional ischaemia

Non-Invasive SaO_2 Monitoring - Pulse Oximetry

- the term oximeter was coined by Millikan et al. in the 1940's
- they developed a lightweight oximeter which measured SaO_2 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 $Sv'O_2$
- 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

- 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,

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

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

- this value varies from,

a. $SaO_2 = 100\%$ R = 0.4

b. $SaO_2 = 85\%$ R = 1.0

c. $SaO_2 = 0\%$ 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 O_2-Hb at 660 nm (red), therefore,

High [CO-Hb] $\rightarrow$ $SaO_2 \sim P_{aO2} + (0.9 \times \text{CO-Hb})$

- met-Hb absorbance in high at both wavelengths, thus increasing both A_{660nm} & A_{940nm} and forcing R $\rightarrow$ 1.0,

High [met-Hb] $\rightarrow$ $SaO_2 \sim 85\%$

- foetal Hb has a greater affinity for O_2 than HbA, however, the absorbance coefficient is identical and the presence of HbF should not affect the SaO_2 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 SaO_2
- the photo-detector diodes of the sensor will also register ambient light
- this interference is reduced by cycling the light signal from red only $\rightarrow$ infrared only $\rightarrow$ 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 $\rightarrow$ 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 SaO_2 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. SaO_2 ~ 100% to 70% → ± 2%

b. SaO_2 ~ 70% to 50% → ± 3%

c. SaO_2 < 50% → unspecified

■ *limitations of pulse oximetry*

a. SaO_2 does not indicate oxygenation unless [Hb] is known

b. insensitive to directional changes in P_{aO2} 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 ~ 830 nm in the near infrared range
- as this wavelength is absorbed by both Hb & O_2-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 CO_2 AND pH

Measurement of pH

- pH is defined as the negative logarithm to the base 10 of the hydrogen ion ***activity*** (~ []'n)
- 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***,

$$\delta pH \sim \delta T°C \times -0.015$$

- 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 CO_2 Electrode*** provides a direct measure of P_{CO2} from the change is 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, CO_2 permeable membrane covering the end of the electrode

- at the end of the electrode CO_2 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,

$$\delta pH \sim \delta \log_{10} P_{CO2}$$

- the output of the voltmeter can be calibrated in terms of P_{CO2}
- 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 CO_2 ~ 4.28um
- 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 though 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 $\rightarrow$ one detector
- alternatively, multiple detectors can be used
- an alternative means of manipulating the accelerated beam is the quadrupole
- here, 4 electrically charge rods are positioned around the beam such that only a molecule of a given charge/mass ration 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