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 an area of 1 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 13.6 x density of water

1 bar = 100 kPa
= 750 mmHg

1 mbar ~ 1.02 cmH_2O *guage on an "Oxylog"

FLUID FLOW

Laminar Flow

Hagen-Poiseuille Equation

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

but as R = δP/Q, so

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

- where eta, h = the ***viscosity*** of the fluid in Pascal seconds
- there are no eddies or turbulence
- flow is greatest at the centre, being ~ twice the mean
- flow near the wall → 0
- flow 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
- 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 summarised,

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

- 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 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. 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 behaviour 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 the 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 liquefied by pressure alone
    i. N_2O = 36.5 °C
    ii. O_2 = -119 °C

- ***Critical Pressure***
  - is the pressure at which a gas liquefies at its critical T
    i. N_2O ~ 73 bar @ 36.5 °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 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 $\rightarrow$ 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***
    - 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***
    - the volume of gas which dissolves in one unit volume of the liquid at the temperature concerned
    - the temperature must be specified
    - ie. 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***
    - 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 and at equilibrium
    - the temperature must be specified

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 than 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
    - these phenomena, depression of freezing point, depression of vapour pressure and 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: One Joule: the amount 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 $F = P.A$
and $V = A.s$, therefore $s = V/A$
thus, $W = P.A \times V/A$

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 nonelastic resistance to breathing,

a. elastic resistance ~ 65%
b. nonelastic 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 VO_2 (250 ml/min)

- ***Mechanical Efficiency***

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

$$\sim \quad 5 \text{ to } 10\%$$

- ***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,

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

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

NB: if the HR = 60, 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 VO_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 VO_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 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 triple point of water is 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 gauge → 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. sterilisation

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 minimised

- ***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 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,

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 vaporisation***
    = ***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*** = 373°C

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

- gases reaching the trachea usually have an upper airway humidity of ~ 34 mg/l
- for a person breathing dry gas at a minute ventilation of 7 l/min then,

Total water vaporised	= 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 vaporiser by two means,

a. plenum vaporisers → gas is driven proximally
b. draw-over vaporisers → 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 vaporiser
• 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. sintered 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 vaporisers 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 pressurising 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 vaporiser 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 vaporisers may be used with the usual settings at different ambient pressures

- ***Vaporiser 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 downstream of the vaporiser
• the control should be off in the clockwise position and both inlet and outlet to the chamber should be occluded

Draw-Over Vaporisers

• 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

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 ionisation detector - organic vapour
b. thermal conductivity detector - inorganic vapour
c. electron capture detector - halogenated vapours

• in a flame ionisation detector, the gas is introduced into a hydrogen/air flame
• as the constituents of flames are ionised 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 polarising voltage is applied across an ionising 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 vaporised and these can also be analysed

- ***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 knowledge of the sample must be available

MASS SPECTROMETER

• the sample is passed through a molecular leak into an ionising chamber
• the ionised 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 ionisation 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

Ultraviolet Analysis

• halothane absorbs light in the UV spectrum, therefore the concentration 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

Piezoelectric Gas Analysis - "Emma"

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

GAS CYLINDERS

Construction

- early cylinders were made of high carbon steel
- the use of chromium molybdenum steel allowed thinner walls, current "C" size ~ 3 mm
- aluminium alloys were then introduced, due to lighter weight, ~ 3.0 cf. 4.4 kg (C size)
- designed to withstand ~ 24,000 kPa (3500 psi)
- to avoid bending forces, cylinders frequently have 1 internal radius, the weakest point then being the neck
- cylinder standards allow concave forms other than single radius, however ellipsoid and toroidal shapes require thicker metal
- large free standing steel cylinders use a reverse curvature base
- modern aluminium cylinders have ellipsoid bases inside and flat outer bases
- in these the commonest site of fracture is the "knuckle" where the wall runs into the base
- cylinder manufacture must conform to the appropriate Australian Standards,

1. ASB110 & ASB111 - older manganese steel cylinders
2. ASB114 - molybdenum and chromium steel alloys
3. AS1777 - seamless aluminium cylinders

Steel Cylinders

- most currently used O_2 and N_2O are molybdenum / chromium steel alloy conforming to ASB114,
    i. molybdenum ~ 0.15-0.25%
    ii. chromium ~ 0.8-1.2%
    iii. small quantities of manganese and silicon are also present

- cylinders of ≤ 2.7 l capacity (~ 400 l capacity) are generally made from 102 mm nominal diameter seamless tube, of 2.5 mm thickness
- larger cylinders are pressed and spun from a flat sheet of metal (~ 500°C)
- all sizes are checked for wall thickness and trimmed
- the neck is heated and spun in a second operation (~ 900 & 600°C), then reamed and threaded
- cylinders are then cleaned inside and out, to an "oil-free" standard < 50 mg hydrocarbon / m^2
- all are hydraulically tested to 23.5 MPa (3400 psi) for at least 30 seconds
- cylinders are then stamped with,
    i. the owner's or manufacturer's mark
    ii. identification number
    iii. water capacity
    iv. tare mass
    v. test pressure
    vi. month and year of test
    vii. specification - ASB114

Aluminium Cylinders

• these cylinders conform to AS1777 for seamless aluminium cylinders up to 130 litres water capacity
• the aluminium is of specific quality, 6351T6, which is,

i. low in copper (< 0.05%) and iron (< 0.4%)
ii. has carefully controlled amounts of - magnesium and manganese (0.5-0.7%)
- silicon (0.9-1.15%)

• magnesium silicides give the alloy its strength, and manganese reduces corrosion
• aluminium stock is tested for flaws by ultrasound then the block stamped, the number remaining after pressing
• the cylinder tube and base are formed in 1 cold pressing at 3500 tonne
• the second and final stage forms the neck, heat pressing at ~ 400°C
• the alloy is unstable and requires heat treating at 525°C to improve strength, followed by aging at 175°C for 8 hours
• a minimum ultimate tensile strength of 320 MPa (46410 psi) is required
• each cylinder is pressure tested to 24.5MPa (3500 psi) then stamped cf. steel cylinders

■ *Cylinder Threads*

• medical gas cylinders have the same thread, regardless of the gas type,

1. tapered 1:8 - ensuring a gas tight fit against high pressure
2. 14 right-handed Whitworth threads per inch
   • angle between adjacent threads = 55°
3. thread must engage the valve for ≥ 16 mm in a standard C size
   ≥ 19 mm in the larger cylinders

■ *Cylinder Shapes And Sizes*

• all medical cylinders are designed to withstand high pressure, as most gasses are either,

1. permanent gases - critical temperature > 0°C, or
2. high pressure liquefiable gases - $0° < T_C < 65°C$
   i. N_2O - $T_C = 36.5°C$
   ii. CO_2 - $T_C = 31.0°C$

• with liquefiable gases, the cylinder pressure is dependent upon ***ambient temperature***, not the contents of the cylinder
• the ***filling ratio*** is important to avoid excessive pressure as the temperature rises

Medical Gas Cylinders						
Letter Code	**G**	**E**	**D**	**C**	**B**	**A**
Nominal Capacity	7,000	3,500	1,400	400	200	85
Water Capacity (kg)	46.5	23.6	9.3	2.8	1.6	0.6
Approximate Volumes (litres)						
Oxygen	7,600	3,800	1,500	**440**	200	
Nitrous Oxide	17,000	8,000	3,200	**950**	450	
Air	6,400	3,200	1,300	400	200	
Entonox	8,000	4,000	1,600	500		
Carbon Dioxide	17,000	8,000	3,200	970		
Cyclopropane					350	150
Nitrogen	6,400	3,200	1,300			

Cylinder Testing

- each batch has a sample selected at random
- 1 cylinder is selected for each 200, or part thereof, made (> 12 kg water capacity 1:100)
- if metal from more than one cast is used, then 1 from each cast batch must be chosen
- cylinders are cut into strips and tested for,

1. steel - tensile strength
   - yield stress (bending)
   - impact stress (notched bar)
2. aluminium - tensile strength
   - yield stress (bending)

- if a cylinder fails, then another 2 are tested, if either of these fail the entire batch is destroyed
- for medical gases, a hydrostatic stretch test (H_2O) is performed every 10 years, except for CO_2 which is performed every 5 years
- in accordance with AS2030, the minimum test pressure is 21000 kPa, except for,

1. N_2O with a filling ration of 0.667 > 24000 kPa
2. cyclopropane > 2400

- in practice all cylinders are tested to 24500 kPa irrespective of their intended use
- the maximal allowable expansion for a 400l cylinder is 0.56 ml

Safety

- generally includes,
    1. clear identification of the gas, and
    2. prevention of fire and explosions

- O_2, N_2O and mixtures containing these gases will support combustion, proportional to pressure

Gas	Valve End	Body[1]
Oxygen	White	Black
Air	Black & White	French Grey
Nitrous Oxide	French Blue	French Blue
Entonox (50:50)	French Blue & White	French Blue
Carbon Dioxide	French Grey	French Grey
O_2 & CO_2 (O_2 > 50%)[2]	White & French Grey	Black
Nitrogen	Black	French Grey[3]
Helium	Middle Brown	Middle Brown
O_2 & Helium	White & Middle Brown	Black
Helium & O_2	Middle Brown & White	Middle Brown

[1] the body colour designates the predominant gas, while the shoulder has quadrants of colour,
in addition, the name of the gas must be marked in proportion to the cylinder size

[2] mixtures are labelled by the percentage of the minor constituent

[3] usually a darker grey than that for carbon dioxide cylinders

Filling of Cylinders

- cylinders with pin-indexed valves are now filled by pin-indexed couplings (not always so)
- the larger free standing cylinders do not have pin-indexes, and the approved thread fitting on these cylinders is the same for,
    1. industrial air, medical oxygen, argon, helium and nitrogen
    2. nitrous oxide and industrial carbon dioxide

- oxygen, nitrogen, air, argon and helium are filled by pressure alone to ~ 13,700 kPa (2000 psi)
- liquefiable gases are filled by weight, a C size cylinder containing ~ 1.9 kg of N_2O or CO_2
- gas mixtures are prepared approximately according to Dalton's law of partial pressures
- *Carbogen* can also be prepared in this manner, as 5% CO_2 requires a partial pressure of only 650 kPa of the final 13,700 kPa, but requires a pressure of ~ 5000 kPa to liquefy at 15°C
- a slightly lower than 5% pressure is used as CO_2 compresses significantly more than an ideal gas

• ***Entonox*** requires a special procedure,

1. the correct amount of N_2O is compressed into the cylinder by weight (~ 5000 kPa)
2. O_2 is then bubbled through the N_2O causing the it to vaporise
   - small cylinders being inverted during filling
   - larger cylinders being filled with an eductor tube
3. when the final concentration is reached (48-52%),
   the cylinder pressure is ~ 12000 kPa (1700 psi) at 15°C

• this mixture remains gaseous unless subject to temperatures < -7°C

1. the ***pseudocritical temperature*** for this mixture is ~ -5.5°C
2. however, the ***pseudocritical pressure*** is slightly higher than the full cylinder pressure, therefore temperatures slightly less than this are required for liquefaction

• the formed liquid contains a lower percentage of dissolved O_2, therefore if used in this state will initially supply a higher concentration of O_2
• however, as the cylinder empties the percent O_2 will fall potentially delivering a hypoxic mixture
• it is recommended that cylinders should be stored at > 10°C in a horizontal position for 24 hours prior to use

Filling Ratios

Def'n: weight of the gas in the cylinder to the ***water capacity*** at 15°C

for a 400 litre N_2O cylinder $\rightarrow$ 1.87 : 2.80 kg
~ 0.667

• Australian Standards were set presuming the likely maximum operating temperature for cylinders would not exceed 65°C, and require that cylinder pressure should not exceed 80% of the hydrostatic test pressure at this temperature

Gas	Filling Ratio	Maximum Pressure	Minimum Hydrostatic Test Pressure
N_2O	0.667 0.625	17,000 15,500	23,500 20,700
CO_2	0.667 0.60	19,000 16,500	20,700 20,700
Cyclopropane	0.48	1830	2300

• as the densities of the liquids is < that of water, the actual volume of liquefied gas in a full cylinder is ~ 85% of the dry volume

Water Vapour Contamination

• cylinders should not be completely emptied, and should be stored with their valves closed
• with moisture in a full cylinder, adiabatic expansion of gas results in cooling with the potential for ice formation and interference with the regulator
• cooling is greatest with N_2O as in addition to adiabatic expansion, vaporisation of liquid N_2O takes up to 43 calories/gm at room temperature
• this is problematic due to the method of manufacture of N_2O, produced by heating ammonium nitrate,

$$\mathbf{NH_4NO_3 \ \textcircled{R} \ N_2O + H_2O}$$

• however, both nitric oxide and nitrogen dioxide are formed by side reactions
• these toxic, acidic substances are removed by scrubbing with caustic and by washing
• the purified N_2O is thus saturated with water vapour, which is removed by refrigeration and condensation, then chemical drying, yielding a final composition,

1. N_2O > 99.0%
2. O_2 < 0.1%
3. N_2 < 0.9%
4. NO & NO_2 < 1 ppm
5. CO < 10 ppm
6. CO_2 < 250 ppm
7. H_2O < 65 ppm (< 65 ml per 1000 litres)

• the H_2O content is measured by determining the ***dew point*** of the gas and comparing this to standard tables, reflecting the contamination by water, the ***Oakridge*** method / apparatus

Cylinder Valves

• standard Whitworth tapered thread, either 18.2 mm or 25.4 mm
• made of brass or bronze subjected to a hydrostatic pressure test ≥ 1.5 x their working pressure
• in accordance with ASB2472, they are also tested against leaks when shut-off
• medical gas cylinders have a unique ***valve spindle***, a 9.5 mm rod with 2 flat surfaces 5.5 mm
• the outlet is threaded in standard valves but not in pin-indexed valves
• valves on D size cylinders or larger may be fitted with a safety bursting disc,

a. threaded valves > 23 MPa
b. pin-indexed valves > 24.5 MPa

• bursting discs are only used on liquefiable medical gases, CO_2, N_2O and larger Entonox cylinders

Pin-Indexing Cylinder Valves

- introduced in Australia in 1955, now an ***international standard***
- only applies to medical gases
- originally designed for sized A, B, C, but is now used on some larger cylinders,

1. the general form of the valve is specified
2. indexing is achieved by 2 pins 6mm long and 4 mm in diameter
3. 6 hole positions are defined on the circumference of a 14.3 mm (9/16") circle, centred on the gas outlet
4. each position slightly overlaps → only 10 of the 15 permutations are possible

Pin-Indexing for Medical Gases		
Gas or Mixture	Pins	
Air	**1**	**5**
Oxygen	**2**	**5**
Nitrous Oxide	**3**	**5**
Oxygen & CO_2 (< 7%)	2	6
Oxygen & Helium (< 80%)	2	4
Carbon Dioxide	1	6
Carbon Dioxide & O_2	1	6
Helium	4	6
Helium & O_2 (< 20%)	4	6
Entonox	single pin	

- in addition to the standard system, Entonox uses a single pin at the 3 ½ position, 5.5 mm in diameter
- misconnection with pin 3 or 4 gases is prevented by the larger diameter and the guards of the yoke block, which allow ≤ 6° vertical misalignment of the valve stem
- on N_2O, O_2 and gas mixtures a ***Bodok*** seal is used, which is a neoprene washer with a metal edge and is self sealing due to gas compression of the neoprene
- nylon or plastic washers should not be used as they are not self sealing

CRYOGENIC GAS STORAGE

• each litre of liquid O_2 evaporates to 840 litres of gas at ambient pressure
• cost is ~ $1/5^{th}$ of bulk cylinder storage
• other gases stored in this manner include nitrogen and argon, tanker couplings for these are different and non-interchangeable
• the tank, or ***vacuum insulated evaporator*** **(VIE)**, consists of 2 shells, each made of steel
• the intervening space is a high vacuum filled with insulating powder
• O_2 can be liquefied at its ***critical temperature*** **-118.4°C**, but requires 5000 kPa (750 psi)
• LOX is stored at ~ -150°C and ~ 1000 kPa, which is well within the design pressure of the tank
• the tank is kept cool by latent heat of vaporisation ~ 6 calories / 100 litres of O_2 gas
• usually heat gain into the tank is less than that lost to vaporisation and tank pressure tends to fall, as does the supply pressure
• to maintain temperature and supply pressure, LOX is diverted through a ***pressure raising vaporiser*** when the tank pressure falls below ***~ 1000 kPa***
• this is effectively a heat exchanger with the external atmosphere and is controlled by a ***pressure raising valve***
• if minimal O_2 is used than tank temperature and pressure rise slowly, until escape through a safety valve is allowed at ~ 1500 kPa, allowing vaporisation and cooling
• thus, the system works best with continuous use, and is most cost efficient when,

1. annual usage > $7x10^6$ litres, or
2. anticipated peak demand > 300 l/min

• VIE should also be considered when annual usage is > $1x10^6$ litres
• a cylinder bank is always held as a backup supply
• older VIEs measured contents by weight, newer versions by ***differential pressure***
• LOX being ~ 1.1 kg/l, the basal pressure exceeds tank pressure in proportion to contents
• O_2 supplied by a VIE is extremely cold and is passed through a secondary heat exchanger

BULK CYLINDER STORAGE

• although large O_2 requirements can be met by LOX, supply of air cannot be done similarly
• O_2 has a boiling point of -183°C and N_2 of -196°C, which allows commercial preparation of these by fractional distillation
• medical air must be dry and contaminant free and is generally met with cylinder banks on pallets
• these frequently contain 20-30 G size (6000l) cylinders, supplying quantities from 110,000 to 240,000
• manifold cylinders are used and refilled without being removed from the pallet

PIPED GAS SUPPLIES

• O_2 and N_2O supply systems have common features, compressed air and suction being different
• supplies can be considered in 3 parts,

1. supply
2. distribution of reticulation
3. outlets

Medical Gas Supply

• whatever the normal supply source, VIE or cylinder bank, a backup supply must exist, equivalent to several hours average use
• systems with an anticipated peak demand < 300 l/min are usually supplied by cylinder banks, above this by VIE for O_2
• VIE is usually rated well above this, at ~ 2000 l/min or greater
• peak demand results in pressure differentials within the piping system, and thus determines much of the design, in order to avoid triggering low pressure alarms

• the "IN USE" supply delivers gas from the 1st stage regulator at either 1030 kPa or 690 kPa
• the reserve bank regulator is set lower, (~ 550-690 kPa), therefore begins to supply as the main bank fails
• a 2nd stage regulator reduces the ***line pressure*** to ~ 410 kPa (60 psi)
• other features of the supply system include,

1. pressure gauges - in use and reserve bank pressures
   - supply line pressure
2. safety relief valves - before and after (~ 620 kPa) the 2nd stage regulator
3. low pressure warning devices
   i. ***before*** the 2nd stage regulator < 655 kPa
      → amber warning lights indicating reserve bank operation
   ii. ***after*** the 2nd stage regulator < 345 kPa
      → red warning lights indicating line pressure failure
4. a switching device changing the settings of the two 1st stage regulators, so that the reserve becomes the "IN USE" bank, allowing replacement of the exhausted bank
5. an isolation valve beyond the 2nd stage regulator, with an emergency supply inlet and valve, allowing disconnection of the manifold for servicing

Medical Breathing Air

- supplied either by cylinder bank as above, or by a compressor plant on site
- compressors generally require > 15 outlets for air or venturi suction before they are economically viable
- air intake has to be clean, therefore only electric motors are used and compressors are oil free with teflon or carbon seals
- 2 compressors are required in case of failure, one usually set to operate at 690 kPa, the other at 550 kPa
- a switching arrangement is usually incorporated to alternate function and wear
- compressed air is usually heavily saturated with H_2O which must be removed
- this is present as a vapour, therefore the partial pressure is a function only of temperature, compression resulting in condensation with no increase in the partial pressure, above saturation pressure
- condensed water is removed in an ***after cooler***, using either air or water, and air is then stored in a reservoir tank
- a final air filter (5 μm) and drying column are passed through before the supply lines, which are regulated to 410 kPa
- these are usually arranged in parallel to allow servicing and also remove other contaminants, such as CO
- high pressure air (up to 690 kPa) may be used for tools, or alternatively oil free dry nitrogen, as water vapour condensation during gas expansion may result in freezing

Suction

• these should be capable of **40 l/min** free flow and at least **-60 kPa** (~ -500 mmHg)
• for effective suction, the wall ***time constant £ 4 sec***, which depends upon the flow resistance and system capacity
• in ward areas, where not all outlets are used simultaneously, design flow may be less than the theoretical maximum, as recommended by AS2120
• operating theatres should have a minimum of 4 suction points, at 160 l/min (4 × 40 l/min)

■ *Piped Vacuum*

• at least 2 pumps with automatic switching, operating through a vacuum storage container
• alternating duty cycles to avoid long 'idle' times
• bacterial filters and suction traps are incorporated
• the pump exhaust discharges above roof level, away from windows, air intakes etc.
• piplines constructed of seamless copper tubing, ≥ 6 mm diameter to service points
• identified by the words 'Medical Suction' and an arrow to indicate flow direction
• problems,

i.	bacterial contamination,	∴ filters required
ii.	water condensation,	∴ traps incorporated
iii.	failure may occur,	∴ back-up system required

■ *Venturi Suction*

• this may be medical or low moisture air, ejected at high velocity to entrain room air
• if blockage of the outlet occurs, pressurisation of the suction line may occur
• therefore, venturi suction should not be used where positive pressure may be deleterious, ie. chest drain suction
• venturi suction piped to theatres etc. must have a device incorporated to prevent pressurisation above 0.5 kPa (4 mmHg)
• venturi powered suction devices require at least 410 kPa driving pressure

Pipelines

• pipes should be colour coded and clearly labelled every 2 m,

1. medical oxygen - white
2. medical vacuum - primrose (yellow)
3. medical N_2O - French blue
4. medical breathing air - black and white

• there are 3 immediately possible mistakes with non-medical pipelines

1. pipes containing steam are silver-grey and may be confused with white in a dim light
2. non-medical compressed air is blue and may be confused with N_2O
3. dangerous material, or ionising radiation should be safety yellow and black, and confused with medical vacuum

• pipelines should be constructed of seamless copper pipe, tested to 1,400 kPa
• all pipes, valves etc must be oil & grease free
• on completion the line should be blown clean with medical air and tested at operating pressure for 24 hours and purged with the intended gas
• each outlet must be tested by the constructor to ensure correct gas composition, and this should be overseen by a medical representative

Wall Outlets

• all wall outlets today must have,

1. non-interchangeable, gas specific indexing, and
2. some form of integral labelling

• three types of indexed outlets are in use in Australia,

1. sleeve indexed system - CIG / Medishield
2. indexed circumferential lugs - Liquid Air
3. "quick connect/disconnect" - Schrader

■ ***Sleeve Indexed System SIS***

• has a screw thread, nominally Whitworth ¼" BSP, with an overall diameter of 13 mm and 19 threads / inch
• indexing is via the diameter of the surrounding sleeve which prevents cross-connection
• however, all outlets have the same thread, so no connection should be used without a sleeve
• there were some early female connections which were grooved to accommodate both medical air and oxygen, principally for driving ventilators
• however these should have been replaced as their use on an anaesthetic machine has the potential for administration of a hypoxic mixture

Sleeve-Indexing for Medical Gases		
Gas or Mixture	Outside Nominal	Inside
Nitrous Oxide	19.8	16.8
Entonox	20.8	17.8
Carbon Dioxide	21.8	18.8
Carbogen (O_2 & 5% CO_2)	22.8	19.8
Scavenging	23.8	20.8
Oxygen	24.9	21.9
Medical Air	25.9	22.9
Suction	26.9	23.9

• early wall fittings had the sleeve screwed onto the thread, so that replacement of the wall panel could result in misconnection
• since ~ 1970 the fitting has been fixed onto the gas line, with a pin-indexed thread block which matches the specific sleeve through the terminal plate
• SIS outlets are commonly self-sealing, via a plunger with a neoprene O-ring, held shut by the line pressure
• on suction outlets the plunger is spring loaded
• these outlets are suitable for gas driven ventilators, as line failure allow the ventilator to be driven by gas cylinders (cf. a line non-return valve which may not allow alternative power)
• the SIS system has been extended to accept a quick-connect fitting in addition to the standard screw fitting, the "Multepoint system"

Indexed Circumferential Lugs

• gas indexing is achieved by,

i. the diameter of the engaging nozzle
ii. the number and position of circumferential lugs
iii. the lug and slot width

• symmetrical configurations of 2, 3, and 4 lugs are used, with each being used for more than 1 gas
• differentiation being on the nozzle and slot sizes, as the nozzle increases, the slot width decreases,

a. 4 lug/slot - N_2O and N_2
b. 3 lug/slot - O_2, O_2 / N_2 mixture and Carbogen
c. 2 lug/slot - air and vacuum

• these may be self-sealing and are engaged by slight rotation of the connector to engage the lugs
• sealing is achieved by a flat neoprene washer

- ***Quick Connect / Disconnect Fittings***

• these are self-sealing units, held together by retaining tongues entering a groove on the probe
• disconnection is achieved either by rotation of the socket body, or by pushing it back, depending upon the design
• seal is achieved by a blunt conical probe against a neoprene washer
• specificity is achieved by diameter indexed collars and corresponding grooves in the socket

PRESSURE REGULATORS

• or reducing valves,

1. reduce the high storage pressure to workable levels, and
2. maintain a steady supply pressure in the face of a decreasing input pressure
   - providing the input doesn't fall below the desired output pressure
   - the outlet pressure should vary < 20% as a full cylinder discharges
   - the common design gives a rising output pressure as the cylinder pressure falls
   - with a 2-stage regulator, pressure will vary little until a cylinder is < 20% full

• modern anaesthetic machines are set to run between 274 kPa (40 psi) and 410 kPa (60 psi)
• common design uses a spring loaded diaphragm and spindle valve, output pressure being the equilibrium between spring tension and pressure against the diaphragm,

1. **direct acting** - driving gas acts to open the spindle valve
   - valve closing movement ***against*** the direction of gas flow
   - as cylinder pressure falls, outlet pressure also ***decreases***
2. **indirect acting** - driving gas acts to close the spindle/flap valve
   - valve closing movement ***with*** the direction of gas flow
   - as cylinder pressure falls, outlet pressure ***increases***

• thus, the direction of change of the static outlet pressure, as cylinder pressure falls, is dependent upon the closing action of the valve mechanism
• the degree of change in outlet pressure is determined by,

a. the initial cylinder pressure, and
b. the relative areas of the diaphragm and valve seat

- ***Flow***

• a small valve area achieve accurate static pressure regulation, however, causes a significant pressure drop at modest flows
• regulators in modern machines should allow at least 50 l/min, with an outlet pressure of 170 kPa or better
• at 10 l/min the pressure drop should not exceed 100 kPa from the static outlet pressure

- ***Temperature Cooling***

• adiabatic gas expansion results in cooling, proportional to the,

1. degree of expansion, and
2. rate of expansion

• therefore, at high flow rates, the temperature of modern regulators may approach -35 °C
• if the temperature falls below the dew point of the gas, then there will be condensation which may form ice and obstruct the orifice
• this is most likely with N_2O, which may already be cooled to 0°C leaving the cylinder and may contain significant amounts of water

- ***Temperature Heating***

• rapid opening of a cylinder may result in acute temperature rises up to 800 °C, due to the rapid compression of gas the effects of the shock wave entering the regulator cavity
• therefore, the inside components should be made of nonflammable materials

- ***M-Series Regulators CIG Medishield***

• these regulators replaced earlier Adams types in about 1960
• like the Adams, this design has the valve closing against the direction of gas flow, and outlet pressure ***declines*** with falling supply pressure
• the outlet pressure can be adjusted from 0-420 kPa via a hexagonal screw (increasing anticlockwise), and is usually set between 315-360 kPa
• a safety relief valve is positioned on the diaphragm plate, set by a spring at ~ 700 kPa
• the bell cover has ventilation holes in case of a high pressure leak

- ***"Minireg" Regulator CIG Medishield***

• currently used on most anaesthetic machines
• valve closing is ***with*** the direction of gas flow, and outlet pressure ***increases*** with falling supply pressure
• this might allow cylinder outlet pressure to rise above line pressure at < 1/3 cylinder volume
• to avoid this,

1. a ***compensator rod*** was used on all machines prior to 1976,
2. a 2 stage regulator has been used in all machines since

• like its predecessor, spring tension is screw adjustable, however, spring tension acts to open the neoprene valve washer, which opposed by the inlet gas pressure
• the washer / valve seat is attached to the compensator rod, which in effect exposes the valve seat to atmospheric pressure, effectively reducing the influence of cylinder pressure variations
• compensation is not perfect, and there is usually a small rise in outlet pressure with falling supply pressure
• the outlet pressure can be adjusted from 0-420 kPa via a flathead screw and is usually set between 350-380 kPa
• overpressure (> 1500 kPa) in the outlet chamber lifts the diaphragm and is vented to atmosphere

• in the ***two stage regulator***, there is an additional stage module, screwed in on the high pressure side of the regulator, the original spring/diaphragm regulating outlet pressure are the same
• this 1st stage module has a valve closing mechanism against the gas flow, therefore has falling output pressure with decreasing supply pressure
• this tends to offset the effects of the 2nd stage above, such that cylinder pressure varies only ~ 20 kPa from a full to almost empty cylinder
• the regulator is sleeve-indexed and the inlet contains a sintered metal filter
• it is designed for a maximum flow rate of ~ 200 l/min

- ***"Entonox" Demand Regulator***

• this is a 2 stage demand pressure regulator, which also incorporates a flap non-return valve for expiration with the face mask
• the regulator connects directly to the cylinder valve, indexed by a single large pin, and has a sintered bronze filter in the inlet
• the 1st stage is a spring loaded, valve closing *with* gas flow regulator, outlet pressure ~ 1400 kPa
• the 2nd stage is a large diaphragm, without spring, at 90 ° to the valve axis, which is opened by tilting and closes with the direction of gas flow
• therefore, as the cylinder empties, the 1st stage outlet increases and slightly greater inspiratory effort is required to initiate gas flow
• the high setting of the 1st stage means ~ 10% of the cylinder contents are unavailable for use

- ***Midogas Nitrous Oxide / Oxygen Blender***

• delivers mixtures above 25% O_2 by intermittent flow on demand
• inspiratory limb pressure falls < 1 cmH_2O can trigger flows > 180 l/min
• this also incorporates a flap non-return valve for expiration with the face mask
• earlier versions had humidification attachments, though, these are absent on present models
• unit controls include,

1. on/off- operating O_2 / N_2O simultaneously
2. blend lever - from 100% O_2 to 75% N_2O / 25% O_2
3. O_2 flush ~ 30 l/min emergency O_2

• two 1st stage regulators drop supply line pressure from ~ 345-410 kPa to 275 kPa (40 psi), thus eliminating any discrepancies between O_2 and N_2O line pressures
• the demand 2nd stage regulators are independent spring loaded diaphragms
• the mixing control is a variable double orifice, which varies the output from each 2nd stage regulator
• the outlet from the mixing chamber is protected by a non-return valve, beyond which enters the emergency O_2 supply
• below ~ 245 kPa O_2 line pressure, the automatic air inlet / oxygen depletion warning unit operates, releasing line N_2O to a whistle and opening the patient inspiratory limb to atmosphere

NB: the N_2O supply is not stopped in the event of an O_2 supply failure

FLOWMETERS

• most convert kinetic energy of flow to pressure & measure indirectly
• commonly this is via an aperture and pressure & flow are not linearly related
• alternatively pressure may be kept constant, and the aperture varied, ***variable area flowmeters***

▪ *Regulator Flowmeter T438 CIG*

• uses a variable pressure regulator to control outlet flow
• valve closure is against the direction of flow, therefore output falls with decreasing supply pressure
• the gauge shows the outlet pressure, with flow through a small orifice (~ 0.6 mm diameter), calibrated in flow from 0-14 l/min (early models 0-16 l/min)
• at maximum flow the back pressure is ~ 310-345 kPa

▪ *Pressure Flowmeter TM17 Medishield*

• a miniature pressure regulator reduces pressure to ~ 410 kPa
• outlet is controlled by a spindle valve, the gauge shows the outlet pressure, with flow through a small orifice (~ 0.6 mm diameter), calibrated in flow from 3-14 l/min
• at maximum flow the back pressure is ~ 380Pa
• because the gauge measures pressure, partial occlusion of the outlet will give an erroneously high reading, ie., the gauge is ***not*** back-pressure compensated
• these are not overly accurate, with,

a. ~ 500 ml error at 5 l/min
b. ~ 600 ml error at 14 l/min

• though they are robust and can be used in any position

Ball Flowmeters

- these are ***high pressure, backpressure compensated*** devices
- usually of the ***variable area, constant pressure*** design
- the ball chamber is on the high pressure side of the circuit, before the needle valve, thus modest changes in afterload have minimal influence on the reading
- these are useful for driving high pressure devices, such as venturi masks or nebulisers
- as the valve is downstream, fracture of the glass chamber allow free flow of gas
- the fittings are indexed, as the ball chamber is calibrated for each gas
- the pressure drop across the ball is constant for a given gas, depending only on,

    1. the weight of the ball, and
    2. the cross sectional area of the ball vs. the tube

    NB: $\delta P \times A$ provides the force to balance the weight of the ball ~ 102 mg

- as the ball weight is unchanged, so the pressure drop practically remains unchanged
- flow is characteristically ***turbulent***, so

$$W \propto \sqrt{\Delta P \cdot r}$$

- where ρ is the gas ***density*** and W is the mass flow rate, weight of gas/minute
- as the operating pressure increases, so the gas density will increase proportionately

    NB: therefore, at any given float level, increasing the operating pressure will increase the actual quantity of gas delivered, proportional to the square root of the pressure rise

- thus, flowmeters must be pressurised to their calibrated level to read correctly
- normally this is 410 kPa (60 psi) in Australia & NZ, but is 50 psi in the USA
- the flow tube must be vertically placed for correct reading,

    i. ~ 10° angulation $\rightarrow$ ~ 5% overread error
    ii. ~ 25° angulation $\rightarrow$ ~ 10% overread error
    iii. ~ 35° angulation $\rightarrow$ ~ 20% overread error

- usually accurate to within their smallest division + 10% of their reading
- many are within 100 ml ± 5%, ie. ± 350 ml at 5 l/min reading
- available in several flow ranges, from 0-2 l/min to 0-15 l/min
- American flowmeters are usually read at the centre of the ball, Australian & NZ at the top

Dynaval Vane Flowmeter

- manufactured by Liquid Air and is a backpressure compensated, dial flowmeter
- it has a semi-linear scale, compressed below 3 l/min, but fairly linear above
- the calibrated line pressure is ~ 300 kPa, and at 410 kPa it may under-read unless adjusted
- flow is adjusted via a needle valve at the outlet
- common units are 0-15 l/min with an accuracy of ± 3% (~0.5 l/min)
- gas is discharged into the circumference of the front of the unit, where it acts against a small vane on the opposite end of the needle indicator
- movement of the needle is resisted by a small hair spring
- gas then flows past the vane, through the back of the unit and the adjustment valve to the outlet
- fully on the unit can supply ~ 30 l/min
- the effects of back pressure must be extreme and on complete obstruction, no flow is indicated
- the unit is robust and will operate in any position

Wright's Respirometer

- this is not a true volume meter, but a wind ***velocity anerometer***
- accuracy is variable,

i.	flows < 3 l/min	→	may not register
ii.	steady flows < 6 l/min	→	~ 10% underreading
iii.	flows > 60 l/min	→	tendency to overread
iv.	minute volumes 4-24 l/min	→	~ 5% accuracy limits

NB: however, reliability and reproducibility is excellent, and ***changes*** in minute ventilation are accurately reflected

- the rotating vane has an area of ~ 3 cm^2 and flow resistance is small ~ 0.2 cmH_2O at 30 l/min
- therefore it is suitable for both SV and IPPV
- large errors may occur if the vane is bent or damaged in any way

Bourne Ventilation Monitor LS75

- consists of a detector and counter unit, relying upon turbulence induced by a small cross bar in the gas stream
- this turbulence is detected downstream by an ultrasonic detector, each flap of the vortex ~ 1 ml
- there are no moving parts and flow resistance is low, thus it is suitable for SV
- gives reasonable accuracy from 4-40 l/min and is little affected by humidity
- no alarm systems are incorporated

Rotating Bobbin Flowmeters

• often called "Rotameters", which is the British trade name
• these are ***constant pressure, variable orifice*** flowmeters, operating at ambient pressure
• thus, they are ***not backpressure compensated***
• they are accurate to 5% of the indicated flow + 0.5% of the full scale reading
• this equates to ± 3% over the mid 70% of their operating range
• they are calibrated for a specific gas, and are within 3% at 20°C at 1 Atm.
• ***temperature*** affects reading by altering density and viscosity, an increase in temperature from 10-35°C, for the common medical gases, results in,

i. ↑ viscosity ~ 7%
ii. ↓ density ~ 8%

• the influence of each depending upon the flow rate,

1. **low flow rates** → ***laminar*** flow ∝ **1/*viscosity***

   ↑ temperature → ↑ viscosity → tendency to ***overread***

2. **high flow rates** → ***turbulent*** flow ∝ **1/*density***

   ↑ temperature → ↓ density → tendency to ***under-read***

NB: at normal temperatures, several degrees δT has minimal effect upon accuracy

• simple flowmeters have a steadily decreasing taper and a flow ratio of ~ 1:10 over their range
• to improve accuracy in the low flow range, early designs used 2 rotameters in series
• rotameters linked in series are read from 1 rotameter only, those linked in parallel each have their own adjustment and are additive
• recent rotameters obviate the confusion by using a ***double conical taper*** tube
• the initial gradual taper gives good accuracy at low flows, the 2nd taper allowing a more compressed scale for higher flows
• commonly these tubes use ½ their taper for 25% of their maximum flow
• bobbin weight generally increases with maximum flow rate,

i. O_2 2 l/min ~ 535 mg
ii. O_2 5 l/min ~ 600 mg
iii. O_2 10 l/min ~ 710 mg

• early bobbins were aluminium, but weighed similar amounts to the modern plastic variety
• accuracy depends upon the bobbin being centred in the gas stream
• more than a few degrees vertical misalignment results in significant overreading
• stability has been enhanced by the double-skirt design, with angled notches to produce spinning in the gas stream
• older bobbins generated static electricity, especially at ***low flows*** where the annular gap was smallest, however this has been reduced by conductive glass tubing (stannous chloride) earthed through a gold band at the base
• the use of rotameters in hyperbaric chambers produces a tendency to overread, due to increases in ***both*** gas density and viscosity,

Flow ~ Reading / Öpressure

Quantiflex Monitored Dial Mixer

- developed by Fraser Sweatman in Canada in the 1970's
- supplies a mixture of N_2O and O_2 set by the percentage O_2 and the total flow
- each has a variable area ball flowmeter from 1-10 l/min, ie. total gas flow from 2-20 l/min
- these contain stainless steel balls, which are read from the centre, are accurate to,
    1. ± 5% in the lower 1/3
    2. ± 2% in the upper 2/3

- the mixer is totally dependent upon O_2, the pressure of which is set by the flow control, which is a variable pressure regulator
- as the flow control pressure increases, 2 slave regulators also increase their pressure, equalising the delivery pressures of O_2 and N_2O to the mixture control valve
- both N_2O and the O_2 slave regulators have double diaphragms to minimise the risk of failure
- if a leak develops, either,
    1. the actuating O_2 is lost to atmosphere and the N_2O supply is shut off, or
    2. N_2O is lost to the atmosphere, decreasing the $\%N_2O$ delivered to the patient

- the mixture control is 2 mirror image spindle valves on a joining thread
- this provides an accuracy better than ± 5% when operated at a line pressure of 400 kPa
- changes of line pressure of ~ 100 kPa reduce accuracy to ± 10%
- however, under no circumstances or setting is < 25% O_2 delivered
- the performance is not degraded by backpressure up to 170 cmH_2O, making it suitable for high resistance vaporisers such as the Fluotec Mk3, and back pressure generating ventilatory such as the Manley
- it is one of the few devices in use where O_2 is the last gas entering the common manifold

Oxygen-Air Blenders

- the "Flexiva" (Aga) and the Bird 5100 Blender operate on similar principals,
    1. first stage balancing regulators match the air and O_2 pressures
    2. second stage regulators finely balance pressures to the mixing valve
    3. the mixer is a proportioning reciprocal spindle valve
    4. these blend ± 5% over the O_2 supply range of 200-600 kPa
    5. flow up to 75 l/min may be achieved
    6. failing gas pressure activates poppets, which divert gas to an alarm whistle
    7. they are also available in N_2O / O_2 format
    8. modest backpressure (< 100 kPa) has little effect upon performance
        - suitable with Bird Mk 7-8 or Manley ventilators

VAPORISERS

• these are designed to add ***volatile*** agent to the gas mixture
• a vapour is any fluid below its ***critical temperature***, which strictly include N_2O and cyclopropane
• all those in common use are ***plenum vaporisers***, which in this context describes forcing fresh gas into a ***vaporiser chamber*** and expelling the vapour mixture
• this is then mixes with fresh gas to achieve the final desired anaesthetic concentration

Def'n: ***vapour pressure***, is that pressure exerted by a substance in the gaseous phase, (below its critical temperature), should that substance alone occupy a given volume, and is

i. independent of atmospheric pressure
ii. contingent only on the physical properties of the liquid and the temperature
iii. termed ***saturated***, when the gaseous phase is in equilibrium with the liquid phase at a given temperature

Def'n: ***boiling point***, is the temperature at which vapour pressure equals ambient pressure

Def'n: ***latent heat of vaporisation***, is the number of calories required to change 1g of liquid into vapour, without a change in temperature
specific heat, is the number of calories required to raise the temperature of 1g of a substance by 1°C, be it solid, liquid, or gas

- ***Splitting Ratio***

  - Halothane SVP ~ 30% (actually 32%)
  - desired concentration ~ 3%
  - final mixture must be diluted 3/30, or 1/10 times,
    therefore 1 litre of vapour laden gas to 9 litres of fresh gas
  - 1000 ml of vapour laden gas requires ~ 700 ml FGF into the vapour chamber
    ie. 9.7 l FGF delivery for 10 l output at 3%

  - if total flow from the rotameters = 5 l/min,

    then the ***bypass*** has (9 / 9.7) x 5 = 4.64 l/min,
    and the ***chamber*** 360 ml/min entering, and 514 ml leaving

    total flow at the common gas outlet ~ 5.15 l/min

• if relying on diluting fully saturated vapour, then the vaporiser must be ***agent specific***
• the irregular inlets and outlets of each channel must maintain a constant relative resistance over a range of flows

MCQ-EV14: Splitting ratio in bypass for isoflurane at 3% ?

- Isoflurane SVP ~ 33%
- desired concentration ~ 3%
- final mixture must be diluted 3/33, or 1/11 times,
  therefore 1 litre of vapour laden gas to 10 litres of fresh gas
- 1000 ml of vapour laden gas requires ~ 670 ml FGF into the vapour chamber
  ie. 10.67 l FGF delivery for 11 l output at 3%
- ***bypass ratio*** **= 670 / 10,000**
  ~ 1 / 14.9 (Answer = C: 1/13)

Flow Characteristics

• the output of all variable-bypass vaporisers is less than the dial setting at low flow rates < 250 ml/min, due to the relatively high ***specific gravity*** of the volatile agents
• at extremely high flow rates, > 15 l/min, the output is less than the dial setting, due to incomplete saturation and mixing with the vapour chamber
• the resistance characteristics of the bypass channel and the vapour chamber can change with varying flow rates,
• with increasing flow, if this remains laminar through the bypass chamber, but becomes turbulent through the vapour chamber, then the final vapour concentration will fall
• this occurs to some extend with an ether Boyle's bottle and the Fluotec Mk2
• the converse of this, with flow becoming turbulent through the bypass, is seen with the Goldman vaporiser, from 2-8 l/min

NB: totally turbulent, or totally laminar flow through both routes results in minimal proportional change when flow varies

Chamber Saturation

1. bubbled fresh gas - hood over gas inlet (Boyles' bottle)
   - sintered metal gas inlet below liquid (copper kettle)
2. vapour wicks - all common vaporisers

Temperature Compensation

• removal of vapour lowers temperature through ***latent heat of vaporisation***, which lowers the saturated vapour pressure
• temperature stability is improved by,

1. chamber material - metal has better thermal conductivity than glass
2. large heat sinks
3. metal meshes - in the liquid as for the Austox
4. manual compensation - thermometer & temperature graduated dial settings (Drager Vapor - halothane & methoxyflurane)
5. automatic compensation
   - despite the use of heat sinks and metal vaporisers, some temperature fall occurs
   - thus, to maintain output concentration, flow is adjusted in favour of the chamber

   i. bimetallic strip valves altering the splitting ratio
      - Fluotec, Pentec, Tritec, Enfluratec, etc.

   ii. thermocompensated bellows which contract and decrease chamber outflow resistance (EMO & Abingdon)

   iii. Teflon sleeve, at chamber outlet altering outflow resistance (Forreger Fluomatic)

NB: 1. the alteration of saturated vapour pressure from 25-15 °C varies between agents, therefore, this is another reason vaporisers are ***agent specific***
2. the alteration of the bypass ratio may be achieved by increasing bypass flow resistance (Fluotec Mk3, Pentec Mk2), or by decreasing resistance through the vapour chamber (EMO, Fluomatic, Fluotec Mk2)

The Pumping Effect

• pressurisation creates a chamber of vapour-laden compressed gas, which can flow backwards into the fresh gas bypass when the pressure is released
• this intermittent augmentation of output concentration = the ***pumping effect***
• this is more pronounced,

i. at low flow rates
ii. at low concentration settings
iii. at low liquid levels in the vaporiser
iv. rapid respiratory rates
v. high peak inspiratory pressures
vi. rapid drops of pressure during expiration

• mechanisms to reduce this effect include,

i. small vapour chamber size, relative to bypass chamber
ii. increased length of the vapour chamber inlet channel
iii. the use of baffle systems in the vapour chamber (Ohmeda Tec4)
iv. check valves prior to the common gas outlet

- ***Carrier Gas Composition***

• when the carrier gas is rapidly switched from 100% O_2 to 100% N_2O there is a sudden decrease in vaporiser output, followed by a slow rise to a new steady state
• this is attributed to N_2O being more soluble in the vapour than O_2, therefore the quantity of gas leaving the vapour chamber is transiently decreased
• the reason for the new steady state value is less understood
• newer units, such as the Ohmeda Tec4 and Drager Vapor 19.1, the output is less with N_2O as the carrier gas
• conversely, the output of some older vaporisers is increased with N_2O as the carrier gas
• the new steady state is achieved faster at higher flow rates irrespective of the direction of change
• factors which influence the change with carrier gas composition include,

i. viscosity and density of the carrier gas
ii. relative solubilities of the carrier gases in the volatile agent
iii. the flow splitting characteristics of the specific vaporiser
iv. the dial setting

Classification of Vaporisers

1. nonspecific, or vapour specific
2. calibration
   - over what range and under what conditions (temp.)
3. temperature compensation
   - automatic or manual, over what range, and with what error
4. flow stabilised
   - flows from 0.5-10 l/min should be within 10% of the designated concentration
5. back pressure compensated
   - should show **< 2x *increase*** in concentration at the lowest setting, and less than the lowest vapour setting when set to zero (not off),
   i. at all flows from 0-10 l/min
   ii. with back pressures ≤ 40 cmH_2O
   iii. for up to 1 sec, up to 20 times / minute
6. flow resistance
   - low resistance makes the vaporiser suitable for use within the breathing system, this should offer < 1 cmH_2O/15 l/min (< 0.06 cmH_2O/l/min)
   - high resistance units can only be used prior to the breathing circuit

- ***Examples***

a. Goldman
- vapour specific, uncalibrated
- uncompensated, unstabilised
- low resistance vaporiser

b. Drager Vapor
- vapour specific, calibrated
- manual temperature compensated, flow stabilised
- back pressure resistant, high resistance vaporiser

c. Fluotec Mk2
- vapour specific, calibrated
- automatic temperature compensated, high flow stabilised
- back pressure sensitive, high resistance vaporiser

d. Fluotec Mk3
- vapour specific, calibrated
- automatic temperature compensated, flow stabilised
- back pressure resistant, high resistance vaporiser

Boyle's Bottle

Def'n: agent specific, uncompensated, unstabilised, moderate resistance vaporiser

• various models are available, intended for different agents,

1. ether
   - large bottle, 8.8 cm in diameter with a hooded plunger
   - design volume of 300 ml with a surface area of ~ 52 cm^2
   - change in vapour concentration ~ 3x with plunger up to fully down
   - maximum vapour concentration ~ 50% ether at 20 °C
   - flow resistance varies with degree on and plunger position from 4-10 cmH_2O
2. halothane / trichlorethylene
   - smaller, 6.3 cm diameter, for 100 ml of either liquid, with 26 cm^2 area
   - there is no plunger on the halothane model to avoid very high concentrations
   - in the inlet, instead of the end-hole, there is a side-hole and output tends to rise with increasing flow from 4-8 l/min
   - maximum concentrations are 8-10% halothane

• all models deliver high concentrations when first turned-on, as the chamber contains saturated vapour at ambient temperature

• the vapour pressure falls quickly as the liquid temperature falls, due to the small surface area and inability to maintain chamber saturation

Goldman Vaporiser

Def'n: vapour specific, uncalibrated, uncompensated, unstabilised, low resistance vaporiser

- originally designed for halothane and is deliberately inefficient
- maximum halothane concentration ~ 3% at 8 l/min at 20°C (≤ 4% max.)
- vapour chamber is a glass bowl, holding ~ 30 ml of liquid, diameter ~ 4.4 cm, SA ~ 15.2 cm^2
- 3 models were manufactured,
    i. Mk1 and Mk2 had 3 divisions between "on" and "off"
    ii. Mk1 had a self locking pin in the "off" position
    iii. Mk2 had a click stop at each position
    iv. Mk3 had only 2 divisions between "on" and "off"

- the gas bypass valve is a vertical mounted cylinder, with the bypass gas flowing horizontally
- the bypass orifice is 1.8 cm diameter, 2.5 cm^2 area
- the chamber orifices are wedge shaped, 3 cm^2 area
- the Mk2 was fitted with 22mm tapers, allowing it to be placed "in circuit"
- the currently supplied Mk3 has 23 mm tapers and therefore cannot be placed in the circuit

Rowbotham

- similar to the Goldman unit, originally designed for trichlorethylene but later adapted to halothane, both models having 22 mm taper connections
- flow pathways are narrower and therefore offer higher resistance than the Goldman
- maximum concentrations of halothane are ~ 2.5% at 5 l/min FGF

Komesaroff

- again similar to the Goldman, originally designed for methoxyflurane, later models for enflurane and halothane
- low flow resistance and fitted with 22 mm tapers for use "in circuit"
- the operating device is the entire top which rotates anticlockwise

Fluotec Mark 2

Def'n: vapour specific, calibrated
automatic temperature compensated, high flow stabilised
back pressure sensitive, high resistance vaporiser

• temperature compensation is achieved by altering the resistance in the ***vapour chamber*** pathway
• there is ***concentration enhancement*** at delivered flows of < 3 l/min with maximum settings
• this is a deliberate design feature, allowing delivery of high concentrations to circle systems at low fresh gas flows,

1. at dial settings above 2.5%, and FGF between 250 ml - 3 l/min

   → output concentration exceeds dial concentration

2. maximum output occurs at ~ 500 ml/min FGF and dial setting of 4%

   → ~ 7% halothane

• uses variable resistance in the bypass channel to achieve flow splitting
• movement of the dial anticlockwise opens the entrance and exit channels to the vapour chamber and partially occludes the bypass channel
• the flow path is tortuous, with abrupt changes in channel size, flow becoming uniformly ***turbulent*** above 4 l/min FGF,

1. at FGF = 500 ml/min and 4%,the vapour chamber flow ~ 70%
2. at FGF = 5 l/min and 4%, the vapour chamber flow ~ 12%

▪ *Vapour Chamber*

1. contains ~ 150 ml of halothane
2. ~ 40 ml is held in a series of 3 cloth wicks
3. combined SA ~ 450 cm^2

▪ *Temperature Compensation*

• uses a temperature sensitive bimetallic strip, made of ***brass*** and ***low expansion steel***
• rising temperature curves the strip, which has a disc on the end, toward the 3 mm vapour chamber outlet, thereby increasing resistance, the reverse occurring with decreasing temperature
• there is a rise above dialled settings above 1%, with temperatures > 24°C
• at 35°C, delivery may exceed dialled concentration by ~ 20%

- ***Pumping Effect***

• the vapour pathway has a large volume ~ 600 ml, cf. the bypass chamber ~ 5 ml
• a 30 cmH_2O intermittent pressure releases ~ 1.2 ml of halothane saturated vapour into the bypass by reverse flow, which is then added to the normal chamber outlet flow

i. this is ***independent*** of dial setting, providing the vaporiser is ON
ii. the small volume of vapour released is most significant at ***low flows***, and at ***low concentrations***
iii. only of clinical importance with a low flow circle absorption technique

NB: at FGF = 500 ml/min, with a pumping effect of 30 cmH_2O x 10/min, the output concentration will be ~ 8% irrespective of the dial setting;
FGF > 4 l/min with pressures < 20 cmH_2O retrograde flow is insignificant

• in the OFF position, the Fluotec Mk2 has 2 venting holes from the vapour chamber which may leak small quantities of halothane into the circuit (normally < 0.1% at 3 l/min)
• there was a special model made, the Mk2 MJ (Michael Johnstone),

1. no enhancement above dialled concentration at low flows
2. calibrated from 0-10% to allow low FGF circle anaesthesia

Pentec Vaporisers

• the Pentec Mk 1 is a variable bypass vaporiser, with temperature and flow compensation, similar to the Fluotec Mk2
• designed for methoxyflurane, it has a greater wick area, and is graduated from 0.1-1.5%
• it is susceptible to the pumping effect, however, flow and temperature compensation are good

• the Pentec Mk2 closely resembles the Fluotec Mk3, being a variable vapour channel vaporiser, with temperature and flow compensation, backpressure resistant with high internal resistance
• the principal difference is the presence of a ***"max" position*** which delivers virtually saturated methoxyflurane vapour

Fluotec Mark 3

Def'n: vapour specific, calibrated
temperature compensated, flow stabilised
back pressure resistant, high resistance vaporiser

• differs from the Pentec Mk2 in that there is no "max" position and it is fully temperature compensated

Characteristics

1. calibrated to deliver halothane from 0-5% in 0.5% increments
2. capacity ~ 170 ml total
3. wick volume ~ 35 ml
   - spiral pathway, with wick between coil and vaporiser wall
4. flow stabilisation is at all concentrations up to 10 l/min, though,
   i. at 1 l/min and 5% → ~ 5.5%
   ii. at 10 l/min and 5% → ~ 4.5%
5. temperature compensation is via a bimetallic strip ***above*** the vaporising chamber
   - decreasing the bypass gas flow with decreasing temperature
6. back pressure ≤ 28 cmH_2O has virtually no effect
7. resistance → δP ~ 35 cmH_2O at 15 l/min
   - flow is principally turbulent, so pressure gradient rises sharply as flow increases
   - maximal pressure drop occurs at low dialled concentrations

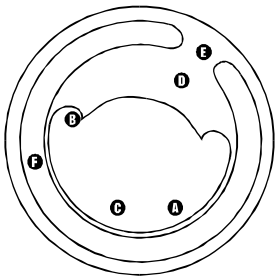
NB: backpressure will rise sharply, and may exceed 200 cmH_2O with flows > 25 l/min, therefore, high resistance vaporisers should be positioned on the back-bar of the anaesthetic machine, upstream to the emergency O_2 flush

Enfluratec

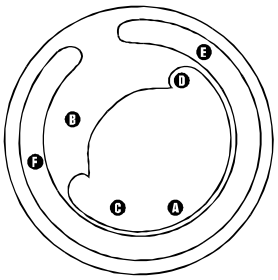
Def'n: vapour specific, calibrated
temperature compensated, flow stabilised
back pressure resistant, high resistance vaporiser

• essentially the same as the Fluotec Mk3
• excellent thermal stability from 20-36°C
• the output is slightly affected at higher concentrations, due to the lower saturated vapour pressure and higher specific heat cf. halothane
• the calibration is from 0-5%, in 0.2% steps to 1%, then 0.5% steps thereafter
• like the Fluotec Mk3 it is a high resistance unit and can only be used out of the breathing circuit, and can develop high back pressures

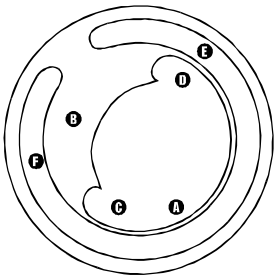
- ***Channelling*** ***Fluotec Mk3 & Enfluratec***



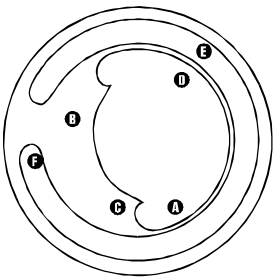
Vaporizer OFF



0.2% Vapour Concentration



1.0% Vapour Concentration



Max Vapour Concentration

1. in the OFF position, gas enters the central chamber **A** and leaves via the large bypass outlet channel **B**
   - in this position, flow resistance is ~ 20% of that in any ON position
2. at low dial settings, the large bypass channel **B** is occluded, flow entering **A** is split,
   i. bypass gas passes through the temperature compensated chamber to the outlet, through **C**
   ii. the remainder through the vapour chamber inlet **D**, and is ducted down a sleeve to the base of the vapour chamber
      - this sleeve forms the outer wall of the bypass chamber, and thus maintains temperature compensation
3. from the base of the vapour chamber, gas passes up a metal spiral between cotton wicks, each having a SA ~ 270 cm^2, giving a total wick area of 0.5 m^2
4. the saturated vapour leaves the chamber to the outer channel through **E**, this is a calibrated channel of uniform width but increasing depth
5. leaves the circular variable resistance channel through **F**, to mix with gas from the bypass chamber
6. once on, the gas pattern is not altered, only the resistance of the outlet channel decreases with anticlockwise rotation, allowing more gas to flow through the vapour chamber
7. on the Pentec ***only*** ("max") rotation past the safety stop closes the thermostat bypass channel **C**, with all gas passing through the central chamber **C**

Ohmeda Tec 4

• used on all contemporary Ohmeda machines, with up to 3 units being attached to a manifold to the right of the flowmeters
• the vaporiser manifolds interlock forming a safety device, which ensures,

i. that only 1 vaporiser can be turned on at any 1 time
ii. gas flow enters only the vaporiser which is turned on
iii. minimal unwanted trace vapour after a vaporiser is turned off
iv. locking the vaporisers into the circuit, with seating of the inlet and outlet seals

• each unit has a single control dial, which requires simultaneous depression of a control dial release button to be activated, preventing accidental operation
• a pair of mobile extension rods are positioned behind the control dial and extend laterally when the unit is turned on
• this movement is transmitted either directly or indirectly to an adjacent rod or vaporiser
• the older manifold present on the 8000 and Modulus II models allow simultaneous operation of 2 vaporisers if the centre unit is removed
• the manifold carries a warning label, advising the user to place the units adjacent each other
• the Modulus II Plus has an advanced manifold, with a mobile interconnecting bracket units
• 2 filling mechanisms are available, a screw-cap filler and the agent specific keyed filler
• both are positioned low to prevent over filling,

i. agent volume ~ 125 ml
ii. wick volume ~ 35 ml

• temperature compensation is by ***bimetallic strip*** in the bypass chamber, above the vapour chamber
• both inlet and outlet to the vapour chamber are protected by a ***baffle system***, which protects against spilling and the pumping effect
• the common gas outlet has a check valve which also protects against the pumping effect

Drager Vapor 19.1

• the Narkomed anaesthesia machines use the Drager Vapor Exclusion system, which is a series of interconnected cams & levers behind the manifold
• this system is external to the vaporisers, cf. the Ohmeda system
• this system will function with any of the units removed, though a short-circuit block must be installed to prevent leakage
• in the off position, the vapour chamber is totally separated from the bypass channel, its inlet and outlet are interconnected and excess pressure is vented to atmosphere at < 0.5 ml/24 hrs at 22°C
• 2 filling mechanisms are available, a screw-cap filler and the agent specific keyed filler
• both are positioned low to prevent over filling,

i. agent volume ~ 140 ml
ii. wick volume ~ 60 ml

• temperature compensation is via an ***expansion element***, varying resistance in the bypass channel
• backpressure compensation is via a long spiral inlet tube, and there is no check valve in the common gas outlet

Hazards

1. incorrect agent - only if the screw-cap filling devices are used
2. tipping
   - entry of agent into the bypass channel can result in excess vapour concentrations
   - the Tec 4 is slightly more immune than the Vapor 19.1 due to the baffle system
   - however, if either is tipped they should be flushed for 20-30 minutes prior to use
3. simultaneous agent administration
   - with the centre vaporiser removed on older Ohmeda machines
   - requires adjacent placement of vaporisers
4. leaks
   - commonly associated with vaporisers, usually the filler cap being loose
   - between the O-ring seal and the manifold
   - the Ohmeda machines require a negative pressure leak test

Free-Standing Add-On Vaporisers

- usually positioned between the common gas outlet and the patient circuit
- multiple hazards,

1. tipping - excessive vapour concentration
2. administration of multiple agents
3. O_2 flushing (35-75 l/min) can deliver excessive vapour concentrations
4. reverse connection of the vaporiser and ~ 2x vapour concentration
5. some freestanding units have a check valve in the vaporiser outlet to minimise the pumping effect, which may mask machine leaks with IPPV

Safety Coding of Liquid Agents			
	Colour coding	Block Index (slot position)	Bottle Neck Size & Thread
Halothane	red	centre left	Manufacturer agreed & agent specific
Enflurane	orange	centre right	
Isoflurane	purple	top right	
Methoxyflurane	green	top left	

Safe Use of Flammable Agents

1. operating theatre design
   i. adequate ventilation to prevent accumulation of spilled agent
   ii. humidity ≥ 55% to prevent to occurrence of static sparks
   iii. low electrical resistance flooring
      - between 2 points 64 cm diameter, 1 meter apart > 25 kΩ
        < 0.5 MegΩ
      - resistance must not be so low as to risk ordinary electrocution
      - the lower limit may be reduced to 10 kΩ in class A or B areas
   iv. theatres must have a yellow or black sign stating they are either suitable or unsuitable for the use of flammable anaesthetic agents
2. anaesthetic and operating equipment
   i. must not be capable of retaining a static charge
      - eg. antistatic anaesthetic hoses
   ii. electrical equipment must be intrinsically safe and labelled as such
   iii. equipment capable of igniting an agent may be used in the theatre, providing only the intrinsically safe part comes into the ***hazardous zone*** near the patient and anaesthetic machine (~ 30 cm above patient and machine)
      - eg. fibreoptic light sources, ECG monitors
3. theatre attire
   i. the outer layer of clothing is most important
   ii. nylon and similar synthetics are safe as underclothing, however should be avoided on the outer layer, which should be cotton or linen
   iii. footwear is extremely important
      - the antistatic properties of rubber deteriorate with time and soiling
      - cotton or linen overshoes over leather shoes or bare feet are preferred

ANAESTHESIA MACHINES

• all are basically gas and vapour delivery systems, thus have various features in common,

1. all have gas delivery into pressure regulators, then into flow regulators
2. the high pressure circuit ends at the flowmeters, and low pressure (< 100 cmH_2O) is present from the common gas manifold onwards
3. from the common gas manifold, out of circuit vaporisers may be used to add anaesthetic vapour
4. flow limited gas ± vapour is then delivered to the ***common gas outlet***
5. an adjustable pressure limiting valve ("pop-off")
6. O_2 failure safety warning device

The High Pressure System

• in a generic "two gas" machine, both O_2 and N_2O have 2 supply sources,

a. pipeline supply ~ 410 kPa
b. cylinder supply
   i. O_2 - from ~ 13,700 kPa (2000 psi) to ~ 350 kPa
   ii. N_2O - from ~ 5,100 kPa (745 psi) to ~ 350 kPa

• there is a "bourdon-type" pressure gauge for both line and cylinder supplies
• regulated cylinder pressure is less than line pressure to prevent bleeding of cylinder gas into the circuit should the cylinder valves be left open
• in addition, non-return cylinder check valves are usually located ***after*** the cylinder pressure gauges, thus once cylinder pressure is registered it should not fall while line gas is being used
• a ***fail-safe system*** is located downstream, which serves to ***shut off*** the N_2O supply should the oxygen supply fail, plus sound an audible alarm
• older devices, such as the "Bosun" whistle, Ritchie whistle and Howison alarm have been superseded
• in accordance with Australian standards, this must be powered by the failing gas, ie. O_2, therefore most current models have an O_2 reserve canister which powers the alarm,

1.
2.

• American machines have both audible and visual alarms registering O_2 supply failure
• in many machines there is a 2nd stage O_2 pressure regulator, which reduces the supply pressure to ~ 100 kPa, and eliminates any significant variation in pressure with line pressure change
• the ***flow control valves*** form the demarcation between the high and low pressure sides of the circuit

The Low Pressure Circuit

• flow from individual rotameters enters the ***common gas manifold*** and may be directed through a calibrated, variable bypass vaporiser
• this mixture then proceeds to the ***common gas outlet***
• some machines have an internal ***check valve*** prior to the CGO
• this helps prevent the effects of breathing circuit pressurisation on vaporiser function, however, it significantly alters the requirements for checking the integrity of the low pressure circuit
• many current machines have O_2 / N_2O proportioning systems integrated in the rotameter control to prevent administration of a hypoxic mixture
• these may be either ***mechanical*** or ***pneumatic***, delivering ≥ 25% O_2

Flowmeter Assembly

• the flow control valve assembly is composed of,

i. a flow control knob
ii. a needle valve
iii. a valve seat, and
iv. a pair of valve stops

• this can receive its pneumatic supply direct from the line supply at 410 kPa, or via 2nd stage regulators at 100-200 kPa (14-30 psi)
• extreme clockwise rotation of the needle valve would result in damage to the needle and the seat, thus valve stops are placed, which come into apposition at zero flow in most cases
• the flowmeter subassembly is composed of,

i. flowtube
ii. indicator float with float stops
- plumb-bob
- rotating skirted float
- ball float
iii. indicator scale

- ***Safety Features***

1. the O_2 rotameter control knob is physically distinct
   i. scalloped octagon in shape
   ii. set forward of the other controls
   iii. larger diameter
2. flowmeter subassemblies are house in colour coded, pin specific housings, and flowmeter scales are calibrated specifically for that assembly
3. O_2 / N_2O proportioning systems

- ***Problems With Flowmeters***

1. leaks
   - older machines traditionally ordered gases such that O_2 was positioned first and N_2O last
   - a leak anywhere before the N_2O flowmeter would result in loss of more O_2 than N_2O and the potential for delivery of a hypoxic mixture
   - this effect of selective O_2 leak is further exacerbated by intermittent back pressure from IPPV
   - this effect is overcome by ensuring O_2 is the last gas into the common gas manifold
   - USA machines all position O_2 to the far right for this reason (Eger 1963)
   - alternatively, various baffles in the common gas manifold will produce the same effect
   - delivery of a hypoxic mixture can still occur with downstream addition of O_2, leakage prior to the joint of the O_2 flowtube and the common gas manifold
2. inaccuracy
   - incorrect assembly, or assembly of unmatched components
   - dirt or static electricity causing the float to stick, especially at low flows
   - backpressure will cause the float to under-read the actual flow
   - alignment away from the vertical axis will cause overreading
3. ambiguous scale
   - at least 2 reported deaths, when the scales were beside the flowmeter, and the operator read an adjacent and erroneous scale
   - this has been solved by etching the scale directly into the flowtube

Proportioning Systems

- ***Link-25 Proportional Limiting Control System***

• used on most contemporary Ohmeda machines, such as the Modulus II
• uses mechanical integration of the N_2O and O_2 control valves, allowing independent adjustment of either valve, but intervening to maintain $\geq 25\%$ O_2
• the N_2O and O_2 control valves are identical, except a 14-toothed sprocket is attached to the N_2O control and a 28-toothed sprocket to the O_2 control
• this results in a mechanical ratio of 2:1, the final 3:1 ratio being produced by the respective 2nd stage regulator setting of 26 and 14 psi respectively

- ***Oxygen Ratio Monitor Control***

• produced by Dräger of North America and used on their machines
• this is a pneumatic system, designed to provide a minimum of 25 ± 3% O_2
• at low flows (< l/min), this device controls O_2 to considerably higher than the nominated 25%
• the ORMC limits N_2O to maintain $\%O_2$, as opposed to the Link-25 which actively increases O_2 flow
• composed of an O_2 chamber, a N_2O chamber, and a N_2O slave control valve, all of which are interconnected by a horizontal shaft
• the pneumatic input is from the respective flowmeters, which are unique in that they have ***flow resistors*** located downstream from the flow control valves
• the backpressure from these resistors determines the minimum $\%O_2$ by moving the shaft and closing the N_2O slave control valve

- ***Proportioning System Limitations***

1. incorrect supply gas
   - neither the Link-25 and the ORMC will detect supply of gas other than O_2
2. defective pneumatics / mechanics
   - the Link-25 depends upon correct supply pressures from the 2 nd stage regulators
   - the interconnecting chain must be intact
   - the rubber diaphragms, flowtube resistors and N_2O slave control valve of the ORMC must be intact
3. administration of a 3rd inert gas - only O_2 and N_2O are linked
4. downstream leaks

Multiple Vaporiser Positioning

NB: the agent ***most volatile***, ie. the highest saturated vapour pressure, should be situated ***downstream*** from other agents

1. the less volatile agent delivers less vapour into the gas stream
   - this is stated by JR but is incorrect, this is a function of the dialled concentration and performance of the vaporiser
2. less of the gas stream is delivered into the vapour chamber of the more volatile agent, thus there is less contamination
3. when contaminated, due to the high bypass ration, the amount of low volatile agent delivered is significantly less

• the reverse situation, say with halothane upstream from methoxyflurane, results in significant contamination of methoxyflurane with halothane
• when used again, the methoxyflurane unit will deliver high concentrations of halothane due to its relatively low bypass ratio

- ***Correction For Multiple Vaporisers***

1. use only 1 vaporiser on the machine at any time
   i. Cyprane Selectatec, and
   ii. Penlon selecting systems
      - makes using a given agent a deliberate act
      - allows easy servicing and filling outside theatre
      - damage to vaporisers in connection/disconnection
      - damage to the mounting seals
      - inadvertent tipping of the vaporiser
      - increases flow resistance
2. Ohmeda Interlocking Vaporisers
3. Drager Vapor Exclusion system

Non-Return / Safety Relief Valve

• most CIG-Medishield units have a ***non-return valve*** between the last vaporiser on the manifold and the CGO
• this is not an anti-pumping valve cf. the Ohmeda machines
• this acts to prevent reverse flow should a leak in the low pressure circuit on the back-bar
• the most likely cause is fracture of one of the flowtubes
• this prevents flow of circle contents back into the manifold and allows supply of gas to the circle via the O_2 flush
• this is usually combined with the ***safety pressure relief valve***, which is a spring loaded disc, designed to blow-off at ~ 50 cmH_2O
• usually mounted at the right of the back-bar, incorporated with but downstream to the non-return valve, and has a manual override button

Emergency O_2 Flush

• usually set to 30-35 l/min and is supplied from the high pressure O_2 line, prior to the flowmeter or 2^{nd} stage regulator ~ 350-410 kPa
• input into the circuit is immediately upstream from the CGO in most machines, and downstream from CGO check valves where they exist
• gas may pass through a freestanding vaporiser,
   i. concentration is usually ***less*** than the dialled concentration
   ii. flow resistance is greatly increased and O_2 supply may be greatly reduced

• some early designs allowed the button to be locked in the ON position, which may result in,
   i. awareness
   ii. pneumothorax in the presence of valve malfunction or misconnection
      - should be limited by the safety relief valve, except where there is a check valve at the CGO

THE BREATHING CIRCUIT

Conical Fittings

- the international and Australian Standard (AS2496) fittings are **22 mm & 15 mm**
- these diameters are nominal at about the middle of a **1:40 conical taper**
- the fittings may be metal or plastic, because the later deforms dimension specifications are inappropriate and satisfactory fit into a test gauge is required
- to avoid misconnections, the Australian Standard specifies, for a circle absorption circuit,
    i. male fittings at both inspiratory and expiratory ports from the absorber
    ii. a female fitting for the reservoir bag
    iii. a retention fitting may be used for the reservoir bag, providing it does not allow attachment of an ordinary 22mm fitting

Other Fittings

- there are 3 other tapers in common use,

1. 23 mm / 1:36 - for high resistance vaporisers
   - used only on the back-bar of the anaesthetic machine
   - also used for free standing vaporisers (in-male/out-female)
2. 30 mm / 1:20 - a male fitting discharging expired gas
   - a spirometer may be connected, cf. in circuit spirometers
3. 19 mm / 1: - widely used in Australia for active scavenging
   - additional lug on the outside to prevent accidental attachment of a 22mm female connector

Site	Fitting	Comment
Common gas outlet	15 / 22 mm coaxial	• adult circuits • Ayre's T-piece
Insp / Expiratory limbs of circle absorption circuit	22 mm male Inspiratory limb may be coaxial with 15 mm female	
Reservoir bag	22 mm male	• circle side may be female fitted with non-obtrusive retention fitting
Patient connection	15 / 22 mm coaxial	• 22 mm for face mask • 15 mm for ETT / LMA
ETT connector	15 mm male	• minimum ID ~ 11 mm
Breathing hoses	22 mm female at machine end	

Breathing Hoses

a. black antistatic rubber
   - available in lengths from 28 cm to 1.1 m, nominal 22 mm has,
   i. internal diameter ~ 20 mm allowing secure elastomeric fit
   ii. internal volume ~ 450 ml / meter length
   iii. compliance ~ 1 ml/cmH_2O
   iv. flow resistance ~ 0.15 cmH_2O / m / (30l/min)
   - stiffens with age decreasing elastomeric fit and compliance
   - able to be wound into a 50 mm ID spiral without kinking

b. disposable plastic
   - usually made of ***polypropylene***, which does not withstand autoclaving
   - available in up to 2 meter lengths, with the same ID but thinner walls, smaller corrugations and a narrower external diameter
   i. internal volume ~ 400 ml / meter length
   ii. compliance ~ 0.3-0.8 ml/cmH_2O
   - decreased elasticity renders these more prone to kinking
   - also form pinholes and split more readily
   - however, they are light weight

Reservoir Bag

- made of rubber or neoprene, both of which have the correct compliance
- ***antistatic*** bags are usually made of carbon impregnated neoprene
- total resistance for these is < 1 MegΩ from neck to tail
- agreed sizes are,

a. 500 ml, 1 litre, 1.5 litre - designed for 15 mm connectors

b. 2.0 litre, 3.0 litre, and 5.0 litre - designed for 22 mm connectors

c. 4.0 and 6.0 litre bags are also produced

NB: measured at 2.5 cmH_2O distending pressure $\rightarrow$ ± 15%

- batch samples are subject to a pressure-volume (compliance) test
- this permanently deforms the bag, increasing its volume and decreasing the resistance,
   i. inflated to 2.5 cmH_2O, its nominal capacity
   ii. then inflated to 4 times nominal capacity
   iii. pressure should not exceed 50 cmH_2O, nor fall below 30 cmH_2O
   iv. on returning to 2.5 cmH_2O, bag volume should have increased ≤ 10%

- most new bags usually show their peak pressure at ~ 4x nominal volume, decreasing by ~ 15% beyond this point to eventual breakage
- during operation, external squeezing may produce far greater pressures, and this does not protect against barotrauma

Twin Canister Absorption

- each canister has a total volume ~ 650 ml, of which ~ 600 ml is available for soda lime
- a single canister, moderately well packed holds ~ 450 g, with an air space ~ 300 ml
- flow resistance through the canister depends mainly upon the diameter (75 mm ID) and cross sectional area (~ 45 cm^2)
- at 30 l/min the pressure drop is ~ 0.5 cmH_2O
- this varies with packing, resistance being highest with small granules packed tightly

Soda Lime

- barium hydroxide lime (Baralyme) is used in the USA and some other centres
- modern soda lime contains (Miller),

i.	calcium hydroxide	~ 94%
ii.	sodium hydroxide	~ 4-5%
iii.	potassium hydroxide	~ 1%
iv.	silicates	< 1% by weight

- water content can vary from 14 - 19% with minimal effect
- however, below 10% absorption falls markedly, and above 20% slightly
- soda lime is considered exhausted with a breakthrough of 0.5%, when the mixed expired ~ 4%
- more effective use of each canister is achieved by using 2 in series, when breakthrough in the first canister is less important
- this may be recognised by warming of the downstream canister
- contains a ***colour indicator*** which changes with the pH of the granules
- fresh granules have a pH ~ 12,

$$\mathbf{CO_2 + H_2O \rightarrow H_2CO_3}$$

$$\mathbf{H_2CO_3 + 2NaOH^{\S} \rightarrow Na_2CO_3 + H_2O + Ca(OH)_2}$$

$$\mathbf{\rightarrow CaCO_3 + 2NaOH^{\S}}$$

- some CO_2 reacts directly with $Ca(OH)_2$, however this reaction occurs at a much slower rate
- due to the regeneration of NaOH, a substantial fall in pH only occurs when the ability of $Ca(OH)_2$ to form NaOH is lost, this change in pH being accompanied by colour change
- RDM states that modern soda lime has less ability to regenerate, due to the addition of KOH and the reduction of added silica
- white soda lime contains ***ethyl violet***, which has a critical pH ~ 10.3 & indicates early
- colour change cannot be relied upon, as significant breakthrough occurs prior to this change
- however, the use of series canisters and ***capnography*** allow complete assessment of exhaustion

Absorptive Capacity

- the minimum absorptive capacity for a 450 g load is ~ 47 litres of CO_2
- however, canisters are rarely used to exhaustion, and capacity ~ 40 litres / 450 g canister (x2)
- thus, an average adult with a VCO_2 ~ 150 ml/min has,
    a. ~ 4 hours per canister on a circle system with IPPV scavenging at the ventilator
    b. ~ 8 hours per canister with SV and a FGF of 3 l/min
        - this occurs as ~ ½ the CO_2 is vented through the exhaust valve, prior to reaching the canisters

- RDM states maximum absorptive capacity ~ 26 litres / 100g absorbent
- however, channelling reduces this to 10-20 litres / 100g

Airflow Resistance

- the size of granules has been determined by trial and error, being a compromise between flow resistance and absorptive capacity
- the currently used size is between ***4-8 mesh***, which has minimal resistance to airflow

Toxic Products

- ***trilene*** in combination with strong alkali and heat desaturates to ***dichloroacetylene***, which results in cranial nerve palsies
- this occurs principally above 60°C, but cannot be ruled out at the normal 40-45 °C operation
- this may be absorbed onto the granules, being released in subsequent anaesthetics
- trichlorethylene also decomposed in the presence of O_2 and hot wire or flame to phosgene

- ***sevoflurane*** is unstable in vivo and in vitro with soda lime
- one of the decomposition products is an alkylating agent
- despite early reports that this may result in toxicity, over 200,000 anaesthetics have been administered in Japan without evidence of hepatic or renal toxicity
- one report of end-organ damage associated with its use actually related to induced MH

Inspiratory & Expiratory Valves

• low resistance is essential and achieved by a large diameter and lightweight discs
• the valve should have a lift clearance ~ ½ the valve seat radius, giving an area equal to the valve orifice
• original valves used mica discs which were prone to fracture and not clearly seen
• metal discs were then used with neoprene seals and retaining pins, however these tended to stickiness and the pins bent and fractured
• they then returned to mica discs, using orange central dots to allow recognition, held in place by a wire cage
• the same design is now used with light weight metal discs
• the discs are 27 mm diameter, held by a 5 wire cage on a 19 mm circular knife edge seat
• each of the arms has a spike underneath to prevent adherence of the mica disc in the presence of moisture
• these have a low ***opening pressure* ~ 0.5 cmH_2O**
• at 30 l/min ***flow resistance* < 1.0 cmH_2O**

Exhalation Valves (Adjustable Pressure Limiting Valves)

• designed to vent excess gas from the circuit, these are normally combined with a scavenge connection
• they are also required in all circuits where gases are exhausted by pressure within the circuit, such as Magill and Bain circuits
• the minimum spill pressure should be slightly less than that required to fill the reservoir bag (usually < 2.5 cmH_2O)
• those which may be closed completely should only be used on circuits where there is a pressure safety valve at 50 or 70 cmH_2O

▪ *Heidbrink Valve*

• a disc valve is held against a knife edge seat by a light spring, giving 3 positions,

i. disc held by gravity only
ii. disc held by gravity and spring pressure
iii. disc held by central pin closed against the seat

• the spring usually gives a range of blow-off pressure from 1-40 cmH_2O
• because of the light disc and spring, flow resistance rises only a few cmH_2O up to 30 l/min
• most common arrangement is vertical valve with a 19 mm gas scavenging port at 90° and a safety protrusion lug on the outside (Nutter Valve - CIG Medishield)

CIG-Medishield Exhale Valve

- principal difference from the Heidbrink valve is a 50 cmH_2O safety pressure relief
- 19 mm diameter nylon disc sits on a 15 mm knife edge
- the adjustable pressure knob sits over the spring and has a spiral cam on its skirt
- a step at the end of this cam limits rotation to 360 ° and blow-off pressure to ~ 50 cmH_2O
- this can be overridden if the knob is manually held down against the seat
- there is a tendency for the spring assembly to become sticky and pressures to vary markedly
- these are in common use an some anaesthetic machines and the "Black-Bag" (Mapleson B) circuits used for short-term manual ventilation

Berner Valve

- a 3 position valve, with modes of operation,

1. fully closed - a pin in the control knob prevents high pressure relief
2. variable resistance blow-off pressure = Heidbrink
3. fully open - valve disc allows venting without an opening pressure
   - sudden high pressure closes the valve against an *upper seat*
   - suitable for manual ventilation
   - avoids adjustment with altered FGF or ventilation rate

- these are accomplished by having a valve disc floating on a central pin, together with a light spring, between upper and lower valve seats
- the lower seat functions identically to the Heidbrink, with blow-off tension determined by the stronger spring in the control head
- the upper seat seals with sudden rises in pressure, when the valve is fully open, closing against the light spring in the valve housing

Checking the Low Pressure Circuit

• most important preoperative check, as it evaluates the portion of the machine that is downstream from all safety devices except the O_2 analyser
• the components in this section are those most subject to breaks and leaks
• the flowtubes are the most delicate components & are subject to cracking & breakage
• a 3 gas machine has ~ 16 O-rings in the low pressure circuit

■ *Machines Without Check Valves*

• traditional positive pressure leak test at ~ 30 cmH_2O, closing the gas scavenge valve
• a circuit leak is reflected by a decline in circuit pressure
• this can be performed quickly and requires no additional equipment
• it is however, less sensitive than tests using ancillary equipment
• the pressurised volume of the breathing bag can mask leaks up to 250 ml/min

■ *Machines With Check Valves*

• most Ohmeda machines have an outlet check valve to minimise the pumping effect
• the valve is located downstream from the vaporisers and upstream from the O_2 flush
• IPPV and O_2 flushing close the valve, therefore Ohmeda recommends a ***negative pressure leak test***
• the test device is a suction bulb, and is included with all machines requiring this test
• a no flow state is established, by either turning off,

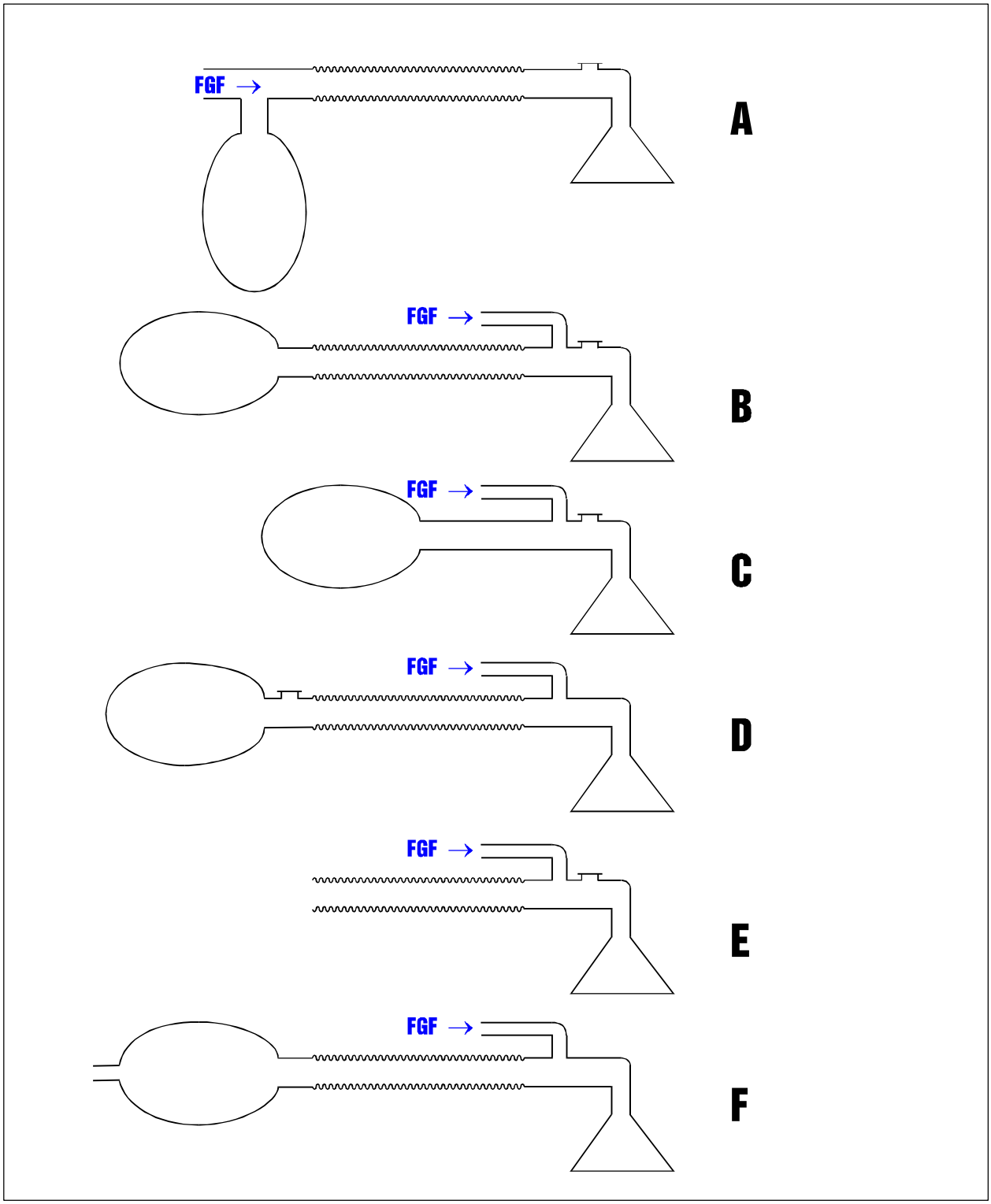
1. all flowmeters - Unitrol
2. the master switch on the Modulus I & II, leaving open the flowmeters

• the bulb is evacuated and the system considered "leak-free" if it remains collapsed for > 30 seconds
• the test must be repeated with each vaporiser ON to detect vaporiser leaks
• the test is extremely sensitive, detecting leaks ~ 30 ml/min
• application of a traditional positive pressure test in the presence of a low pressure check valve may be negative in the presence of a large leak
• the latest Ohmeda machines, the Modulus II Plus and the CD ***do not*** have check valves

ANAESTHETIC CIRCUITS

Mapleson Systems

- originally described as A to E, with F being added by Willis *et al*. 1975



Mapleson A Magill's Circuit

• rebreathing during ***spontaneous ventilation*** can be prevented with relatively low FGF's
• the spring loaded exhalation valve being located at the patient end of the circuit
• on expiration, some dead-space gas enters the inspiratory/expiratory limb of the circuit, with most of the alveolar gas exiting through the valve once pressure rises
• rebreathing of dead space presenting no problem as it contains no CO_2
• several studies have confirmed Mapleson's original finding, that significant rebreathing can be prevented if the **FGF = *minute ventilation* (MV)**

• the circuit is ***inefficient*** during ***controlled ventilation***, as venting occurs during inspiration
• expiratory valve resistance must be increased to ventilate the patient
• a large percentage of the expired gas then enters the inspiratory limb of the circuit and is rebreathed with the next breath before pressure rises sufficiently to open the valve
• to prevent significant rebreathing a **FGF > 20 l/min** is required

Lack Coaxial Circuit

• functionally resembles a Mapleson A, with the reservoir bag ***upstream*** of the patient connection, and the expiratory valve (Heidbrink type) downstream
• externally it resembles a Bain circuit, with the reservoir bag and expiratory valve mounted at the common gas outlet, however, the FGF or inspiratory limb is on the outside
• the original circuit was opaque, however, like the Bain should be transparent to allow inspection of the inner tube
• during spontaneous inspiration, the exhaust valve closes and gas from the reservoir bag and FGF are inspired, no gas is taken from the expiratory inner limb
• during expiration, mixed fresh gas, dead space and some alveolar gas fill the reservoir bag, then once circuit pressure rises, predominantly alveolar gas enters the inner limb & is vented
• much like the Mapleson A, during SV, a **FGF ~ MV** will prevent rebreathing
• during IPPV venting occurs at end inspiration, predominantly FGF
• excess mixing of alveolar and FGF occurs, and **FGF > 150 ml/min** are generally required
• this is close to that required for a Bain circuit (see later), although FGF requirements are significantly less than those of the Mapleson A

Mapleson B

• the fresh gas inlet is at the patient end of the circuit, just distal to the exhalation valve
• this circuit functions similarly in both SV and IPPV, with a mixture of alveolar gas and fresh gas filling the reservoir bag and expiratory limb
• to prevent significant rebreathing a **FGF > 2x MV**

Mapleson C

• also known as a ***Water's circuit***, without an absorber
• this is identical to the Mapleson B, except that the expiratory limb is shorter
• this allows more complete mixing of alveolar and fresh gas, thus a slightly smaller FGF is required, **FGF ~ 2x MV**

Mapleson D

• essentially this is a T-piece with an expiratory limb
• the FGF enters at the patient end, however the exhalation valve is at the patient end, near the reservoir bag
• with expiration during ***spontaneous ventilation***, dead space, FGF and alveolar gas enter the expiratory limb, with predominantly a mixture of alveolar and dead space gas being expelled
• during inspiration the patient receives a mixture of gas from the tubing and FGF, determined by,

i. FGF rate
ii. tidal volume
iii. the length of the expiratory pause

• a long expiratory pause allows more of the alveolar gas to be flushed from the circuit, prior to the next inspiration
• short expiratory times result in significant rebreathing
• large tidal volumes (cf. FGF) provide more alveolar gas to the expiratory limb, increasing rebreathing
• during inspiration with ***controlled ventilation***, alveolar and dead space gas, rather than FGF are expelled from the exhalation valve
• therefore this system causes less rebreathing than Mapleson B or C systems
• therefore, rebreathing is reduced by long expiratory times and higher FGF's,

1. Mapleson **- FGF > 2x MV**
2. Bain and Spoerel
   i. spontaneous ventilation **- FGF > 100 ml/min**
   ii. controlled ventilation * tidal volume 10 ml/kg @ 12-16 bpm
      • infants < 10 kg **~ 2 l/min**
      • patients 10-50 kg **~ 3.5 l/min**
      • patients > 60 kg **~ 70 ml/kg/min**

Bain Circuit

• essentially a Mapleson D, modified as a coaxial system
• gas flows and behaviour are virtually identical to above
• advantages of this circuit are,

i. light weight
ii. convenient
iii. easily sterilised & reusable

• disadvantages are,

i. unrecognised disconnection, kinking or leakage from the inner gas hose
ii. hypercarbia from inadequate FGF

• the outer hose should be transparent to allow inspection of the inner hose
• checked by filling the reservoir bag then flushing with O_2
• if the inner hose is intact, the venturi effect will empty the reservoir bag

- ***Mapleson E***

• a modification of Ayre's T-piece, developed by Phillip Ayre in 1937
• this consists of simply a FGF inlet near the patient and an expiratory limb
• there are no valves, minimal dead space and low flow resistance
• the expiratory limb is the reservoir, being greater than the patients tidal volume preventing entrainment of room air
• controlled ventilation may be achieved by intermittent occlusion
• to prevent significant rebreathing a **FGF > 3x MV**

- ***Mapleson F***

• this is the most commonly used T-piece, the Jackson-Rees modification of the Mapleson D
• effectively Ayre's T-piece with an open reservoir bag at the end of the expiratory limb
• there may or may not be an adjustable valve attached to the expiratory hole of the bag
• flow requirements are similar to the Bain circuit for IPPV
• with SV, to prevent significant rebreathing a **FGF > 3x MV**
• mainly used for paediatrics
• advantages include,

i. inexpensive
ii. light weight and simple construction
iii. no valves except that on the reservoir bag
iv. observation of the reservoir bag allows assessment of the depth of anaesthesia
v. controlled ventilation may be easily instituted
vi. scavenging is easily achieved at the reservoir bag

• disadvantages include,

i. lack of humidification - easily solved however
ii. requirement for high FGF rates
iii. occlusion of the expiratory hole may result in barotrauma

Circle Systems

• prevents rebreathing of CO_2 but allows partial rebreathing of other exhaled gases
• the system can be used,

1. semiopen - high FGF with no rebreathing of gases
2. semiclosed - low-moderate FGF with some rebreathing of gases
   - excess FGF vented either from the Exhaust valve or ventilator
3. closed - FGF exactly matches patient uptake
   - all gas following CO_2 elimination is rebreathed

• the degree of such rebreathing depends upon the FGF and the arrangement of the system components, of which there are 7,

i. FGF inlet source
ii. inspiratory and expiratory unidirectional valves
iii. inspiratory and expiratory limbs
iv. a Y-piece connector
v. an overflow, or pop-off valve
vi. reservoir bag
vii. CO_2 absorber cannister(s)

• there are various arrangements, however to prevent CO_2 rebreathing 3 rules must be observed,

1. a ***unidirectional valve*** must be located between the patient and the reservoir bag, on both the inspiratory and expiratory limbs of the circuit
2. the FGF inlet must ***not*** enter the circuit between the patient and the expiratory valve
3. the overflow valve must ***not*** be located between the patient and the inspiratory valve

NB: if these rules are followed, the arrangement of the other components will prevent rebreathing (Eger 1974)

• the most efficient arrangement, with the highest conservation of FGF, has the unidirectional valves near the patient, and the overflow valve just downstream from the expiratory valve
• this conserves dead space and preferentially eliminates alveolar gas
• the more common arrangement, with the unidirectional valves remote from the patient, is less efficient as it allows mixing of alveolar and dead space gas before venting

- ***Advantages***

1. allows low FGF anaesthesia with conservation of gas usage
2. relative constancy of inspired concentration
3. conservation of respiratory moisture and heat
4. minimisation of operating room pollution

- ***Disadvantages***

1. complex design
2. approximately 10 connections all of which may leak
3. potential for valve malfunction - rebreathing
   - total occlusion
4. cumbersome and heavy

VENTILATORS

Hand Bag and Circle

• expiratory valves are usually of the ***Heidbrink*** or ***Medishield*** type, which vent during inspiration when circuit pressure is increased
• inspiration is positive pressure, with gas flow divided between the expiratory valve and the patients lungs
• expiration is passive, exhaled gas plus fresh gas refilling the bag
• the leak from the expiratory valve must balance the FGF, minus the small amount of O_2 taken up across the lungs
• for a given tidal volume, the valve resistance must be increased if the FGF is decreased, the frequency increases or the patient lung compliance decreases
• conversely, for a given compliance, frequency and FGF, the valve must also be tightened if the tidal volume is increased

• valves which allow gas venting during expiration, such as the Georgia or Berner, create a much less interdependent system
• however, these systems may result in circuit overpressure if a safety release valve is not included

• most ventilators for use with a circle system vent through a valve which is held closed during expiration, therefore require the circle vent valve to be closed

Adelaide Box Transfer Unit

• developed in 1963 by Drs Waterhouse and Cotton
• required for use with Bird ventilators to separate the anaesthetic and driving gases
• consists of a 4 litre bag in a perspex box, with a modified CIG circle inspiratory valve for venting
• the weight of the venting valve is ~ 6 g, and requires ~ 1 cmH_2O circuit pressure for venting
• scavenging is done at the venting valve, and only the terminal portion of the vented gas is contaminated
• usually driven by older, pressure limited ventilators, however, tidal volume is limited by the reservoir volume, ie. 4 litres
• the patient is able to trigger inspiration through this arrangement
• disconnection causes a sharp change in ventilator tempo,

i. the first few breaths are longer, then once the reservoir empties
ii. the ventilator cycles against the empty box compliance
iii. there is no flow in the expiratory limb of the circle

• because of the relatively high resistance in the total circuit, inspiratory flow rates should be as high as possible, allowing sufficient time for expiration and minimising mean intrathoracic pressure
• however, with very high flow rates and the Bird ventilators, there is a significant pressure drop along the circuit, and not all of the inspiratory pressure is transferred to the patient airway (fig. 10.4 p90 JR)

• failure of the venting valve to seal, or perforation of the reservoir bag results in dilution of the anaesthetic mixture
• there is usually no change in tempo of ventilation, or tidal volume, however the [N_2O] may be substantially reduced

Classification

1. ***power source***
   i. pneumatic
   ii. electronic
   iii. combined
2. ***drive mechanism*** = double circuit, pneumatically driven
   i. the patient circuit is isolated from the driving gas
   ii. the patient bellows are pneumatically driven
   iii. the driving gas may be either 100% O_2 or Air/O_2 with venturi driven devices
3. ***cycling mechanism***
   i. time cycled
   ii. pressure cycled
   iii. combined
   • cycling may be driven by fluidic logic or electronic solid state
4. ***bellows operation*** = movement during expiration
   i. descending
   ii. ascending
   • ascending is safer as the descending type continue to fill in expiration with circuit disconnection

Pneumatic Ventilators

• Bird (+ Adelaide Box), Ohio Anesthesia Ventilator, Ohio V5(+A), Drager AV, and Campbell
• excepting the Bird, all are pneumatically powered, double-circuit, pneumatically driven, time-cycled, fluidically controlled, tidal volume preset ventilators, which are most commonly used in the control mode

- ***Advantages***

   i. require only a pneumatic power source
   ii. functional design is simple & they are easy to operate
   iii. most are mobile, freestanding units
   iv. fluidic control components have no moving parts, depending solely upon flow and pressure, therefore less susceptible to failure
   v. maintenance requires no knowledge of electronics

- ***Disadvantages***

1. unrecognised disconnection - major problem & outweighs advantages
   i. majority are of the descending bellows variety
   ii. most have only 1 alarm - low pressure disconnection alarm ~ 8-10 cmH_2O
2. limited number of controls & lack of versatility

Campbell Ventilator

• designed by Ulco Engineering in Australia, principally for use with circle systems
• it is a ***gas driven***, ***descending bellows*** ventilator, using fluid logic controls
• a pneumatic on/off switch allows selection of IPPV, with or without expiratory control
• a positive or negative expiratory phase can also be selected
• the fluidic controls function such that the ventilator is usually ***time cycled*** in both inspiration and expiration
• expiration may also be terminated by patient effort if the triggering control is enabled, however inspiration is entirely time dependent
• ***tidal volume*** may be preset by an adjustable rest upon which the bellows sit (100-1000 ml), or by setting the pressure limit, ie. it may be volume, time or pressure limited

• during ***inspiration*** gas enters the pressurised box, and is transmitted to the patient circuit through the bellows
• the rate of pressure rise is determined by the degree of air entrainment with the driving gas (up to ~ 5:1), as it enters the pressurised compartment
• emptying of the bellows continues until either,
   i. the bellows are empty
   ii. the pressure limit is reached, or
   iii. the inspiratory time expires

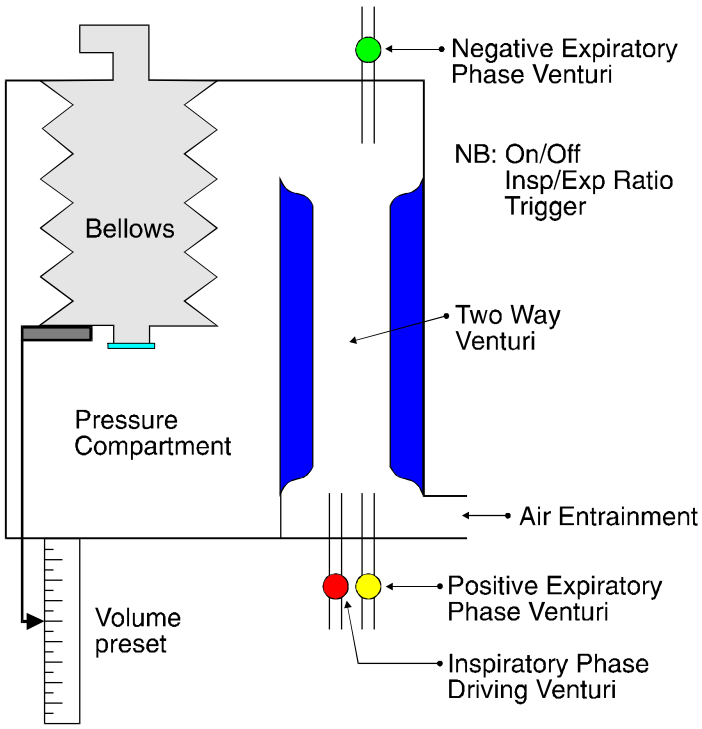
• if the bellows do not empty, early models (pre-1981) could deliver pressures up to 100 cmH_2O
• later models have a 50 cmH_2O exhaust valve

• ***expiration*** is usually set for time
• with normal IPPV, the pressure in the compartment falls to atmospheric, and the bellows refill under their own weight, generating a slight negative pressure in the patient circuit
• when the bellows have completely filled, excess gas is vented into the outer chamber through a valve in the base of the bellows
• negative pressure during expiration may be generated by a venturi & entrainment out from the pressure compartment
• this results in significant exhausting of patient gases, with the requirement for large amounts of scavenging

• driving gas consumption is high, IPPV without NEEP/PEEP uses ~ 15 l/min
• this equates to a full C size cylinder in ~ 30 minutes
• the application of ~ 5 cmH_2O PEEP increases gas consumption by ~ 10 l/min

Functional Characteristics

- intended to be used primarily as a ***volume preset*** device, ***time cycled*** in both phases
- with patient disconnection there is no change in tempo, though, there may be a slight change in the inspiratory phase
- if disconnection is within the circuit, the bellows will still fill and may register the same expired volume
- the use of negative phase expiration continues beyond removal of tidal volume and continues to remove gas from the patient circuit
- although the bellows can be volume set, any circuit leaks must be subtracted from the volume and the FGF for the duration of inspiration added
- therefore, the expired gas volume should be independently measured, or an adjustment made
- changing either the fresh gas flow rate, or the inspiratory flow time will alter tidal volume without adjustment of the bellows



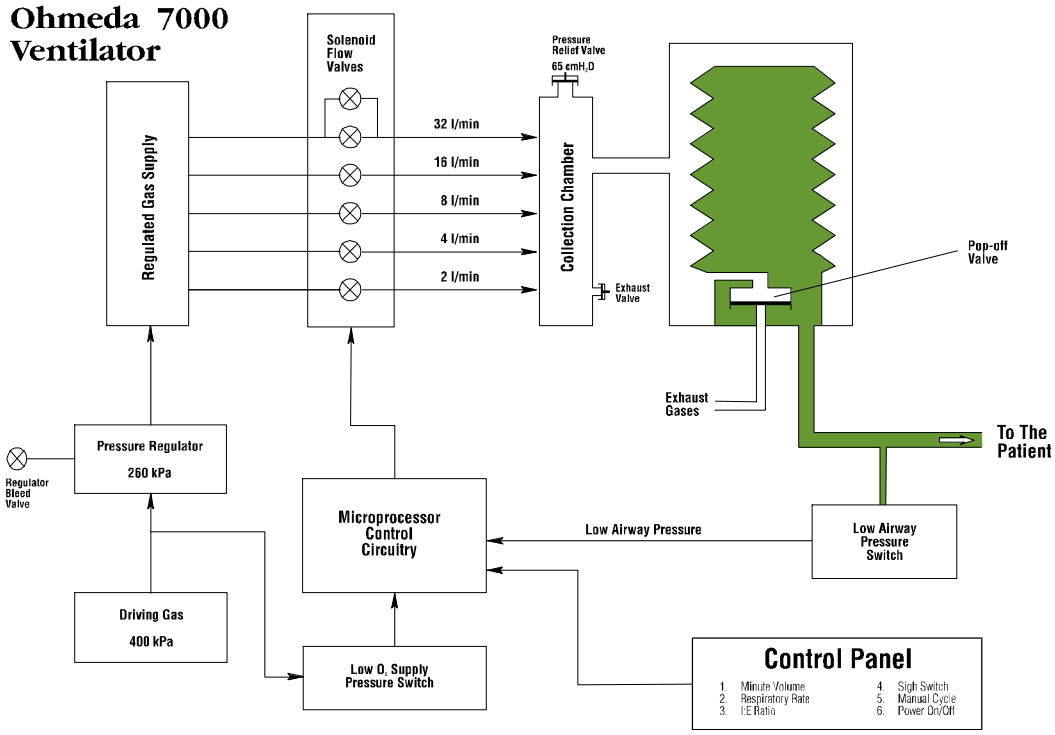
CAMPBELL VENTILATOR

Electronic Ventilators - Ohmeda 7000

Def'n: pneumatically and electronically powered, double-circuit, pneumatically driven, ascending bellows, time-cycled, electronically controlled , minute volume preset controller

- functionally consists of 2 units, the control assembly and the bellows assembly
- the control assembly has 6 functions,
    i. minute volume dial
    ii. respiratory rate dial
    iii. I:E ratio dial
    iv. power switch
    v. sigh switch
    vi. manual cycle button

- the bellows assembly sits within a plastic housing, and has a scale from 100 ml to 1600 ml, increasing from top to bottom
- the ventilator relief valve cannot be seen, being housed beneath the bellows



- ***Function***

• the driving gas is 100% O_2 at ~ 410 kPa, which is reduced through a regulator to ~ 260 kPa
• this is directed through calibrated solenoid valves, giving a range of flows from 2-60 l/min
• a volume of gas equal to the tidal volume is delivered to the chamber, at a rate determined by the ventilator settings
• thus the bellow are depressed only by an amount equal to the tidal volume
• for this reason the scale on the bellows housing increases from top to bottom, cf. the Campbell, where it increases from bottom to top
• a relief valve located within the control assembly vents excess gas to atmosphere if excessive pressure occurs during inspiration (> 65 cmH_2O)
• anaesthetic gases enter the bellows chamber during expiration
• the ventilator relief valve is located within the bellows and has a threshold ~ 2.5 cmH_2O, opening only when the bellows are fully extended

Ohmeda 7810

• essentially the same as the 7000, though it also serves as an O_2 analyser, airway pressure monitor, and volume monitor
• it combines these to provide an integrated ventilator alarm system
• the bellows assembly is identical, however the control module is significantly different,

1. 4 dial controls
   - tidal volume (cf. minute volume on the 7000)
   - rate
   - inspiratory flow dial
   - inspiratory pressure limit dial
2. on/off switch
3. push-buttons
   - inspiratory pause (25% T_I)
   - alarm silence
4. O_2 calibration thumb -wheel
5. alarm set push-wheels
   - low V_E
   - low and high O_2

• major differences between the 7800 and the 7000 include,

1. tidal volume cf. minute volume preset
2. greater versatility of I:E ratios
   i. 7000 → 1:1 to 1:3
   ii. 7800 → 1:0.33 to 1:999
3. inspiratory pause feature
4. operator adjustable high airway pressure relief valve
5. inbuilt O_2 analyser with adjustable alarm limits

Ventilator Problems / Hazards

▪ ***Breathing Circuit Problems***

• circuit disconnection is a leading cause of critical incidents in anaesthesia
• these may be ***complete*** or ***partial*** and commonly occur at,

i. the Y-piece
ii. the exhaust valve, due to failure to close upon initiation of IPPV

• numerous disconnection monitors exist,

i. vigilant anaesthetist ± an oesophageal stethoscope
ii. pressure monitors
iii. respiratory volume monitors
iv. exhaled CO_2

• factors which influence the functioning of ***pressure monitors*** include,

i. the disconnection site
ii. the pressure sensor location
iii. the threshold pressure limit * factory preset or adjustable
iv. the inspiratory flow rate
v. the flow resistance of the disconnected breathing circuit

• the threshold pressure limit may be factory preset or adjustable
• if adjustable, it should be set within 5 cmH_2O of the peak inspiratory pressure, to allow detection of partial disconnections
• tidal volume meters are similarly useful, but require the alarm limits to be set close to the actual volume to function effectively
• $ETCO_2$ is best monitored at the Y-piece for detection of disconnection

▪ ***Bellows Assembly Problems***

1. leaks or improper seating of the bellows may result in,
   i. ventilation of the patient with driving gas - 100% O_2 or Air/O_2
      * altered F_IO_2
   ii. barotrauma with some models, especially venturi driven devices
2. malfunction of the ventilator relief valve
   i. incompetent → hypoventilation & loss to scavenging
   ii. closure → barotrauma
   iii. excessive scavenging pressure → effective closure of the valve

- ***Control Assembly Problems***

1.	electrical failure	- total - partial
2.	pneumatic failure	- driving gas failure - valve malfunction, obstruction - regulator malfunction, miscalibration - solenoid malfunction

SCAVENGING

1. air conditioning
2. prevention of leakage
3. removal of exhaust gases

- ***Air Conditioning***

• the majority of theatres have 5-15 changes / hour
• effectiveness of clearance depends upon ***fresh gas changes/hr***, ie. the degree of recirculation
• recirculation, in addition to reducing the effectiveness of clearance, may contaminate other areas

- ***Leakage***

• these may occur either in the high pressure or the low pressure circuits
• high pressure leaks commonly occur from worn cylinder valves, poor yoke fittings, pressure regulators, etc.
• decline of the cylinder content gauges following cylinder check is a strong indicator
• low pressure leaks may be minimised by thorough testing of the circuit prior to use
• different authorities allow different rates of leakage during routine check

200 ml/min FGF & 40 cmH_2O pressure $\rightarrow$ < 50 ml/min leak (without reservoir bag)

• even if the circuit is leak-proof, frequent contamination occurs during mask ventilation, suctioning and during intubation/extubation
• preferably both N_2O and volatile agent should be turned off during extended periods of disconnection from the patient

Scavenging Equipment

• 5 components,

1. gas-collecting assembly
2. transfer tubing
3. scavenging interface
4. gas disposal tubing
5. an active or passive gas disposal assembly

▪ ***Gas-Collecting Assembly***

• gas is vented through the ventilator relief valve and the exhaust gas valve of the given circuit
• early assemblies, such as on the Bird, have the collecting shroud separate from the valve system
• all modern ventilators and circuits have the shroud integral with the valve

▪ ***Transfer Tubing***

• the tubing must be 19 or 30 mm and rigid enough to prevent kinking
• the Australian Standard colour is ? red (pink)
• the ventilator and circuit overflow valve usually have separate tubes, which merge at the scavenging interface

▪ ***Scavenging Interface***

• this is the most important component, as it protects the breathing circuit from excessive positive or negative pressure,

i. $< 3.5\ cmH_2O$ - RDM says $10\ cmH_2O$
ii. $> -0.5\ cmH_2O$

• positive pressure relief is mandatory, irrespective of the disposal system type, to vent excess gas in the case of downstream leak
• if the disposal system is active, the circuit must also be protected against negative pressure
• interfaces may be open or closed, depending upon the methods used for +/- pressure relief,

1. open interfaces
   - contains no valves and is open to atmosphere providing +/- pressure relief
   - should be used only with ***active*** scavenging systems, with a central vacuum
   - require a reservoir, as waste is accumulated intermittently
   - commonly used arrangement is a simple T-tube, or ***bassoon***, which also incorporates a suction flow indicator
   - factors which affect the performance include,

   i. vacuum flow/minute must be > waste flow/minute
   ii. the reservoir must be > a single exhaled breath
   iii. flow characteristics, spillage may occur with turbulent flow, even with exhaust volumes well below the reservoir volume

2. closed interfaces
   - communicates with the atmosphere through valves
   - all must have a positive pressure relief valve
   - those for use with passive systems require no reservoir system
   - those for use with active systems also require a negative pressure relief valve
   - typical opening pressures are -0.5 and 5 cmH_2O
   - in contrast to open systems, performance is determined only by reservoir volume, gas inflow and suction, gas flow characteristics play no part

- ***Scavenging Interface The Bassoon***

- cylindrical tube 1.4 m in length, with an internal volume of 3 litres
- has two 19 mm female conical connectors for attachment of transfer tubes
- the bottom is closed, however there are circumferential holes for venting
- there is a vacuum gauge with a flow restriction to adjust vacuum
- the green zone on the gauge indicating 8-10 kPa, or 20-30 l/min flow rate
- this is prone to obstruction of the filter and misreading
- later models use a floating ball meter
- if the flow rate is > 20 l/min, there is no spillage, even with dumping of a 4 l reservoir bag

- ***Gas Disposal Tubing***

- carries gas from the interface to the disposal assembly
- ideally it should be collapse-proof, and run overhead to minimise the chance of occlusion

- ***Gas Disposal Assembly***

1. active
   - utilises a central vacuum
   - requires differentiation from surgical and anaesthetic suction, usually a sleeve index system
   - an interface with a negative pressure relief valve is mandatory
   - a reservoir is desirable, the larger this is, the lower the suction flow rate required
2. passive
   - the pressure of the waste gas provides exhaust
   - positive pressure relief is mandatory
   - negative pressure relief and a reservoir are unnecessary

- ***Hazards***

1. added circuitry complexity, risks of misconnection
   - previously with the use of 22 mm fittings, the expiratory hose could be connected to the exhaust shroud of the overflow valve, preventing expiration
   - this resulted in rapid circuit overpressure and has been corrected by the specification of 19 or 30 mm fittings
2. transmission of excessive ***positive*** pressure to the anaesthetic circuit
   - circuit obstruction anywhere from the patient circuit to the wall
   - worse upstream of the scavenging interface
3. transmission of excessive ***negative*** pressure to the anaesthetic circuit
   - obstruction of the negative pressure relief valve
   - maladjustment of the suction on a closed scavenging interface
   - the results of this depend upon the design of the ventilator and circuit overflow valves, producing either,
     i. a negative circuit pressure and loss of anaesthetic gases
     ii. closure of the overflow valve and barotrauma
4. ? loss of means of monitoring (smell)

RESPIRATORY MONITORS & ALARMS

- ***Medishield Oxygen Pressure Failure Alarm (Bosun)***

- now obsolete, but was in wide use until recently
- O_2 line pressure expands metal bellows, which are attached to a metal rod
- failure of the O_2 supply collapses the bellows, moving the rod which activates the warning light and allows N_2O to supply the warning whistle
- both warning devices function between 170 & 275 kPa
- there were 2 basic flaws of this device,

1. the alarm whistle depends upon a supply of N_2O
   - if no N_2O is used, or its supply fails prior to the O_2 failure, then no alarm will sound
   - this is not a great problem with 100% O_2 / volatile anaesthesia, as hypoxia ensues slowly and collapse of the ventilator bellows occurs
   - however, with O_2 / air anaesthesia subsequent hypoxia may result
2. the use of a "dry cell" battery
   - these commonly have a shelf-life < 1 year and may not have been replaced regularly
   - they are also of low power output and exhaust quickly, especially if the line supply is disconnected at the end of the operating list/day

- early designs had on/off switches for both the light and whistle, rendering the alarm inoperative

- ***Audio Visual Warning Device CIG BA110***

• like the Bosun, operates from the N_2O supply and a "dry cell" battery, and is obsolete
• the unit operates on a neoprene diaphragm and spring, which are balanced against the O_2 and N_2O line pressures
• although similar to the Bosun, if both gases are disconnected, the diaphragm does not move and the alarm light is not activated if the machine is disconnected from the line supply

Ritchie Whistle

• developed at Dunedin by John Ritchie (McKay & Howison) in the late 1960's
• this is a spring loaded diaphragm & valve which is designed to operate on the residual O_2 within the system when failure occurs,

1. the diaphragm holds the valve closed > 270 kPa
2. valve opens < 210 kPa, allowing O_2 to pass to the whistle
3. at the commencement of the alarm, the O_2 supply to the patient will fall to ~ 70% of the original flowmeter setting
4. with a 400 l size C cylinder the whistle sounds for ~ 2 minutes
5. the warning time will be reduced where,
   i. O_2 is supplied from the piped wall supply via noncompliant tubing
   ii. O_2 is used as the driving gas to the ventilator
6. the warning time may be increased by adding a ***reservoir*** to the high pressure line
7. when O_2 failure occurs, N_2O continues to flow, therefore immediate action is required
8. should be tested ~ 3/12 by fitting an almost empty O_2 cylinder & recording the alarm time
9. the whistle will also sound briefly each time the system is pressurised

Howison Oxygen Failure Alarm

• described in A&IC 1978 by Dr R.G. Howison, as a refinement of the Ritchie whistle
• with falling O_2 supply pressure, this device has 3 functions,

1. the alarm whistle sounds
2. as the O_2 supply falls below 275 kPa, the N_2O is immediately shut-off
3. O_2 is supplied at a reduced rate through the O_2 flowmeter

• this device was fitted to a large number of machines from ~ 1979
• like the Ritchie whistle,

1. it is usually located beneath the tray-top of the anaesthetic machine and is thus inconspicuous
2. the whistle should sound briefly upon system pressurisation

• the Howison valve is effectively composed of 3 in series chambers,

1. **O_2 supply chamber**
   - O_2 acts against a diaphragm and spring, to hold closed a ***shut-off valve***
   - this valve allows communication with the whistle chamber (→2)
   - the alarm pressure is set by the spring tension
   - O_2 is supplied, via a non-return valve, from this chamber to the ***reserve cylinder***
   - as supply pressure falls, the shut-off valve opens activating the whistle
2. **whistle chamber**
   - the shut-off valve from (1) is in series with the ***N_2O valve***
   - as the spring depresses the O_2 diaphragm in the O_2 chamber, opening the shut-off valve, this inturn depresses the N_2O valve
   - this has 2 functions,
   i. depresses the N_2O diaphragm (→3), shutting-off the N_2O supply
   ii. with continued O_2 pressure loss, opening the ***reserve O_2 release valve***
   - reserve O_2 is then supplied to the whistle, and via the shut-off valve and O_2 chamber to the O_2 supply line
3. **N_2O chamber**
   - the valve stem from the N_2O valve (2) acts against a diaphragm, which closes the N_2O supply line

• the reserve cylinder holds ~ 800 ml and supplies some O_2 to the whistle, but most to the O_2 line
• on failure the flowmeter will read ~ ½ the original setting, supply lasting,

i. pipeline failure ~ 1 minute
ii. "C" cylinder failure ~ 4 minutes

NB: because N_2O is cut-off and O_2 continues to be supplied, the breathing circuit is never supplied with a hypoxic mixture, and
patient oxygenation is assured for several minutes following failure.

■ ***Alarm Requirements UK***

1. the energy for the device should be solely derived from the O_2 supply source
2. the alarm should have a distinctive sound, being audible above the usual operating room noise
3. O_2 failure should shut-off all other gas supplies
4. following failure, a low resistance path between the breathing circuit and the atmosphere should be opened

• the Howison alarm meets all of these except the later, which may in fact be disadvantageous in a paralysed patient requiring IPPV

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 g.% of reduced Hb must be present
• alternatively, "clinical cyanosis" may appear at a [MetHb] ~ 1.5 g.%
• with a normal haematocrit this corresponds to a **$SaO_2 \sim 60\text{-}70\%$**
• 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 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 HbO_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 COHb

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 VO_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*** electrode → P_{O2}
- prior to this the P_{O2} had not been measured
- the Severinghaus CO_2 electrode, developed in 1958, revolutionised arterial blood gas analysis
- P_{O2} may also be measured by,
    i. fuel cell
    ii. paramagnetic analysis
    iii. the optode
    iv. mass spectrometry

▪ ***Clarke Electrode Polarographic***

- the circuit consists of,
    i. DC voltage source (~ 0.6 V)
    ii. an ammeter
    iii. a ***platinum cathode***
    iv. a silver/silver chloride anode
    v. an electrolyte solution (KCl, ?KOH) 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
- factors apart from O_2 which affect the current generated include,
    i. the age of the membrane
    ii. the condition of the buffer solution
    iii. temperature

    → should be calibrated prior to use
    ~ 3% accuracy at 50% O_2

- the response time is ~ 30-60 seconds, therefore not used for breath-to-breath analysis
- some specially designed units, with electronic enhancement → 0.25s response time
- unlike fuel cells they don't deteriorate when exposed to air, however, their shelf-life is limited by the life of the membrane and the buffer solution → ~ 6 months
- susceptible to errors from other gases
    i. N_2O 100% → reading of ~ 4% O_2
    ii. halothane may have a small effect

Oxygen Fuel Cell

- effectively an O_2 limited gold/lead battery, consisting of,
    a. an ammeter
    b. a mesh ***gold cathode***
    c. a lead anode
    d. a compensating thermistor
    e. an electrolyte solution (KCl) and O_2-permeable membrane

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

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

- thus, 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
- like other batteries, the fuel cell will eventually expire → ~ 10^6 mmHg P_{O2} hours
  ~ 8/12 exposure to air

- the output is affected by ***temperature***, as is that of the Clarke electrode, however compensation may be achieved by means of a parallel ***thermistor***
- if a F_IO_2 < 50% is being used then calibration with air alone is sufficient
- if a F_IO_2 > 50% is being used then calibration with 100% O_2 is required → ~ 3% error at 50%
- the typical response time ~ 20-30 s (10-60s)

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 shape or similar
• these indicate either by direct rotation of a pointer or deflection of light, or may be arranged in a ***null deflection*** system
• the later requires a manual, or electronically derived force to return the dumbbells to their original position → greater accuracy
• problems with use include,

1. they require ***calibration*** before use with 100% N_2 and 100% O_2
2. the presence of ***water vapour*** biases the result,
   therefore gases should be dried through silica gel before analysis
3. they are not well suited to continuous analysis, ie. breath-to-breath analysis
   flows > 100 ml/min through the chamber affect accuracy
4. limited ***response time*** doesn't allow breath-to-breath analysis

• their advantages include,

1. O_2 specific
2. don't wear-out
3. with a manually operated analyser, the only power requirement is a light source for the mirror beam

Hummel Cell

• based upon the paramagnetic principal & used in the ***Datex*** instruments
• both the sample gas and an air reference sample are drawn into a magnetic field through a T-piece
• each sample line is connected in parallel to a sensor chamber, where the differential pressure is measured across a diaphragm
• in the resting state both sample lines are at equal pressure, however as a magnetic field is induced across the T-piece sample set, each gas (air & sample) is "held-up" in prportion to the O_2 content
• this then reults in a pressure differential within the sensor chamber
• by oscillating the magnetic field the sensor diaphragm also oscillates, in proportion to the O_2 content of the sample gas
• the diaphragm effectively acting as a microphone, with the amplitude reflecting $\%O_2$

- ***PO_2 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 HbO_2 and dissolved O_2
- normal adult blood contains four species of Hb,

1. HbO_2
2. Hb
3. MetHb
4. COHb

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

▪ ***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 solutes, then the concentration for each one can be solved

- by convention, ***oxyhaemoglibin saturation,*** $\mathbf{SaO_2}$ is taken as the saturation as measured by ***cooximetry***, which is a 4 wavelength device, and includes COHb and MetHb in the denominator

$$\mathbf{SaO_2} = \frac{HbO_2 \times 100\ \%}{(HbO_2 + Hb + COHb + MetHb)}$$

- ***pulse saturation,*** $\mathbf{SpO_2}$ is based on only a 2 wavelength device, therefore has only Hb & HbO_2 in the denominator
- hence the later is subject to errors in the presence of significant concentrations of the other haemoglobin species

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 miniaturisation 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. miniaturisation of the entire electrode

• umbilical Clark electrodes in neonates have been associated with a number of complications,

a. thrombosis
b. sepsis
c. embolisation
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 PaO_2'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, analogous 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 "arterialises" the capillary blood

• a large amount of data has been analysed 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*** (COHb & MetHb), 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 PO_2*

• when the eyes are closed the cornea receives its blood supply from the palpebral conjunctiva
• thus, this inner layer of cells is well vascularised, 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
d. direct ocular trauma

Invasive SpO_2 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 fibreoptic 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

• Kramer optically measured the O_2 in arteries of animals in the early 1930's
• Karl Matthes in 1936 was the first to measure O_2 from transmission of red and blue-green light through the human ear
• the term ***oximeter*** was coined by Millikan *et al*. in the 1940's
• they developed a lightweight oximeter, a smaller version of Matthes' design, which measured SpO_2 by transillumination of the earlobe using red & green filters covering Kramer's barrier layer photocells
• the signal detected from the photocell under the green filter later proved to be in the IR range
• 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 bloodless "baseline" measurement the ear was heated to "arterialise" the blood
• this device was shown to accurately predict intraoperative desaturations, however, due to the technical difficulties was never adopted on mass

Nomenclature

1. SaO_2 = 100.(O_2 content)/(O_2 capacity)
   - arterial blood saturation measured *in vitro*
   - O_2 content ≠ 1.39 x [Hb], but the amount of O_2 which can combine with reduced Hb, ***without*** removing COHb or MetHb when they are present
   - thus, at high P_{aO2} the SaO_2 = 100%, irrespective of the [COHb + MetHb]
2. HbO_2 = ***oxyhaemoglobin concentration*** (fraction or %)
   - multiwavelength spectrometers measure all Hb species as fractions or percentages of the total [Hb] = HHb + O_2Hb + COHb + MetHb
   - this has been inappropriately termed "fractional saturation"
   - SaO_2 computed from P_{O2} and pH approximates SaO_2, not HbO_2
3. SpO_2 = ***pulse oximeter saturation***

Methodology

- 2 wavelengths of light,
  1. red = 660 nm
  2. IR = 910-940 nm

- the signal is 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 (0.3)
  b. **SaO_2 = 85%** **R = 1.0**
  c. SaO_2 = 0% R = 3.4 (4.87) - Severinghaus

• being a 2 wavelength device, the pulse oximeter assumes that there are only two light absorbing Hb species in arterial blood
• 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 480-1000 Hz in an attempt to subtract the ambient light signal, even when this is oscillating
• this allows accurate estimation of SaO_2 at arterial pulse frequencies ~ 0.5-4 Hz (30-240 bpm)
• data is averaged over several cycles

Uses of Pulse Oximetry

- ***Monitoring Oxygenation***

  i. anaesthesia & recovery
  ii. intensive care
  iii. emergency care & transport
  iv. labour
  v. premature & newborn infants
  vi. home & hospital monitoring for SIDS
  vii. patients in remote locations - XRay, MRI
  viii. "office" procedures - dentistry, endoscopy

- ***Monitoring Circulation***

  i. systolic BP & pleth waveform appearance *inflation better than deflation
  ii. sympathetic blockade with central neuraxis anaesthesia
  iii. autonomic dysfunction with valsalva manoeuvre

  iv. patency of the ductus arteriosus [§] [§]anecdotally reported uses only
  v. level of ischaemia in PVD[§]
  vi. patency of arterial grafts[§]
  vii. circulation in reimplanted digits or grafts[§]

- ***Controlling Therapy***

  i. optimise F_IO_2 in ventilated patients
  ii. optimise CPAP or PEEP
  iii. extubation of ventilated patients
  iv. adjust O_2 therapy in preterm infants * no consensus - see below
  v. optimisation of home O_2 therapy

Premature Infant Oxygenation

• Hb_F has a greater affinity for O_2 than HbA, however, the absorbance coefficient is identical and the presence of Hb_F should not affect the SpO_2 reading
• the presence of Hb_F is only important if the aim of therapy is to maintain a specific P_{aO2}, as opposed to a specific SaO_2
• multiple studies comparing the efficacy of SpO_2 versus tcP_{O2} in prevention of ROP
• however, these have been hampered by,

a. multifactorial aetiology of retinopathy of prematurity
   - ? duration, ? concentration, ? mode of delivery of O_2
   - gestational age, hypercapnia, state of the ductus, light etc.

b. unknown whether ROP correlates better with P_{aO2} or SaO_2

c. lack of consensus as to ideal SaO_2, however most agree ~ 90-95% range
   - especially upper limit of safety
   - definition of neonatal ***hyperoxia*** $\rightarrow$ P_{O2} > 80 , > 90 mmHg, and > 100 mmHg

d. inherent 2-3% error in this region = large δP_{O2}

e. studies of different machines have shown the requirement for different safe upper
   - consensus limits are not valid, oximeter type must be specified

NB: SpO_2 is not currently recommended as the sole monitor, but should be used in conjunction with intermittent AGA's, or tcP_{O2}
SpO_2 is better suited to prevention of hypoxia, due to the shape of the curve, whereas tcP_{O2} is more sensitive in the hyperoxic range

Limitations of Pulse Oximetry

Reading Failure

• Freund *et al.* reported a 1.12% failure (cumulative > 30 mins) in 11,046 anaesthetics
• Gilles *et al.* found a 1.1% incidence (2 x 15 mins) in 1,403 anaesthetics
• ~ 90% of failures were at the beginning of the stay in the post-anaesthesia care unit

Vasoconstrictors

• with shock of hypothermia may virtually stop tissue flow through the fingers without eliminating pulsatility in arterioles, resulting in gradual desaturation of blood,

- Severinghaus (1990 Anesth.) case of a 70 y.o. lady in haemorrhagic shock, initially treated with ephedrine; SpO_2 fell from 98% to 45% while the HR detected by the monitor continued to be correct, at a radial artery P_{O2} = 550 mmHg

• local finger desaturation has been confirmed in animal models
• finger vasoconstriction can lead to delays in detection of desaturation up to 6 minutes, or completely miss changes seen with an ear probe
• cold & hypothermia following CPB frequently precludes finger measurement of SpO_2
• anecdotal reports suggest finger ring block with lignocaine may allow adequate assessment

Low Signal : Noise Limits

• 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 once the ***ac*** component falls below an arbitrary fraction of the total transmitted light (0.2% for the Biox-Ohmeda)
• signal reduction may occur 2° to,

i.	low perfusion pressure	
ii.	motion artefact	
iii.	ambient light	
iv.	skin pigments & dyes	
v.	probe position	→ the "penumbra effect"
vi.	ventilation	- a large paradox may lead to searching
vii.	venous pressure waves	- TI, reflectance operation
viii.	electrocautery	- most unit are now immune
ix.	MRI interference	- rare, usually probe lead distorts MRI image

Low Perfusion Limits

• laser-Doppler flow studies show that these oximeters will estimate saturation down to ~ 8% of the control pulse strength, using a variety of tests, including arm elevation, C-clamping of the brachial artery and noradrenaline induced vasoconstriction
• studies in volunteers show that induced hand hypotension, or vasoconstriction, show considerably lower mean systolic functional thresholds for failure than those seen clinically
• this suggests that the combination of ***hypotension & vasoconstriction*** is usually responsible for failure in the clinical setting
• on a variety of tests the Ohmeda, Criticare and Datex Satellite units tended to outperform the Nellcor and Physio-control units

Motion Artefact

• predominantly motion in the range **0.5-4 Hz**, with induced vibration > 4 Hz having little effect
• most oximeters employ signal averaging circuitry to reduce this, however, by increasing the signal averaging time, so the response time of the device is increased
• considerable difference between units in software rejection of artefact
• improved by ***coupling*** with the ECG signal, which also improves the hypotensive threshold
• in neonates this has reduced the failure rate by up to 50% (4.1-2.1%)

Ambient Light

• despite the filtering achieved by cyclical probe function, ambient light can produce erroneous readings, especially when ambient light oscillates at a harmonic of the LED pulse rate
• fluorescent OR lights, especially ***xenon*** lights may cause false reading without a patient attached
• more commonly seen with Nellcor units
• the sensors is usually covered with an opaque material

■ *Skin Pigments & Dyes*

• in black-skinned patients false high readings (~ 3-5%) and a higher incidence of reading failure have been reported
• injected methylene blue and indocyanine green produce transient false desaturation
• nail polish decreases total transmitted light & may result in signal failure
• Cote (1988 A&A) found that despite non-pulsatility, nail polish may result in erroneous readings
• ***jaundice*** has no significant effect upon SpO_2 but may result in confusion with multiwavelength laboratory devices, being read as COHb or MetHb with a resultant decrease in **O_2Hb**

■ *Dyshaemoglobins*

• **COHb** is virtually indistinguishable from HbO_2 at normal wavelengths, therefore in the presence of 15% COHb and 10% HHb due to desaturation, readings will tend to,

1. HbO_2 ~ 75%
2. SpO_2 ~ 90%
3. SaO_2 ~ 90% by gasometric analysis
   ~ 88% by blood gas analysis (L shift of HbO_2 curve)

NB: ***none*** of these actually indicate the presence of COHb

• **MetHb** absorbance in high at both wavelengths, increasing both A_{660nm} & A_{940nm}
• this tends to force R $\rightarrow$ 1.0, however the decrease in SpO_2 approximates,

1. MetHb 0-20% $\rightarrow$ SpO_2 decreases by ~ ½[MetHb]
2. MetHb > 20% $\rightarrow$ SpO_2 ~ 85%

• MetHb is commonly caused by benzocaine 20% sprays and IV prilocaine

NB: when clinically significant levels of either are suspected, the *in vitro* oximetry and arterial gas analysis should supplement SpO_2, not only because dyshaemoglobins interfere with SpO_2 but because they reduce O_2 carrying capacity

■ *Wavelength Variability*

• 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
• the 660 nm LED is on the steep part of the Hb extinction curve, making SpO_2 very sensitive to wavelength drift (temperature, age, probe-probe variation)
• manufacturers claim accuracies around,

a. SaO_2 ~ 100% to 70% $\rightarrow$ ± 2%
b. SaO_2 ~ 70% to 50% $\rightarrow$ ± 3%
c. SaO_2 < 50% $\rightarrow$ unspecified

Effects of Anaemia

- at normal SpO_2 there is no significant effect
- at low SpO_2 (< 80%) in the presence of anaemia (Hb = 8.2) there is a negative error up to 15%
- this is in effect a ***fail-safe*** error, in that it provided exaggerated warning of desaturation in the presence of anaemia
- no problems were encountered in use with 27 burned patients

Potential Dangers

- 2^{nd} & 3^{rd} degree burns have been encountered with,
    1. oximeter use with MRI
    2. defective probe design - Datascope, Nellcor
    3. use of the wrong probe * Physiocontrol probe + Ohmeda oximeter

Limitations of Pulse Oximetry

a. SpO_2 ***does not*** indicate oxygenation unless [Hb] and CO are 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. motion artefact
    iii. light artefact
    iv. abnormal pulses
    v. dyshaemoglobins
    vi. intravenous dyes
    vii. pigments
    viii. probe variability errors

Alternative Sites

• generally signals from the ears are weaker than from the fingers, because the DC component is greater, ie. the ear transmits more light
• however, under conditions of peripheral vasoconstriction ear recordings may be more accurate and track the actual SaO_2 more accurately (Severinghaus 1987 Anesth.)
• nose & forehead probes perform poorly, possible due to,

1. low blood flow with local tissue desaturation
2. light leakage around rather than through tissue
3. venous pulsations
4. variations in tissue thickness

▪ *Reflectance Operation*

• peak absorbance is in the green region of the spectrum, however this is not used clinically
• signal failure is more common than with finger transilluminance, however several units have designed probes with similar accuracy (CSI, Datex & Kontron)
• IR light penetrates tissue more deeply than red light, therefore,

1. the IR LED needs to be located slightly ***closer*** to the detector than the red LED
2. the space between the IR LED and the detector should be ≥ 1 cm

• some units required heating of the skin to 40°C for an adequate signal

▪ *Foetal Measurement*

• has had limited success due to,

1. stagnation of blood in the foetal scalp & caput
2. difficulty with attachment of the electrode

• suggestion has been made that probe design should allow placement between the cervix and foetal head, beyond the caput when present

Patient Safety

• multiple studies showing superiority of oximetry to clinical judgement in detecting desaturation
• as yet, ***no*** published paper has shown a statistically significant reduction in ***morbidity*** and ***mortality*** resulting from the use of oximetry
• major problems relating to the detection of desaturation relate to,

1. what level of desaturation is ***unacceptable***?
2. for how long is this unacceptable?
3. in whom do these limits apply?

• SpO_2 cycling repeatedly down to 30-40% has been recorded during sleep, without detectable end-organ damage, on both,

1. chronic mountain dwellers with polycythaemia
2. obese patients with obstructive sleep apnoea syndrome

• Cote *et al.* Anesth.1988 showed that at least 50% of desaturations, $SpO_2 < 75\%$ were clinically undetected in children, hence praised use of SpO_2
• however, no ***morbidity*** was documented in any patient, in either group resulting from hypoxia
• Moller *et al.*, Anesth.1991, looking prospectively at 20,802 cases in which half were monitored by SpO_2, failed to show any reduction in morbidity or mortality, except for a decreased incidence of intraoperative myocardial ischaemia (?? this would seem contradictory)

• the ASA Closed Claims Project, in reviewing 348 "preventable" deaths or injuries, came to the conclusion that "pulse oximetry....would have been efficacious in preventing injury in 138 cases."
• using the ASA data, Caplan described 14 cases of arrest under spinal anaesthesia, 12 of whom had IV sedation/opioids without SpO_2 monitoring and hypoxia was believed to contribute
• Eichorn, Anesth.1989, looked at 1,001,000 ASA I&II patients between 1976-1988 and found that,

1. 11 major anaesthesia related incidents, of which 7-8 related to inadequate O_2
2. only 1 of these occurred after the introduction of SpO_2 in mid-'85

• this paper was accompanied by an editorial by Orchin, which pointed-out that this was not statistically significant, and this, nor any other paper had yet shown a clear cost-benefit justification for the use of pulse oximetry

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NB: Severinghaus concludes, "pulse oximetry *probably* did contribute to increasing the safety of anaesthesia...however, this change may have come through the device's educational role in promoting vigilance and awareness of inadequacies in technique"

Accuracy

- many early studies used regression analysis, which was inadequate as no deliberate wide variations in SaO_2 were introduced
- ***bias***, which is the mean error (SpO_2 - SaO_2) and its standard deviation are the currently preferred indices
- however, a single bias value derived from a large range is less than ideal, as accuracy varies with SaO_2 and the bias is usually greater at low SaO_2's
- in general, the claims of most manufacturers, that errors are < ± 3% above a SpO_2 of 70% have been confirmed
- thus, they are more than accurate in most clinical circumstances, except probably the detection of neonatal hyperoxia
- the ability to detect ***trends*** in SpO_2 is as least as important as absolute accuracy

Cytochrome aa_3 Saturation Monitoring

- this enzyme is distal in the cytochrome oxidase chain and contains copper
- when oxidised this enzyme has an absorbance peak **~ 830 nm** in the near infrared range
- as this wavelength is absorbed by both Hb & HbO_2, 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
- effectively only measures saturation in the superficial cortical layers

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}

- 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

• pH changes such that,

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

• 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 P_{CO2} monitoring

CAPNOMETRY

Def'n: ***capnometry*** is the measurement and display of CO_2 concentrations on a digital or analogue display;

capnography is the graphic recording of instantaneous respired CO_2 concentrations during the respiratory cycle

• the first IR CO_2 measuring and recording apparatus was introduced by Luft in 1943
• these were expensive, bulky and principally only used for research
• widespread use within the last 10-15 years with cost and size reduction
• ASA closed claims → 93% of anaesthetic mishaps preventable by $ETCO_2$ / SpO_2

Principals of Measurement

1. mass spectrography
   - ionisation and fragmentation according to charge:mass ratio
   - remains very expensive & bulky
   - multiplexed units have been developed for up to 16 sample lines but sample rate decreases to 1/3.2 minutes
2. Raman spectrography
   - ***Raman scattering*** occurs with illumination with high intensity argon laser light
   - absorbed light energy produces unstable energy states (rotational & vibration)
   - emitted low energy light, Raman light, is measured at 90° to the laser path
   - this can be used to identify all types of molecules in the gas sample, and has been incorporated into new monitors (RASCAL) which instantaneously identify & quantify CO_2 and ***inhalational agents***

3. ***infrared spectrography***
   - more compact and less expensive than other methods
   - assymetric, ***polyatomic gases*** of two or more molecules, absorb IR radiation (> 1.0 µm) → H_2O, N_2O, CO_2
   - the absorbance peak is characteristic for a given gas and for **CO_2 ~ 4.28 µm**
   - the ***Lambert-Beer 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*** **~ 100 ms**, enabling end-tidal CO_2 estimations

4. ***photoacoustic spectrography***
   - also relies on the absorbance of IR light by CO_2 → gas expansion
   - IR light is pulsed at acoustic frequencies and the energy absorbed is detected by microphone
   - the amount of light absorbed is measured *directly*, without the need for a reference chamber → no zero point drift
   - other claimed advantages over IR spectrometry include,

   i. higher accuracy

   ii. increased reliability

   iii. reduced maintenance & reduced need for ***calibration***

▪ ***Classification***

- monitors types are divided according to the location of their sensor,

1. ***side-stream*** capnometers
   - sensor is located within the main unit and gas is aspirated from the circuit
   - sampling flow rate may be high (> 400 ml/min) or low (< 400 ml/min)
   - ***optimal gas flow*** is considered to be 50-200 ml/min, ensuring reliability with both adults and children
   - exhaust gases contain anaesthetic agents & should be routed to the scavenging unit

2. ***mainstream*** capnometers
   - sensor is located at the patient, with a curvette placed within the circuit
   - these are heated to > 39° to prevent occlusion by water vapour
   - no mixing of gases occurs during sampling and the response time is more rapid
   - curvettes tend to be bulky, add dead space, are heated, and are expensive if dropped & broken

Infrared Spectroscopy Accuracy

- ***Atmospheric Pressure***

• alterations do not affect the CO_2 concentration, but do affect what is interpreted as CO_2,

1. ***direct effects***
   - i. - ***gas density***
     - for a given chamber thickness, the number of molecules increases with increasing atmospheric pressure
     - this may be eliminated by calibration against a known P_{CO2} (% x Atm.)
     - units calibrated against C_{CO2} require correction proportionately (1%:1%)
   - ii. - ***IR absorbance***
     - increased pressure increases the intermolecular forces and IR absorbance for a given CO_2 concentration

       $\uparrow$ Atm ~ 1% $\rightarrow$ $\uparrow$ absorbance ~ 0.5-0.8%

     - atmospheric pressure changes with weather are ~ 20 mmHg, which may result in errors ~ 0.5-0.8 mmHg, therefore corrections are unnecessary
   - increases in the sampling ***flow rate*** in side-stream analysers may reduce pressure within the sample chamber & result in errors accordingly

     $\rightarrow$ units should be calibrated for a given sample rate
   - application of ***PEEP*** may therefore increase the P_{CO2} reading

     $\rightarrow$ PEEP ~ 20 cmH_2O $\rightarrow$ $\uparrow$ P_{CO2} ~ 1.5 mmHg
   - some units automatically monitor the pressure within their chamber and adjust the readings automatically
2. ***indirect effect***
   - occurs with analysers reading in ***volume percent***, where $P_{CO2} = F_{CO2}$ x Atm.
   - where the atmospheric pressure at the time of calibration is different to that at the time of measurement

- ***Nitrous Oxide***

• absorbs IR light at 4.5 µm, cf. CO_2 at 4.28 µm
• therefore, the presence of N_2O $\rightarrow$ ***falsely elevated*** CO_2 readings
• this effect may be minimised using a narrow bandwidth filter
• however, the presence of N_2O molecules results in ***collision broadening*** of the absorbance peak of CO_2, also resulting in apparently elevated CO_2 readings

1. the simplest correction is to calibrate the monitor with the same background gas as is to be used during anaesthesia
2. alternatively correction factors may be applied,
   - i. 50% N_2O $\rightarrow$ P'_{CO2} ~ P_{CO2} x 0.9
   - ii. 70% N_2O $\rightarrow$ P'_{CO2} ~ P_{CO2} x 0.94

- ***Water Vapour***

1. ***condensed water***
   - result in falsely ***high*** readings
   - prevented in mainstream units by heating the sensor to prevent condensation
   - side-stream units use water traps prior to the sensor unit
   - some units use Nafion® tubing, which is semipermeable, allowing water vapour to pass from the interior to the exterior of the tube
2. ***water vapour***
   - mainstream analysers measure gas in the breathing circuit
   - this is generally saturated at body temperature but may be affected by the use of humidifiers, FGF's, and the ambient temperature
   - in side-stream units, cooling of the gases results in a decrease in water vapour pressure, and an apparent ***increase*** in P_{CO2} ~ 1.5-2%

- ***Response Time of the Analyser***

1. ***transit time***
   - that require to move from the circuit to the analyser
   - delays the appearance of the waveform, creating a ***phase shift***, but no distortion
   - however, the gas is subject to ***mixing*** in the sample line, with overdamping of a square waveform
   - this results in underestimation of $ETCO_2$, especially in children
   - this error increases both with,

   i. increased width and length of the sample tubing

   ii. reduced sample flow rates < 50 ml/min

   iii. higher frequency breathing patterns
2. ***rise time*** $\mathbf{T_{10\text{-}90}}$
   - time taken for the analyser to change from 10% to 90% of the final value, following a step change in P_{CO2}
   - this is dependent upon the size of the ***sample chamber*** and the sample ***flow rate***
   - ranges of capnographs used clinically ~ 50-600 msec
   - prolongation may decrease the slope of phase II, and underestimation of anatomical dead space
   - most units measure $ETCO_2$ in adults at < 30 bpm with **± 5% *accuracy***
   - however, faster units are required in children, T_{70} < 80 msec
   - the response times of newer units has been markedly reduced by,

   i. use of more powerful signal amplifiers

   ii. minimising the volume of the sample chamber

   iii. use of relatively high sample flow rates > 150 ml/min

- ***Other Factors***

1. ***oxygen***
   - O_2 does not directly absorb IR light, but may affect reading by collision broadening
   - results in falsely ***low*** P_{CO2} readings
   - this effect is not as great as with N_2O but some units incorporate automatic correction
2. halogenated agents
   - these absorb IR light at ~ 3.3 µm and the interference is not clinically significant
3. alinearity of CO_2 analysis
   - the concentration of the calibration gas should be as close as possible to the measured gas sample

Physiological Factors

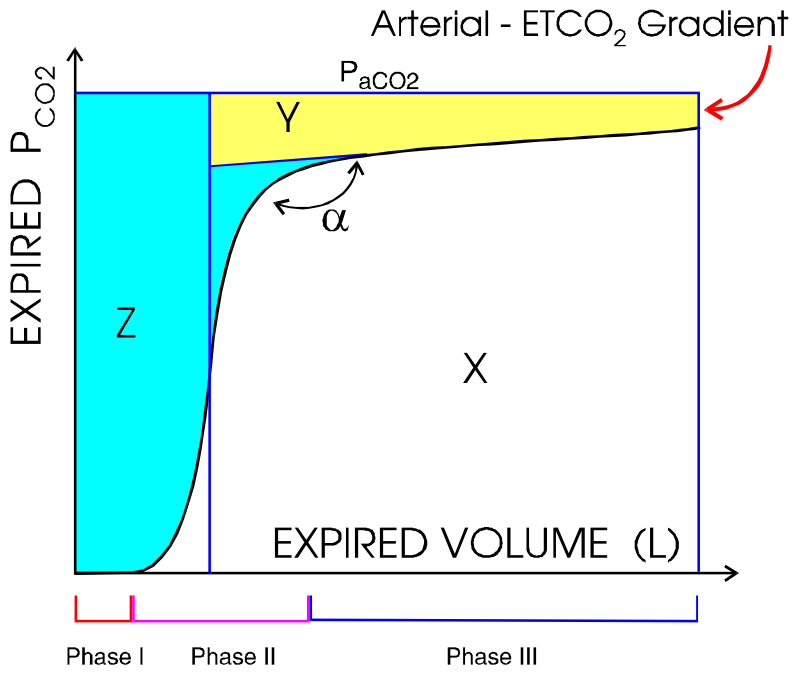
NB: $ETCO_2$ is dependent upon P_{ACO2} and is therefore influenced by changes in,

i. barometric pressure
ii. mean F_ICO_2
iii. VCO_2
iv. alveolar ventilation

$$P_{A_{CO_2}} = P_{Atm.}\left(F_{ICO_2} + \frac{\dot{V}_{CO_2}}{V_A}\right)$$

- ***Capnogram Analysis***

• 2 recording speeds, allowing analysis of single breath records, or trends over time
• most high speed capnograms are plotted P_{CO2} or F_{CO2} against time
• a more accurate assessment is obtained from the ***single breath test - CO_2*** (SBT-CO_2), where changes are plotted against ***expired gas volume***
• this gives a better analysis of V/Q mismatch within the lung, and a more accurate estimation of anatomical and alveolar dead space



1. phase I - equipment and anatomical dead space
2. phase II - mixed dead space and alveolar gas
3. phase III - alveolar plateau

- factors responsible for the slope of ***phase III*** include,
  a. cyclical variation in alveolar CO_2 → increased P_{ACO2} in ***expiration***
  b. late emptying of alveoli with lower V/Q ratios, therefore a higher P_{ACO2}
     i. within the terminal respiratory unit - alveolar mixing defect
        - temporal mismatching of V/Q
     ii. between respiratory units - synchronous
        - asynchronous (sequential)

NB: thus, the slope is dependent upon the emptying patterns of various alveoli with different V/Q ratios, as well as the continuous excretion of CO_2 into the alveoli

- the angle between phase II and III is the ***alpha angle***, and increases with the slope of phase III
- thus, this is an indirect indication of the V/Q status of the lung
- assessment of a P_{CO2} / time capnograph provides adequate information for most circumstances

NB: ***physiological dead space*** can only be determined from a SBT-CO_2 tracing (above),

i. area X → effective ventilation
ii. area Z → anatomical dead space
iii. area Y → alveolar dead space

▪ *Alveolar - $ETCO_2$ Gradient*

• normal **$\delta Pa\text{-}ET_{CO2}$ ~ 2-5 mmHg**
• this has previously been taken to represent ***alveolar dead space***
• however, changes in $\delta Pa\text{-}ET_{CO2}$ only correlate with changes in V_D^{Alv} when phase III is flat or has minimal slope
• if phase III has a steep slope its terminal part may actually intercept the P_{aCO2} line, creating either a zero, or negative $\delta Pa\text{-}ET_{CO2}$
• therefore, $\delta Pa\text{-}ET_{CO2}$ is dependent upon both,

1. alveolar dead space, and
2. factors which influence the slope of phase III

NB: an increase in V_D^{Alv} need not always be associated with an increase in $\delta Pa\text{-}ET_{CO2}$

• ***negative values*** were first noted by Nunn over 30 years ago, and have been observed,

a. normal subjects ~ 12%
   - IPPV with large tidal volumes and slow rates
   - better ventilation of dependent, well perfused alveoli
   - greater contribution from slow alveoli at end-expiration

b. ***pregnant subjects*** ~ 50%
   - ↑ VO_2, ↓ FRC and compliance
   - greater cyclical variations in P_{ACO2} and more alveoli with long time constants
   - late upslope of phase III, similar to phase IV of the N_2 closing volume test

c. ***infants*** ~ 50%
   - ↑ VO_2, ↓ FRC and compliance
   - closing volume may encroach upon FRC

d. post CPB ~ 8%

• ***cardiac output*** and pulmonary blood flow affect CO_2 excretion,

1. ↓ CO → ↓ $ETCO_2$ & ↑ $\delta Pa\text{-}ET_{CO2}$ ∝ ↑ $V_D^{Alv.}$
2. ↑ CO → ↑ $ETCO_2$ & ↓ $\delta Pa\text{-}ET_{CO2}$ ∝ ↓ $V_D^{Alv.}$

Clinical Applications

1. estimate of P_{aCO2} ± 2-5 mmHg in normal subjects
   - increased in - elderly
     - pulmonary disorders (CAL, asthma, emphysema)
     - PE, hypovolaemia, decreased CO
     - anaesthesia
   - decreased in - infants & young children
     - large V_T / low frequency IPPV
     - pregnancy
   - changes/trends are of greater benefit than absolute values
   - varies little, in the absence of major haemodynamic change, during anaesthesia
2. adequacy of spontaneous ventilation
   - useful assessment of the degree of respiratory depression under anaesthesia with a LMA, or SV with an ETT
   - serves as an apnoea monitor with mask ventilation
   - various nasal canulae etc, available but variations too great
3. adjustment of FGF - rebreathing systems
4. integrity of anaesthetic circuitry
   - leaks, disconnections, partial obstructions
   - faulty Bain circuits
   - exhausted CO_2 absorbent canisters
   - one-way valve malfunctions
5. confirmation of endotracheal intubation
   - at least ***6 breaths*** must be observed
   - blind nasal intubation - confirmation and directional guidance
   - correct positioning of double lumen tubes
6. hypermetabolic states
   - MH, MNS, thyrotoxicosis, severe sepsis
7. detection of VAE
   - an abrupt decrease in $ETCO_2$ in the absence of hypotension, hypovolaemia
   - supported by an increase in CVP, decrease in PAWP and CO
8. venous CO_2 embolism
   - rapid, transient rise during laparoscopy etc. ? may get drop
9. adequacy of CPR
   - $ETCO_2$ correlates well with outcome > 15 mmHg survivors
     < 10 mmHg non-survivors
10. Pa-ET_{CO2} assessment of best-PEEP
11. assessment of HFJV, using a single large breath test

Factors	Increased $ETCO_2$	Decreased $ETCO_2$
CO_2 output	fever thyrotoxicosis MH HCO_3^- administration tourniquet release venous CO_2 embolus return of NMJ blockade	hypothermia NMJ blockade
Pulmonary perfusion	increased CO increased BP	reduced CO hypotension hypovolaemia PE cardiac arrest
Alveolar ventilation	hypoventilation bronchial intubation partial airway obstruction rebreathing	hyperventilation apnoea total airway obstruction partial airway obstruction tracheal extubation
Equipment	exhausted CO_2 absorber inadequate FGF circuit leaks ventilator malfunction valve malfunction	circuit disconnection sampling tube leak ventilator malfunction

Care & Precautions

1. ***testing***
   - coarse reference test is a single breath trace of one's own
   - accurate measurements require ***2 point calibration***, at zero and at a reference concentration, preferably close to that to be measured
   - omission of the ***sampling tube*** will result in changes in sample chamber ambient pressure, with subsequent error
2. ***infants & children***
   - a sample flow rate of **150 ml/min** provides for accurate estimates of P_{aCO2} in neonates, infants and small children
   - in small children using rapid rates, phase III may be "absent", however, estimation of P_{aCO2} from the $ETCO_2$ remains accurate
   - distal ETT samples better reflect P_{ACO2} and P_{aCO2}, however generally increase flow resistance through the ETT and are prone to obstruction with secretions

3. zero reference gas
   - most side-stream analysers use room as the zero reference gas
   - mainstream units use Fi_{CO2} as the zero reference, which may result in errors during rebreathing
4. sampling from closed circuits
   - closed circuits with low flow anaesthesia must account for the 150 ml/min loss
5. ***condensation***
   - increases flow resistance in the sample tubing, with lowering of the sample chamber ambient pressure
   - sample tubes may be occluded
   - water may enter the main unit despite water traps, resulting in corrosion etc.
   - this is avoided by incorporation of the sample port into the proximal side of HME's
6. ***tachypnoea***
   i. end-tidal gas in no longer a good representative of alveolar gas
   ii. analysers may underestimate $ETCO_2$ at > 30 bpm, especially if the response time of the analyser is > the respiratory cycle time
   - in these cases, more accurate assessment is achieved by examination of a single large breath, sigh or "squeeze" $ETCO_2$
7. ***hypoventilation***
   - mainly for SV patients, where at the end of expiration flow may be < the sample flow rate, resulting in fresh gas being admixed with exhaled gas
8. technical problems
   - falsely low $ETCO_2$'s frequently result from errors in sampling of end-tidal gas
   - circuit leaks, high FGF's and rebreathing circuits, Bain & T-piece circuits
   - T-piece measurement may be improved by sampling down the ET, or by adding a right-angle elbow between the FGF and the sample port

HUMIDIFICATION

• 4 different terms may be used to describe the amount of water in a gas,

1. water content
2. vapour pressure
3. absolute humidity
4. relative humidity

• ***water content*** is a statement about the final amount of water present, per final volume of a gas, usually expressed in **mg/litre** of the humidified gas
• this is usually water vapour, but may be fine ***particulate*** suspension
• these particles should be between ***2-6 microns***, as larger particles precipitate in the delivery tubing and smaller particles are not retained in the lung
• particulate water must take-in heat to form water vapour, which at 37°C ~ 2400 J/g
• ultimately this heat energy is derived from the body
• ***humidity*** and ***vapour pressure*** refer only to water in the gaseous phase

Absolute Humidity

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

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

$$\textbf{\textit{Relative Humidity}} = \frac{\text{actual vapour pressure}}{\text{saturated vapour pressure}}$$

Vapour Pressure of Water

- is the partial pressure of water vapour in a gas or gas mixture
- if free water is present, then this is usually taken as the saturated vapour pressure, otherwise this is equal to the RH x SVP

NB: relative humidity ***cannot*** be calculated as the ratio of vapour pressures at different temperatures

Temperature	Absolute Humidity	Saturated Vapour Pressure	
°C	mg/litre = g/m^3	mmHg	kPa
10	9.4	9.2	1.2
15	12.8	12.8	1.7
20	17.3	17.5	2.3
25	23.1	23.8	3.1
30	30.4	31.3	4.2
35	39.6	42.2	5.6
37	43.4	47.1	6.3
40	51.2	55.3	7.4
45	65.2	71.8	9.4
50	82.7	92.5	12.2

Humidifier Temperature

- in order to achieve at least 70% saturation at 37 °C, then full saturation must be achieved at 30 °C
- temperatures less than 30°C ***cannot*** achieve satisfactory humidification
- most humidifier standards require ≥ 85% saturation at body temperature, which corresponds to full saturation at 34°C

Latent Heat of Vaporisation

- the LHV for water varies with temperature, such that,
  - i. 100°C ~ 2.26 kJ/g(540 cal/g) * critical temperature = 373 °C
  - ii. 37°C ~ 2.42 kJ/g(570 cal/g)
  - iii. 20°C ~ 580 cal/g

- LHV may be a cause of significant heat loss if water is nebulised without heating
- under normal resting conditions, man loses ~ 250 ml of H_2O and 1.5 kJ/d
- 10-25% of the heat is returned to the upper airway → ***condenser effect***
- gases reaching the ***upper trachea*** are usually ~ 32-36°C with a RH ~ 90%
- this equates to an absolute humidity of ~ 34 mg/l
- bypassing this, for a person ventilated with dry gas at a minute ventilation of 7 l/min then,

Additional LHV required ~ 2.42 kJ/g x (7.0 l/min x 34 mg/l)
~ 576 J/min → 829 kJ/d (~ 200 kcal/d)

- this degree of heat loss is significant predominantly in ***infants***
- the main problem in adults is the drying of ***secretions*** and inhibition of ***ciliary action***
- ciliary activity ceases > 41°C and decreases < 75% RH at 37°C
- temperature appears to be less important at RH ~ 75-100%

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
   - they should not be read in direct sunlight

3. Regnault's Hygrometer
   - condensation occurs in air fully saturated at a given temperature $\rightarrow$ 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,

$$\text{Relative humidity} = \frac{\text{SVP at dew point}}{\text{SVP at ambient temp.}}$$

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

- ***Clinical Applications of Humidification***

1.	tracheal intubation	- maintain ciliary activity - prevent inspissation of secretions - prevent microatelectasis & airways obstruction * reduces respiratory complications postanaesthesia * reduces large temperature falls during surgery
2.	rewarming	- following hypothermic injury or therapy
3.	drug delivery	- principally bronchodilators
4.	R_X of URTI	- mainly anecdotal data, no proven benefit
5.	R_X of LRTI	- cystic fibrosis, emphysema, CAL, pneumonias - useful in preventing desiccation of secretions * no proven benefit in outcome

Humidification - Ideal Features

a. inspired gas delivered to trachea at
- 32-36°C
- 90-100% relative humidity

b. ***no fluctuation*** of temperature & humidity
- with time
- at high gas flows
- with gas composition

c. low ***resistance*** to gas flow
- useful for SV & IPPV
≤ 5 cmH_2O at 50 l/min

d. low ***compliance*** * prevents overreading of V_E
   i. neonate < 1 ml/cmH_2O
   ii. child < 3 ml/cmH_2O
   iii. adult < 5 ml/cmH_2O

e. low ***dead space***

f. inbuilt ***alarms*** for
- high/low temperature
- over/underhydration

g. protection against
- microshock (Class A)
- scalding, overheating (< 42°C max)
- "rain out" & "drowning"
- dehydration/overhydration

h. simple to use, service & sterilise

i. maintenance of sterility

- ***Complications - Dangers***

a. ***infection***
   - water reservoirs frequently grow *Pseudomonas*, which multiplies at 45°C
   - aerosols from bath humidifiers (previously thought not to be produced)
   - some operate on "continuous pasteurisation" at ~ 60°C, or by the addition of chlorhexidine gluconate 0.02%
   - with all units, the water reservoir and tubing should be changed 24 hourly
   - aerosol generators, especially ultrasonic, are particularly vulnerable
   - the newer HME's ***do not*** appear to be at increased risk of infection, despite becoming heavily contaminated with micro-organisms

b. ***drowning*** - especially US nebulisers in paediatric use

c. ***burns*** - a delivered temperature ~ 35°C provides a safety margin
- correct functioning of the thermostat & alarms is essential

d. ***electrocution***

Types of Nebulisers

a. cold water bubble humidifiers
b. condenser
c. hot water bath
d. heated Bernoulli nebuliser and anvil
e. ultrasonic nebuliser

NB: * these are in order of increasing efficiency

Humidifiers

Cold Water Bubble Humidifiers

• numerous unheated, "bubble through" humidifiers, which may be attached to O_2 flowmeters
• these generally cannot deliver > 9 mg/l or 50% relative humidity at ambient temperature
• these may be useful for SV patients using a mask, but are ***inadequate*** for intubated patients

Condensers

• perform the function of the nasopharynx, retaining heat and moisture from the expired gases
• efficiency depends upon,

1. the thermal capacity and surface area of the gauze
2. the inspired gas humidity and temperature

• ***disadvantages*** include,

1. increased airway resistance and dead space
2. extra weight attached to the ETT
3. risk of infection

• newer units use a variety of hygroscopic materials and bacterostatic chemicals to enhance performance → Portex "Humidivent" - $CaCl_2$ impregnated microporous paper
• these are capable of providing up to ~ ***30 mg/l at 27-30°C***
• thus they are useful for short-term ventilation, such as during anaesthesia
• paediatric forms are available, however their efficiency is reduced, especially in neonates, due to the leak around the ETT

Water Bath Humidifiers

- the commonest & most effective method in common usage
- problems include,
    i. thermostat problems - may not allow fine enough control of temp.
    - failure may occur
    ii. condensation
    iii. efficiency is not constant
    iv. infection is a hazard

■ *Fisher & Paykel Humidifier*

- functionally in 3 modules,

1. base plate & power heater
    - heated base plate, total power consumption ~ 100W
    - on/off switch & thermostat controls
    - 24V heating lead to the delivery tubing
    - illumination of the perspex reservoir → green with correct operation
    → red with alarm & shut-off
2. water reservoir
    - clear plastic housing with an aluminium base, which sits against the heater base
    - used to be reusable, disposable since ~ 1981
    - capacity ~ 200 ml
    - a metal scroll and wick sit inside against the aluminium plate and the top of the housing → a spiral gas channel
3. delivery hose & heating wire
    - polycarbonate plastic tubing with a 1.2 m loop of flat, silicone insulated wire
    - the 24V power lead attaches into the side of the power heater

- the base plate is heated & thermostatically controlled, with overtemperature automatic shut-off
- the baseplate thermostat has maximum setting of ~ 47°C and the safety thermostat in the baseplate operates at ~ 70°C with an audible alarm
- the housing is indirectly heated through the base plate, as is the aluminium scroll
- the absorbent paper within the scroll acts as a wick, SA ~ 280 cm^2 (disposable)
- gas enters at the periphery of the tank, and spirals around the scroll to emerge at the centre to the delivery hose
- the hose heater is not automatically set, but manually adjusted via a slotted knob in the heater base to provide a delivery temperature of 37°C at the patient end of the tubing
- this prevents "rainout" in the delivery hose
- there are no alarms for the water level within the unit, which must be visually inspected
- overfilling is possible if the delivery port is used instead of the side filling port
- under normal operating conditions, 20° tilt does not result in spilling into the delivery tube, allowing movement of the unit without drowning the patient

• the base temperature control may be adjusted for flows from 3-25 l/min
• circuit compliance varies with the water level and the hose assembly used,

a. full reservoir ~ 0.38 ml/cmH_2O ~ 11.5 ml/breath at 30 cmH_2O

b. minimum level ~ 0.82 ml/cmH_2O ~ 24.5 ml/breath at 30 cmH_2O

• this is unlikely to be important except in neonates, and there is a separate housing and hose assembly for paediatric use
• flow resistance is low,

a. adult circuit ~ 0.8 cmH_2O at 50 l/min

b. paediatric circuit ~ 1.5 cmH_2O at 50 l/min

• the unit has low current leakage and meets Class A specifications

▪ ***Grant Humidifier***

• this is a simple heated reservoir tank, with no attempt to saturate the inspired gas
• temperature is elevated to ~ 41 ℃ with a RH ~ 80%
• there is a controlled drop in temperature along the delivery tube, such that delivery at the patient is fully saturated at body temperature
• a platinum resistance temperature sensor monitors the patient delivery end and regulates the heated delivery tubing
• this has a low thermal inertia and rapid response time

▪ ***Aerosol Generators***

• as these are not subject to the temperature limitations of vapour saturation, they may deliver a ***supersaturated gas mixture***
• aerosols are more stable the smaller are the droplets, size also affecting distribution,

i. < 1 μm → reach the alveoli
ii. ~ 5 μm → deposited in the bronchi
iii. 7-10 μm → deposited in the naso & oropharynx

• the types of aerosol generators are,

1. gas-driven nebuliser
   - produces droplets in the range ~ 5-20 μm
   - relies on the Bernoulli effect to produce a jet stream of water & an anvil
2. mechanical nebuliser - spinning disc
3. ultrasonic nebuliser
   - use piezoelectric crystals at radiofrequencies
   - produce uniform, smaller droplets, < 5 μm
   - very high mist density, up to 100-200 mg/l, with the risks of overhydration and increased airways resistance

ELECTRICAL SAFETY

- ***Ohm's Law***

  i. $V = I . R$ - for DC circuits, or

  ii. $V = I . Z$ - for alternating circuits, of frequency (f)

  where the ***impedance, Z*** $\propto \omega.f$ - for inductive loads
  $\propto 1/f$ - for capacitive loads

Def'n: ***Ampere***: = 1 coulomb/second, = 6.28×10^{18} electrons/second
Watt: = V x I - unit of power
- measure of ***work*** = watts/s

- ***Mechanisms of Injury***

1. high tension / lightning injuries
   - tissue thermal injury/necrosis $\propto$ ***Joule's Law***: Heat $\propto I^2 \times \Omega$
   - electrical flash burns and flame burns 2° to clothing ignition
2. electrocution
   - disruption of normal physiological function
   - tissue thermal injury

- ***Macroshock***

  - effects of current applied to the body through intact skin, usually **> 100 mA** / 50 Hz
  - ***skin resistance*** is the principal determinate of current flow
  - this varies from 1000-100,000 Ω depending,
    i. skin moisture content - main factor
    ii. surface area of contact

- ***Microshock***

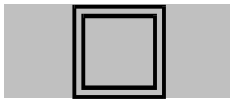
  - effects of current applied directly to the heart, through an introduced conductor
  - VF may result from currents **> 60 µA** (usually > 100 µA)

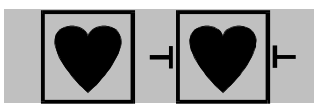
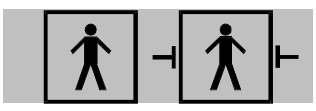
- ***Ventricular Fibrillation***

- the likelihood is determined by,
  i. the current ***density*** passing through the heart
  ii. the current ***frequency*** $\rightarrow$ $\uparrow$ risk at ***30-100 Hz***

- high frequency currents such as diathermy (0.5-3.0 MHz) will not result in depolarisation unless the current is large enough to result in burns

50 Hz Electrical Current		
Current	**Clinical Effects**	
10 µA	No sensation	**Class A**
60 µA		***Microshock***
100 µA		**Class B**
300 µA	Sensory threshold	
1 mA	Pain threshold	
9-25 mA	Tetanic muscle contraction	
> 100 mA	Probable VF and death	***Macroshock***
> 2 A	Severe shock with burns	

General Equipment Protection			
	Class I	Class II	Class III
Description	Earthed	Double insulated	Extra-low Voltage
Australian Standard Symbol			
Case leakage current	Class Dependent	100 µA	

Patient Circuit Protection			
Classification	Cardiac Protected	Body Protected	Unprotected
Old Classification	Class A	Class B	Class Z
Circuit leakage current	**10 µA**	**100 µA**	100 µA
Circuit leakage current * earth disconnected	50 µA	500 µA	500 µA
Earth leakage current	**100 µA**	**500 µA**	500 µA
Standard Symbol			

Equipment Classes

NB: equipment and area classifications in Australia are with reference to 240 V / 50 Hz

- ***Class I***

• this is connected to the 240V mains and is earthed
• the class is subdivided according to the ***patient circuit isolation***
• in addition the current leakage limits listed above, these devices are tested under fault conditions (earth disconnected) for maximum current flow with patient contact with 240 V,

1.	cardiac prot.	< 50 µA	→	imperceptible
2.	body prot.	< 5 mA	→	painful, but no risk of macroshock
3.	unprotected	no limit	→	risk of macroshock rely upon earthing and secure environment

- ***Class II***

• this is also mains operated but is ***double insulated***
• a functional earth may be connected to internal components, but the outer case has double or reinforced insulation, denoted by a double square symbol
• the inductive case leakage current should be < 100 µA, which still poses a risk of ***microshock***

- ***Class III***

• is special low voltage equipment, not exceeding,

1. 40V DC, or
2. 40V AC(RMS), supplied by an isolating transformer

• this provides good protection against macroshock, and some Class B procedures, but does not protect against microshock
• for use in Class A procedures, these must have a leakage current < 10 µA and the equipment must be earth-free or connected to an equipotential earthing point
• these criteria also apply to battery operated equipment

- ***Defibrillator Use***

• in addition to Class A or Class B protection, some equipment should be capable of withstanding discharge from a defibrillator → ***5000V*** across the patient circuit
• equipment of this class is given the appropriate symbol with defibrillator paddles applied to the side of the case

■ ***Body Protection***

• skin is usually the major component of body resistance
• situations where this barrier is lost constitute an increased, but not extreme risk, of increased shock, eg.,

i. ECG electrodes with conductive paste
ii. intra-arterial pressure monitoring

■ ***Cardiac Protection***

• ***intracardiac electrocution*** can occur from,

1. 50 Hz AC flowing through the ***patient connections***
   - AS 3200 limits flow from cardiac equipment to **< 10 µA**
   - with the earth disconnected this must still be **< 50 µA**
2. current flowing from the patient connections to earth
   i. the capacitive leakage current to earth is also **< 10 µA**, and **< 50 µA** if the earth becomes disconnected and another means of earthing is supplied
   ii. induced earth leakage current from the case of a piece of equipment, (collected by a flat hand etc.)
      - this enclosure leakage current must also be < 10 µA
3. ***earth loop*** current flow between earth points of different potential
   - associated with earth current flow from a faulty piece of equipment, often remote from the patient
   - two pieces of equipment attached to the patient, then have their earths at different potentials

   i. ***all*** earthed equipment → a total resistance in the earth connection **< 0.2** Ω
   ii. the earth current leakage on Class A equipment is limited to **< 100 µA**
   iii. all Class A wiring areas have provision of ***equipotential earthing***
   iv. supply earthing must be such, that a 1 ampere leakage current into any 1 socket will not raise the voltage in any earth terminal in the area by **> 100 mV**
   v. maximum resistance between earthing points on the bus **< 0.1** Ω
   vi. the use of extension cords is contraindicated

Supply Grounding

• the mains grid supply is always grounded in order to prevent high voltage transmission to domestic homes, or charge build-up during electrical storms
• standard supplies are then ***multiple earthed neutral***, with the neutral of the power grid tied to earth at the supply station, at step-down transformers and at each domestic outlet

▪ *Domestic Supply*

• protection against electrical hazard is provided by,

1. education and safe practices
2. equipment / appliance earthing
3. equipment / appliance insulation or double insulation
4. fuses ~ 10-20 A
5. circuit breakers ~ 10-20 A
6. earth current leakage detectors
   - "safety switch"
   - earth leakage core balance relay (ELCB)
   - ground fault circuit interrupter

NB: factors 1-5 ***do not*** protect against electrocution in the presence of faulty equipment

▪ *Earth Leakage Core Balance Relays*

• detect any ***imbalance*** between the current flowing in the active and the neutral wires

1. inductive coil around both active and neutral supply lines
2. as current flows in opposite directions, these effectively cancel each other
3. any discrepancy between the two induces a current in the coil, the discrepancy assumed to be leakage to earth
4. an imbalance can be detected with 10 msec at 50 Hz (20 msec cycle length), however an additional delay occur in tripping of the relay
5. the device ***does not*** protect against,
   i. electrocution between active and neutral
   ii. microshock

• if this current is **> 10 mA** the power supply is disconnected within **60 msec** (AS 3003)
• most common units working within 30 msec and medical devices sound an audible alarm
• in accordance with AS 3190, all such devices should have a test button, enabling function of the relay to be checked regularly
• the disadvantage of this device is shutdown of all equipment connected to the supply

Ungrounded / Isolated Supply

■ *Line Isolation Transformer*

• produces a floating supply of 240 V potential difference, not referenced to earth
• equipment casings are earthed, in common with the neutral of the transformer ***primary*** winding
• a shortcircuit within a piece of equipment (line to case) represents no shock hazard, but effectively converts the ungrounded supply to a grounded one
• if this faulty piece of equipment continues to be used, and a ***second fault*** exists in another unit, then a shock hazard exists

■ *Line Isolation Monitor*

• monitors the integrity of the isolation system, ie. its degree of reference to ground

1. alarm limits, usually ≤ **2-5 mA**
2. if line supply is 240 V and the alarm limit is 5 mA, then
   → line-ground ***impedance*** = 240/0.005 ~ 48,000 Ω
3. the monitor continuously checks the impedance from lines 1& 2 to ground
4. the equipment ground-wire is integral to detection of a fault
5. ***unable*** to protect against microshock

• effectively this estimates the "worst case" or potential current flow should an earthed individual contact either power line
• effective earth isolation decreases with heavy power consumption and with multiple pieces of equipment all in use the advantage of this system is in the event of breakdown in isolation, the power supply is continued, monitoring allowing "fault-finding" to take place while vital support functions are continued

■ *Microshock Protection*

• methods for avoiding these include,

1. the procedure must be in a cardiac protected area, with ***equipotential earthing***
   • ***mains isolation*** offers additional but not essential protection
2. ***all*** intracardiac connected equipment
   i. patient circuit current < 10 µA leakage / < 50 µA
   ii. patient circuit - earth leakage
      • cardiac protected ***equipotential earthing***
      • ***double insulation***, earth free
      • isolated battery operated equipment
3. ***all*** other equipment connected to the patient < 500 µA earth leakage current
   • this may be Class A, B, or Z, connected to an ***equipotential earthing*** point

MONITORING DURING ANAESTHESIA

- ***Aims***

1. to improve overall ***patient safety***
   i. to forewarn of a potentially hazardous physiological state
   ii. to forewarn of equipment malfunction & disconnection
2. to provide ***measurement*** of,
   i. "important" physiological variables
   ii. system function & integrity
3. to determination of the degree or ***severity*** of change, and the ***trend*** of such a change
4. to assessment of the impact of ***specific therapy*** upon a physiological state

- ***Range***

1. ***clinical*** - colour, respiratory rate & pattern
   - HR, manual BP, perfusion
   - auscultation of the chest & heart
   - eye signs, other neurological signs
2. ***non-invasive***
   i. equipment - gas supply, cylinder pressures
   - anaesthetic machine "line" pressures
   - F_IO_2, disconnect, circuit pressures

   ii. patient - ECG, NIBP
   - S_pO_2, $ETCO_2$, spirometry
   - PNS
   - precordial doppler, doppler CBF
   - SSEP's
3. ***invasive***
   i. minimally - $ETCO_2$ with an ETT
   - temperature probes
   - oesophageal stethoscope, temperature, pressure

   ii. moderately - IABP
   - TEE
   - CVP

   iii. highly - PA catheter
   - LA line
   - extradural bolt, intraventricular drain

Arterial Lines

- ***Relative Indications***

1. continuous arterial ***pressure monitoring***
   i. any patient with severely compromised CVS function
   ii. procedures with potential for massive or rapid blood-loss
   iii. procedures which may severely impair venous return or alter afterload
      - thoracotomies
      - mediastinal procedures
      - aortic or caval clamping/declamping
   iv. for control of ICP
   v. where potent vasoactive drugs are to be used
      - induced hypotension
      - inotrope infusions
   vi. cardiopulmonary bypass
2. repeated arterial ***blood sampling***
   i. AGA's - neonates, ICU patients
      - severe airways disease ($ETCO_2 \neq P_{aCO2}$)
      - severe metabolic disturbance, acid-base management
   ii. biochemistry - severe metabolic disturbance, emergency surgery
      - liver transplant
3. ***research***

- ***Absolute Contraindications***

1. AV shunt for dialysis
2. absence of collateral circulation
   - a positive Allen's test ***is not*** an absolute contraindication
   - frequent false positives, therefore only relative
3. severe Raynaud's disease
4. Buerger's disease
5. Wegener's granulomatosis
6. infection at the chosen site

- ***Information Gained***

a.	accurate MAP	- beat-to-beat SAP, DAP - trends
b.	hypovolaemia	- increased pulse paradox - lower dichrotic notch - steeply peaked systolic wave - ↑ δSAP down with IPPV
c.	decreased contractility	- reduced upslope - reduced peak pressure
d.	indication of myocardial O_2 supply/demand	- pulse pressure product - systolic area vs diastolic area
e.	pulsus paradoxus	- hypovolaemia - tamponade, constrictive pericarditis - high intrathoracic pressure - acute asthma - severe CCF, myocarditis - RV AMI - PTE - ascites - pregnancy
f.	hyperdynamic pulse	- sharp rise & fall - sepsis - AI - AV fistula - anaemia - thyrotoxicosis - pregnancy
g.	pulsus alternans	- pericardial effusion - severe LV dysfunction
h.	pulsus bisferens	- AI
i.	access for frequent blood analyses	

Central Venous Catheters

- ***Indications***

1.	CVP measurement	
2.	vascular access	- difficult or prolonged
3.	hypertonic or irritant fluids	- TPN, HCl - inotropes
4.	infusion of large volumes	- ***not*** for rapid administration, except S-G sheath
5.	aspiration of air	- RA multilumen catheter
6.	other therapies	- pacemaker - PA catheter - haemodialysis, haemoperfusion, plasmapheresis

- ***Complications***

a. ***during insertion***

i.	failure to site in SVC	~ 5% subclavian (some ≤ 25%) ~ 0-4% IJV
ii.	haematoma	
iii.	arterial puncture	~ 5% subclavian ~ 1-2% IJV
iv.	pneumothorax	~ 2% subclavian < 1-2% IJV
v.	damage to other structures	- vagus/recurrent laryngeal nn. - stellate ganglion, cervical plexus - thoracic duct, trachea, ETT cuff !

b. ***during use***

i.	venous thrombosis	- hypertonic solutions ± thromboembolism
ii.	colonisation	- line infection, bacteraemia, septicaemia ~ 10% of colonised → bacteraemia
iii.	accidental removal, bleeding	
iv.	SVC perforation	- catheter stiffness - duration & site
v.	embolisation	- air, thrombus, septic thrombus - catheter tip (shearing)
vi.	AV fistula	

c. ***during removal***

i. embolisation

ii. haematoma formation

PA Catheters

- ***Indications***

1. optimisation of ***LV preload***, where the CVP will not reflect LVEDV
   - i. LV dysfunction - present or anticipated
     - severe IHD - global or regional dysfunction
       - recent myocardial infarction
       - ischaemia-induced valvular dysfunction
     - cardiomyopathy
     - valvular heart disease - this is argued due to validity of measurement
     - aneurysmal heart disease
     - HOCM
   - ii. aortic surgery - poor LV function
     - suprarenal clamping
   - iii. severe pulmonary disease
     - pulmonary hypertensive disease
     - multiple pulmonary emboli
   - iv. states of increased ***oedemagenesis*** - pre-eclampsia, ARDS
2. optimisation of ***perfusion*** & ***oxygen delivery***, in patients unresponsive to therapy
   - i. sepsis syndrome / SIRS / MOSF
   - ii. LV dysfunction
3. ***ancillary*** capabilities
   - i. ventricular pacing
   - ii. mixed venous S_pO_2
   - iii. diagnostic categories
     - angiography in PE
     - air embolism
     - preoperative assessment of post-pneumonectomy risk
   - iv. therapeutic - regional thrombolytic therapy
4. ***research***

- ***Guidelines For Use***

1. check position with a CXR
2. never use fluid to fill balloon & inflate the balloon slowly
3. use the minimal volume to achieve a wedge trace
4. never let balloon remain wedged
5. never withdraw the catheter across the heart with the balloon inflated
6. be aware of increased risk of PA rupture in elderly

- ***Complications***

NB: complication rate similar to ***CVC catheters***, especially complications of ***insertion***

1. ***misuse & misinformation***
2. minor complications common
   i. **arrhythmias** - **VEB's**, AEB's, persistent VEB's
      - transient RBBB, 3°HB
      - SVT
   ii. haematoma
   iii. catheter thrombosis
3. major complications rare

i.	pulmonary infarction	≤ 7%
ii.	carotid puncture	~ 1-4%
iii.	infection	~ 1-2%
iv.	thrombotic endocardial vegetation	≤ 1%
v.	pneumothorax	~ 0.5%
vi.	PA rupture	~ 0.1%

   vii. valvular damage
   viii. papillary muscle damage
4. catheter knotting
5. bacteraemia / sepsis
6. balloon rupture

- ***PA Catheter - Clinical Aspects***

a. no absolute indications

b. essentially a poor indicator of preload
   - trends of far greater value than isolated readings
   - derived data probably of greater benefit than PCWP

c. no improvement in ***outcome*** in CCU patients

d. no improvement in outcome in severe respiratory disease

e. some suggestive evidence for improved survival,
   i. in major postoperative and severely septic patients (Shoemaker)*
   ii. perioperative MI < 3 months (Rao, El Etr) §

f. results depend upon the use of information derived

NB: *this improvement was not necessarily related to PA catheter
§this was a none peer reviewed paper, subsequently claimed benefits withdrawn

Transoesophageal Echocardiography

- ***Advantages***

1. relatively noninvasive, low risk procedure in anaesthetised patients
2. excellent image quality
3. no interference with surgical field
4. stable continuous cardiac monitoring

- ***Clinical Uses***

1. global and regional cardiac function
2. monitoring for myocardial ischaemia
3. assessment of valvular function and integrity
4. assessment of anatomical abnormalities
   i. atrial myxoma
   ii. valvular vegetations
   iii. mural thrombi
   iv. calcific disease
5. detection of embolisation - air, fat, thrombi, other

- ***Indications***

1. optimisation of ***LV preload*** in patients at risk of decompensation
   i. severe LV or valvular dysfunction
   ii. major vascular, thoracic or other surgery
2. monitoring for ***myocardial ischaemia***
3. monitoring and assessment of valve replacement surgery
4. monitoring for VAE, or other embolisation
5. assessment of myocardial anatomy

- ***Contraindications***

1. operator inexperience
2. oesophageal disease - tumour
   - stricture, previous surgery
   - varices