R. Principles of Measurement

http://www.netspace.net.au/~jam/anaesth/measurement.html

a. Explain mathematical concepts such as exponential functions, integration and differentiation.

Any process in which the rate of change of a quantity is proportional to the quantity is an exponential function. An example is the emptying of a bath: the rate of change of the volume of the bath (the plug-hole flow) is proportional to the volume remaining in the bath (which determines the pressure at the plug-hole):

$$\dot{V} = -kV$$

Integrating with respect to time gives the exponential function:

$$V_t = V_{t=0}e^{-kt}$$

This situation is analogous to the elimination of a drug which demonstrates first-order kinetics, such as the washout curve of an inhaled anaesthetic. It is also analogous to the natural expiration from the lungs where -k equals the rate constant of expiration, the reciprocal of the time constant (compliance times resistance).

Integration is the derivation of a function which expresses the area under a function $y = f(x)$ from $x = 0$ to any value of x.

Differentiation is the reverse process: deriving a function which expresses the rate of change of $f(x)$.

b. Explain electrical concepts such as current, potential difference, resistance, impedance and capacitance as they relate to biomedical apparatus.

Current is the flow of charged particles resulting from a potential difference or changing magnetic field. Most commonly this is a flow of electrons through a metal or other conductor (such as graphite) which has freely mobile electrons. A current can also flow through solutions containing charged particles. All body fluids contain ions and so are capable of conducting current. The unit of current is the Ampere (1 Coulomb/second). Many quantities in monitoring devices are measured indirectly as electrical current. Nerve stimulators are calibrated to deliver a determined current through the tissue between the electrodes.

Solids which do not contain many unbound electrons and solutions with few ions are poor conductors and are known as insulators.

Seimconductors contain electrons which are loosely bound and may conduct a current if electrons are given enough energy to become unbound. This effect is seen in thermistors and photodetectors used in monitoring equipment. It is also the basis for transistors and silicon-based integrated circuits which are universally present in electronic equipment.

Potential difference is the difference in electrical energy between two points. Its unit is the Volt (1 Joule/Coulomb) and it generates a electromotive force which drives a current of charged particles.

Resistance is a measure of the electromotive force required to drive a current through a material. Its unit is the Ohm (1 Volt/Ampere). Thermistors display a change in resistance over a range of temperature and so with calibration the current flow for a specified voltage can be measured and used to determine temperature. Similarly some materials display an increase in resistance as they are stretched, allowing for tension or pressure to be measured indirectly.

When a small change in resistance is to be measured, a Wheatstone Bridge circuit is commonly employed. Classically, R_4 is measured by adjusting R_3 until the galvanometer reads 0. In this situation, $R_1/R_2 = R_3/R_4$. In practice, a monitor is set up so that R_1 and R_4 vary together and inversely to R_2 and R_3. The deflection of the galvanometer is then read as output.

Impedance is the resistance of a component or circuit with a specified characteristic current flowing. Resistance of many components (capacitors and inductors) varies with frequency of alternating current. In a surgical diathermy device, a capacitor is part of the circuit, providing low impedance at the high frequency typically used (1 MHz), but high impedance to low frequency currents likely to cause arrhythmias (50 Hz).

Capacitance is a measure of the charge a device can hold. Its unit is the Farad (1 Coulomb/Volt). Defibrillators are based on a capacitor which is charged with a calibrated voltage to provide a determined energy output for DC reversion. The energy stored in a capacitor is 0.5 x charge x potential. A typical output of 360 J is usually produced by about 5000 V across about 150 mC. An inductor is used to slow the discharge of the defibrillator.
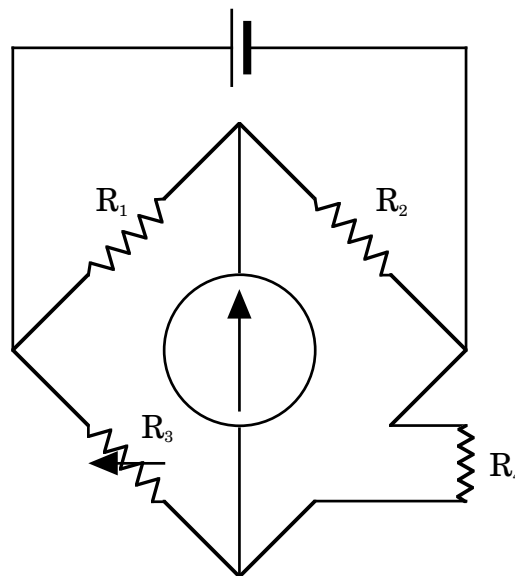
c. Explain the SI system of units.

Seven basic SI units from which all other units are derived

mass	kg
time	s
distance	m
current	A
temperature	K
luminous intensity	cd
amount of substance	mol

Derived SI units (some of them)

temperature	°C	K - 273.15
force	N	$kg\ m\ s^{-2}$
pressure	Pa	$N\ m^{-2}$
energy	J	N m
power	W	$J\ s^{-1}$
frequency	Hz	s^{-1}
volume	l	$10^{-3}\ m^3$
charge	C	A s
potential	V	$W\ A^{-1}$ or $J\ C^{-1}$
capacitance	F	$C\ V^{-1}$
resistance	Ω	$V\ A^{-1}$
magnetic flux	Wb	V s
radiation dose	Gy	$J\ kg^{-1}$ water
radiation exposure	Sievert	Gy · tissue factor · radiation type factor

Prefixes (multipliers)

atto	a	10^{-18}
femto	f	10^{-15}
pico	p	10^{-12}
nano	n	10^{-9}
micro	μ	10^{-6}
milli	m	10^{-3}
kilo	k	10^{3}
mega	M	10^{6}
giga	G	10^{9}
tera	T	10^{12}
peta	P	10^{15}
exa	E	10^{18}

Some non-SI units with conversions

pressure	mmHg	132 Pa
	cmH_2O	98 Pa
	atm	101.325 kPa
	psi	6.89 kPa
energy	calorie	4.18 J
resistance	dyne s cm^{-5}	80 mmHg l^{-1} min
catheter size	French	external circumference in mm
	Gauge	20 (1 – log external diameter in mm)
glucose	mg/dl	mmol/l x 18

d. Outline the conversion between different units of pressure measurement.

Given above.

e. Describe the laws governing the behaviour of fluids.

Fluids are gases or liquids. They exhibit flow, which is defined as quantity (Q) moved per unit time (t):

$$\dot{Q} = \frac{Q}{t}$$

Flow is characterized as laminar or turbulent. In laminar flow, fluid moves without eddies and flow is equal to pressure (P) over resistance (R):

$$\dot{Q} = \frac{P}{R}$$

In a cylindrical tube, resistance to flow is related to radius (r) and length (l) of the tube and viscosity (η) of the fluid, yielding the Hagen-Poiseuille equation:

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

Above a critical speed, laminar flow changes to turbulent flow. For a smooth cylindrical tube, the transition occurs when Reynolds number is approximately 2000. For rough or bent tubes, the transition occurs at lower numbers. Reynolds number (RN) is defined in terms of speed (v), density (ρ) and viscosity (η) of the fluid and diameter (d) of the tube:

$$RN = \frac{v\rho d}{\eta}$$

For turbulent flow, the relationship determining flow is described empirically:

$$\dot{Q} \propto \sqrt{\frac{P}{l\rho}}$$

The relationship with tube diameter is complex and roughly related to slightly

greater than diameter to the power four.

The behaviour of gases is described by the gas laws. Because gases are composed of small molecules or atoms widely spaced, their physical properties are very similar regardless of the identity of the molecules or atoms.

Boyle's Law states that for a constant quantity of gas at a constant temperature, the absolute pressure is inversely proportional to the volume. Charles's Law states that for a constant quantity of gas at a constant pressure, the absolute temperature of the gas is proportional to its volume. Avogadro's Hypothesis states that equal volumes of gas at the same temperature and pressure contain the same number of molecules. One mole of gas occupies 22.4 dm^3 at s.t.p. (273.15 K, 101.325 kPa). These laws combine to give the relation:

$$PV = nRT$$

Where R is the universal gas constant.

Real gases all have a temperature at which they condense into liquids (boiling point at standard pressure). Over a range of pressures, the temperature at which a gas will condense varies below the critical temperature (the temperature at which the gas will condense at critical pressure and above which it will not condense). At a temperature well below critical temperature, a gas will start to condense with decreasing volume, maintaining a constant pressure over a range of volume until it is entirely condensed.

With gas mixtures, separation of the constituents by condensation of one into the liquid phase may occur below the "pseudo-critical" temperature over a range of pressures.

f. Describe the principles of measurement employed by apparatus in clinical use, including transducers and describe their calibration.

Resonance

All oscillating systems display resonance with a peak resonant frequency (f_0)

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{\text{stiffness}}{\text{mass}}}$$

Frequencies close to the resonant frequency will be distorted in the absence of damping

High resonant frequency allows accurate reproduction of waveforms

Damping

The property of a system which diminishes resonance

Damping ratio is the ratio of the amplitude of successive resonant peaks following a "square-wave" stimulus ($D_2 \div D_1$)

Damping coefficient is derived from damping ratio

$$\beta = \sqrt{\frac{(\ln\frac{D_2}{D_1})^2}{\pi^2 + (\ln\frac{D_2}{D_1})^2}}$$

ß = 0.64 is the coefficient for optimal damping

Corresponds to a damping ratio of about 0.07

Eliminates phase lag

Allows accurate reproduction of frequencies up to $^2/_3$ of the resonant frequency

Underdamped systems (small ß, damping ratio close to 1) respond rapidly but overshoot, so they oscillate around their final value e.g. bathroom scales

Overdamped systems (ß close to 1, damping ratio close to 0) move slowly to their final value and do not overshoot e.g. thermometer, arterial line with bubbles.
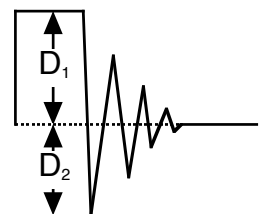
g. Describe the measurement of flow, pressure and velocity in fluids.

Flow is the change of volume over time. In gases it may be most simply be measured by a device which records volume against a time baseline, such as the Benedict Roth spirometer in which a sealed drum moves up as it is filled with gas, recording directly

onto a chart moved with time, or with a bellows which moves a pen with its expansion as in the Vitalograph more commonly used for spirometry.

For the measurement of continuous flows, an alternating bellows device is used in gas and water supplies, with the direction of flow into the bellows alternating as it is filled. In anaesthesia, the Wright respirometer connects in series with the circuit and records tidal volume with each breath. A set of slits generates a circular flow inside the meter which spins a vane connected directly to a rotating dial via a gearing system. It is not accurate for continuous flow.

Most commonly in anaesthesia, tidal volume and flow is measured using an electronic flow meter. Sets of blades cause the flow of gas to spin a mounted vane which interrupts a light beam shone through the housing of the device. Electronic processing of the frequency and duration of the interruption of the light beam allows calculation of flow (Ohmeda). Alternatively the cooling of a fine heated wire across the gas flow can be used to calculate flow (Dräger). These devices all measure gas flows at ambient temperature and pressure.

Measurement of continuous flow also occurs in the flowmeters of the anaesthetic machine. These consist of a calibrated glass tube of variable internal diameter in which a grooved bobbin is suspended by the flow of gas. The flow through a flowmeter tube is complex and dependent on the characteristics of the particular gas being measured, so they are calibrated empirically for a specific gas or mixture at a specific temperature and pressure. The pressure drop across the bobbin is constant and determined by the weight of the bobbin. The size of the orifice around the bobbin increases as it moves up the glass tube, allowing more gas flow for the fixed pressure drop. This is a "fixed pressure, variable orifice" flowmeter.

Highly variable flows may be measured with specific devices such as the peak flow meter. In this a ratcheted marker is moved against a variable resistance as the patient breathes out forcefully. The maximum displacement of the marker is calibrated to show the peak flow rate. This measurement is highly effort-dependent.

For constant measurement of respiratory flows, a pneumotachograph may be used. In this device a heated gauze screen maintains a region of laminar flow which provides a fixed resistance which results in a pressure drop across the gauze proportional to flow. By electronically integrating this pressure drop against time, the device can calculate the flow continuously.

Measurement of flow in liquids is simpler than gases because the variations in volume with temperature and pressure are much less. In IV giving sets, flow may be measured using a calibrated drop chamber in which the drop rate is counted either manually or electronically. The accuracy of this method depends on the composition of the fluid.

More common in slow infusions is the use of volumetric pumps. These incorporate an electric pump in the infusion line which is calibrated to deliver a controlled volume and operated at a rate programmed into the pump.

For small volumes, a mechanical syringe-driver operated by a stepper motor is used. Combined with calibrated syringes, this can deliver very accurate flows of small volumes over extended periods, such as in subcutaneous infusion of narcotics by portable battery-driven devices.

Measurement of liquid flow in the body is generally by indirect methods with the exception of dialysis and bypass devices where mechanical or electromagnetic methods can be used. Dilution of a marker such as fluorescent dye, radioactive tracer or thermal dilution with cold crystalloid produces a washout curve when introduced into a fluid flow. The curve can be integrated to calculate flow rate. This technique is used to measure cardiac output.

Flow can also be deduced from concentration changes in a marker across an organ if the rate of excretion or absorption of the marker can be separately measured. This is the Fick principle and is used in the calculation of cardiac output from the rate of oxygen uptake from the lungs and the change from mixed venous to arterial oxygen concentration. It is also used in the calculation of GFR from creatinine output.

An approximation of flow can be determined from ultrasound Doppler studies of

fluid velocity and vessel area. This is used to estimate flows across heart valves.

h. Describe and compare the methods of measuring temperature.

Heat
> The quantity of thermal energy contained in a substance.

Temperature
> An expression of the *specific heat* of a substance and the amount of thermal energy in it.
> Determines the direction of flow of thermal energy (from hotter to cooler).

Specific heat
> The thermal energy required to produce a given temperature rise in a substance.

Mercury thermometer
> A bulb contains mercury which expands to force its way up a narrow calibrated column containing a vacuum. To produce a maximum-reading thermometer, a constriction just above the bulb splits the column when it contracts. Alternatively, a metal index sits above the column.
> It is slow to equilibrate (with the time constant of equilibration being printed on the side), fragile and cannot read temperatures below -39°C.

Bimetallic thermometer
> A coiled strip of two metals turns a pointer as the two metals expand at different rates with heat. It is slow to equilibrate.

Bourdon thermometer
> A pressure-measuring device in which expansion of a fluid turns a dial. It is slow and sensitive to pressure changes.

Resistance thermometer
> A piece of wire displays increasing resistance linearly with a rise in temperature. A Wheatstone bridge provides accurate measurement of the resistance. The changes in resistance over a useful clinical range are very small.

Thermistor
> Many metal oxides display large resistance changes over small temperature ranges. These provide for accurate measurement in the clinical range using a very small probe. It is sensitive to heat damage from sterilization.

Thermocouple
> Different metals generate an electrical potential when in contact which is related to their temperature. This allows for thin needle probes to be made to measure temperature. Their disadvantage is that the reference electrode must be kept at a fixed temperature, or compensation made for its temperature.

In practice
> In the anaesthetized patient, the most practical method of measuring temperature is a small probe (thermistor) inserted into the nasopharynx, oesophagus or rectum.

i. Describe and compare the methods of measuring humidity.

Humidity
> The amount of water vapour present in air or another gas
> Absolute (gm^{-3}) or relative (% of saturation) terms
> Saturation humidity of air is highly dependent on temperature
> > 17 gm^{-3} at 20°, 44 gm^{-3} at 37°

Hair hygrometer
> A hair stretches more readily as it becomes moist. If balanced against a spring, a simple hygrometer is formed. This is a primitive device, accurate over a limited range.

Wet and dry bulb hygrometer

Evaporation of water from around the bulb of a constantly moistened thermometer cools the thermometer an amount dependent upon the relative humidity and air flow over the bulb. If the sir flow is constant, the relative humidity can be determined from the ambient temperature and this cooling effect.

Regnault's hygrometer

Air is blown through ether in a tube until condensation occurs on the outside of the tube. The temperature at which this occurs is the "dew point": the temperature at which the current absolute humidity represents 100% relative humidity. From this temperature, the absolute humidity can be determined and the relative humidity derived from knowledge of the saturated vapour pressure at ambient temperature. This is an impractical device as it involves ether and measurement of the dew-point with precision is difficult.

Other devices

Electrical measures of humidity depend on probes whose resistance or capacitance depends on their water-content.

Ultraviolet absorbance spectrophotometry can measure absolute humidity as can mass spectrometry. These are more precise and rapid methods of measuring humidity.

j. Explain in detail the principles of pulse oximetry including calibration, sources of errors and limitations.

Pulse oximeter

Device which measures functional saturation of haemoglobin by spectrophotometry through intact tissue.

Haemoglobin species absorb light of different wavelengths with different intensities

Oxyhaemoglobin absorbs less red light and more infrared than deoxyHb

Beer-Lambert Law describes absorption of light in a fluid

$$I_{transmitted} = I_{incident} e^{-dC\varepsilon}$$

where I is light intensity, d is path length, C is concentration, ε is extinction coefficient

$$Absorption = \log (I_{transmitted}/I_{incident})$$

Practical application

Two wavelengths: 660 nm (red) and 940 nm (infrared)

Rapidly alternating LEDs, one on at a time

$I_{incident}$ known

Single photodetector for both wavelengths measures $I_{transmitted}$

Constant absorbance due to tissue, venous and capillary blood

Variation in $I_{transmitted}$ for each wavelength assumed to be due to arterial pulsation

Rate of pulsation read as heart rate

Ratio of pulsatile to constant proportions at different wavelengths is calculated

$$R = \frac{pulse_{660} \div const_{660}}{pulse_{940} \div const_{940}}$$

Functional saturation varies with R (non-linear)

100% corresponds to R=0.4, 85% to 1.0 and 0% to about 3.4

Functional saturation

Saturation assuming

HbO_2 and deoxyHb are the only species present

Dissociation curve is not markedly shifted (pH, temp normal)

$$Functional \ SaO_2 = \frac{[HbO_2]}{[HbO_2] + [Hb]}$$

Fractional saturation

Percentage of total Hb present which is HbO_2.

Measured in arterial sample with co-oximeter (typically 7 wavelengths used)

Sources of error

Sensor
        Inadequate light transmitted (nail polish, onychomycosis)
        Extraneous light
        Movement or diathermy causing "noise" in received signal
Processing
        Human calibration only for $SpO_2 > 80\%$
        Increasingly unreliable with low SpO_2
Haemoglobin
        High concentration of MetHb ($\downarrow$ to 85%), COHb ($\uparrow$) or other species
        Other light-absorbing species in blood (methylene blue, other dyes)
Blood flow
        Poor perfusion (vasoconstriction, hypothermia, BP cuff)
        Pulsatile venous flow (tricuspid regurgitation)

        The clinical usefulness of pulse oximetry diminishes with high haematocrit, as an adequate PO_2 may yield a lower saturation than expected. The peripheral placement of the probe reduces its usefulness in cold or peripherally vasoconstricted patients as the oxygen saturation in the central circulation may be substantially higher than in the fingertips.

k. Explain the principles involved in the analysis of gases using ultraviolet or infrared absorption, paramagnetic analysis, gas chromatography, mass spectrometry and Raman scattering.

Absorption spectrophotometry
        covered in j. and l.

Paramagnetic analysis
        Most gases are diamagnetic, being repelled by a magnetic field, because of the characteristics of their outer shell electrons. Oxygen is paramagnetic because of its unpaired outer shell electrons and so is attracted by a magnetic field. This effect is used to produce a paramagnetic analyzer to determine oxygen concentration.
        In a paramagnetic analyzer, a dried gas sample flows through a chamber in which a nitrogen-filled dumbbell is balanced in a magnetic field. The dumbbell is displaced by the paramagnetic force on the oxygen in the sample and either its displacement against a torsion spring or else the force required to keep it in position is measured.
        By calibrating the device with 100% nitrogen and 100% oxygen, a very accurate measurement of the oxygen concentration in a gas sample may be made.
        A more modern design of paramagnetic analyzer uses an alternating magnetic field at the junction of two gas streams (sample and reference). A pressure wave is induced by the change in magnetic field and a pressure transducer between the gas streams can detect differential pressure and allows calculation of the oxygen concentration of the sample rapidly and continuously.

Gas chromatography
        Chromatography relies on the separation of compounds by their different affinities for a stationary and mobile phase in a chromatography column. In the case of gas chromatography, the mobile phase is usually an unreactive gas such as nitrogen or argon and the stationary phase is a fine crystalline material such as silica coated in polyethylene glycol or silicone oil. The column is kept at a constant temperature and the sample to be analyzed is injected into the gas flow before the column.
        At the end of the column a detector records the appearance of the components of the sample against the time since injection. The detector may be a flame ionization detector, a thermal conductivity detector (suitable for inorganic gases) or an electron capture detector (best for halogenated compounds).
        Control samples are used to determine the chromatographic characteristics of known gases. These are compared with the unknown sample's trace to determine its

constituents. The detector can also be calibrated for quantitative analysis of the sample. Gas chromatography is suitable for analysis of all gases and many compounds which can be made to yield volatile products.

Mass spectrometry

Mass spectrometry separates molecules or atoms according to their mass and charge after stripping their outer electrons. A sample is allowed to leak very slowly into an ionization chamber in which an electron beam is used to ionize the sample. The ions are accelerated and focussed through an electric field and then deflected either using a strong magnetic field or an oscillating electric field between four rods ("quadrupole mass spectrometer").

The ions are separated according to their mass and charge and so the components of the sample can be determined quantitatively by analyzing the composition of the ionized sample which will include breakdown products of the components of the sample. This analysis is simple for small molecules and difficult for mixtures of several larger molecules because of the wide variety of breakdown products.

Mass spectrometry can measure very small concentrations in very small samples and can be made to have a response time as little as 0.1 s, but it remains a complex and expensive analysis tool.

Raman scattering

The Raman effect occurs when gas molecules absorb energy from photons resulting in quantized changes in vibrational or rotational states. Light is re-emitted with further changes in state producing a spectrum of wavelengths characteristic of the molecules involved. Spectral analysis allows identification of known compounds by comparison with their Raman spectra. This is a technique of similar accuracy to mass spectrometry.

Oxygen electrodes

The Clarke oxygen electrode is a polarographic electrode. Oxygen from the sample fluid equilibrates across a membrane with a buffered KCl solution surrounding a glass electrode. The electrode has a platinum cathode and a Ag/AgCl anode. With between 0.5 V and 0.9 V applied across the electrode, the consumption of O_2 at the cathode and hence the current in the circuit is dependent on the O_2 concentration in the solution which rapidly equilibrates with the sample. In practice, 0.68 V is used. Performance is affected by N_2O and halothane.

$$\text{anode: } 4Ag \rightarrow 4Ag^+ + 4e^-$$
$$\text{cathode: } O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$$
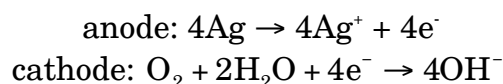
The fuel cell detector operates on the same principle as the Clarke electrode, but using a lead anode which is oxidized in the operation of the cell. It is oxygen-powered with a voltage output proportional to the oxygen concentration in the electrolyte. In this case the electrolyte is KOH solution.

$$\text{anode: } 2Pb + 4OH^- \rightarrow 2PbO + 2H_2O + 4e^-$$
$$\text{cathode: } O_2 + 4e^- + 2H_2O \rightarrow 4OH^-$$
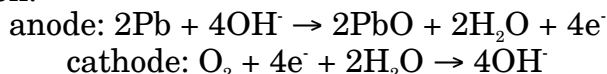
Both these devices require temperature and pH compensation and have limited lifespans.

Blood gas electrodes

Arterial sample stored on ice in lithium heparin tube and analyzed quickly
PO_2, PCO_2 and pH are measured directly
    PO_2 using a Clark electrode
    pH using a pH electrode
        Ag/AgCl or Hg/Hg_2Cl_2 reference electrode in contact with sample via KCl

solution and membrane

Buffer solution of 0.1 M [H$^+$] in contact with sample via H$^+$-sensitive glass

Voltage generated by H$^+$ gradient converted to pH reading

PCO_2 using a Severinghaus electrode

Similar to pH electrode except H$^+$-sensitive glass is surrounded by $NaHCO_3$ solution in contact with sample via CO_2-permeable membrane

CO_2 equilibrates across membrane, changing pH of buffer solution

pH change read by glass electrode and converted to PCO_2 reading

HCO_3^- (mmol/l) calculated from pH and PCO_2 (mmHg)

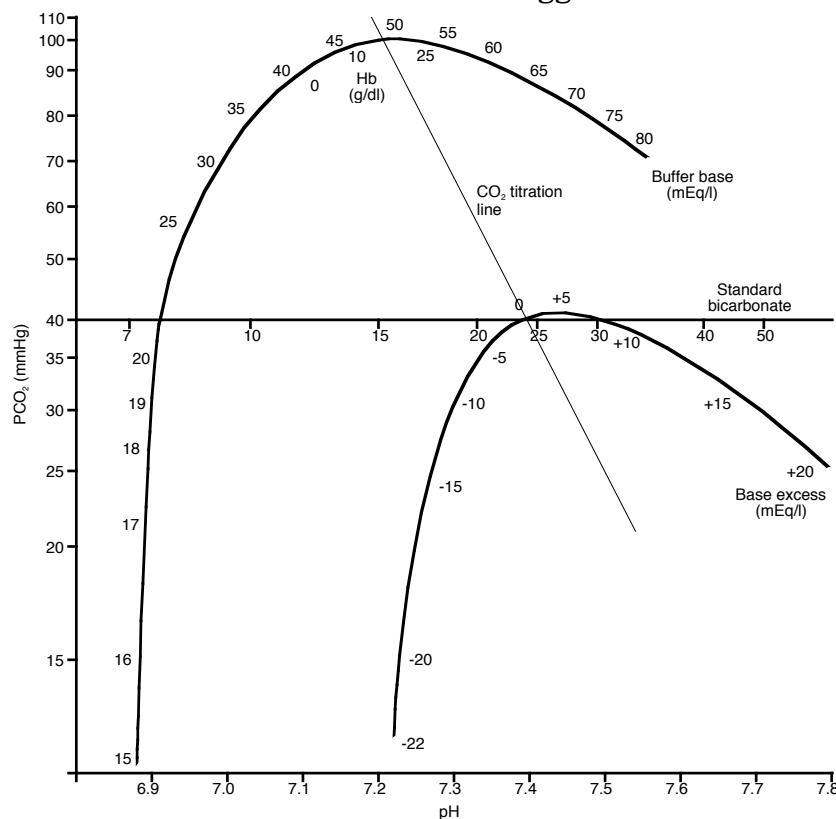$$pH = 6.1 + \log_{10} \frac{[HCO_3^-]}{0.03 \ PCO_2}$$

$$\Rightarrow [HCO_3^-] = 0.03 \ PCO_2 \cdot 10^{pH-6.1}$$

Base excess is measured by determining the sample's buffering capacity

Sample is equilibrated to two known PCO_2 values

pH is measured at each PCO_2

These two points fall on a "titration line" on the Siggaard-Andersen curve nomogram

Nomogram is a graph of log(PCO_2) versus pH

Intersection of the titration line with the PCO_2=40 mmHg line gives a value for "standard bicarbonate" which represents what the [HCO_3^-] would be without respiratory compensation

Titration line also intersects two curves on the nomogram, reading "buffer base" (concentration of proton acceptors in the blood, normal 48 mEq/l) and "base excess" (mEq/l of H$^+$ required to correct blood to pH 7.4 at PCO_2 40 mmHg)

Other values commonly measured by blood gas machines

Na$^+$, K$^+$, Ca^{2+} using sensitive glass electrodes

Hb, glucose, lactate

l. Explain in detail the principles of capnography including calibration, sources of errors and limitations.

Capnography is the continuous measurement of PCO_2 in a gas sample. It is used in anaesthesia to monitor respiration and, by measuring $P_{ET}CO_2$, to give information about acid-base status and adequacy of gas exchange. Capnographs are usually set up either as "main stream" with a sensor on the circuit or "side stream" with gas sampled from the circuit at around 150 ml/min and analyzed separately. Side stream circuits are more common as they are cheaper and more robust.

Capnographs measure the CO_2 content of gas by infrared spectrophotometry. CO_2 molecules absorb infrared light at a 4.28 μm by altering their vibration and rotation. Infrared radiation is shone through the sample chamber containing a continuous flow of sampled gas at a controlled pressure. The absorbance at the specified wavelength may be compared with that in a calibration cell containing no CO_2 and must also be calibrated periodically to zero. The absolute amount of absorbance may be increased by using a reflected beam which passes through the sample chamber many times.

Some capnographs use multiple light wavelengths and so are able to measure the concentration of volatile anaesthetics and other gases such as NO_2.

There are several potential problems with capnography. Side stream capnography has an increased response time as gas from the circuit must be drawn through the sampling line. There is potential for leakage at each connection of the sample line, reducing the CO_2 concentration. The gas drawn from the circuit is not a true end-tidal sample even at the end of expiration because of the dead-space in the large airways and circuit, and so there is always an underestimate of P_ACO_2. Mixing within the sample chamber will "blunt" changes in the CO_2 trace. Pressure changes in the sample chamber either as a result of airway pressure changes or constriction of the sample line will alter the absolute CO_2 concentration in the chamber. Physiological derangements such as V/Q mismatch may result in a wide disparity between $P_{ET}CO_2$ and P_aCO_2 (an increased A-a gradient), reducing the usefulness of capnography.

Main stream capnographs avoid the problems associated with the sample line but are more prone to pressure changes and as the sample chamber windows are made of sapphire, they are very expensive if damaged in handling or cleaning.

Measurement of cardiac output

Fick principle (Adolph Fick)
Pulmonary venous oxygen flux (q_3) equals pulmonary arterial oxygen flux (q_1) plus alveolar oxygen uptake (q_2)
$$q_1 + q_2 = q_3$$
$$q_1 = Q \, [O_2]_{pa}$$
$$q_3 = Q \, [O_2]_{pv}$$
$$\Rightarrow Q = q_2 \div ([O_2]_{pv} - [O_2]_{pa})$$
so cardiac output (Q) can be calculated from pulmonary O_2 uptake, and mixed venous and pulmonary venous oxygen concentrations.
Mixed venous oxygen concentration can be measured using a Swan-Ganz catheter and pulmonary venous oxygen concentration approximated with a systemic arterial sample.
This method requires determination of oxygen uptake over several minutes and so requires either a completely closed breathing circuit in anaesthesia or an approximation using mixed expired and inspired oxygen concentrations or a laboratory setting.

Indicator dilution
A known amount of an indicator is introduced into the circulation at a point where the entire cardiac output is passing.
The concentration of the marker is measured downstream after mixing has occured and its value is plotted over time. The entire cardiac output need not be passing the

sampling point so long as no other blood flow has been added. For example, the indicator might be injected in the right atrium and the sampling done from the pulmonary circulation.

The amount of indicator (n) is related to its mean concentration ($\bar{c}$), cardiac output ($\dot{Q}$) and the time for which it is detected ($t_2 - t_1$):

$$n = \bar{c}\dot{Q}(t_2 - t_1)$$

$$\bar{c} = \frac{\int c \ dt}{t_2 - t_1}$$

$$\Rightarrow \dot{Q} = \frac{n}{\int c \ dt}$$

The conventional expression is in the Stewart-Hamilton equation:

$$\dot{Q} = \frac{n}{\int c \ dt} = \frac{k(T_{core} - T_{indicator})V_{indicator}}{\int_{t_1}^{t_2} -\Delta T \ dt}$$

This can be done using a dye indicator (which requires a semi-log plot to determine t_2 when recirculation occurs) or more commonly using cold saline with temperature being the "indicator". There is an inherent inaccuracy in thermodilution when thermal exchange occurs between the blood and the vessel and structures surrounding it and when cool fluids may be being infused peripherally in a variable fashion.

Echocardiography

Cardiac output ($\dot{Q}$) can be calculated using the TOE probe to measure cross-sectional area (A) and flow velocity (V) over the duration of one cardiac cycle (t) at a point where the entire cardiac output is passing (e.g. pulmonary outflow tract).

$$\overline{V} = \frac{\int V \ dt}{t}$$

$$\dot{Q} = A \times \overline{V}$$

This method assumes equal flow over the whole area and it is technically difficult to perform. With continuous wave Doppler and a multiplane probe this method should have a bias of zero and limit of agreement of 1 l/min compared to thermodilution.

Outline methods and principles used to measure regional blood flow.

Cerebral

Kety-Schmidt technique

Uses Fick principle

Total uptake of tracer = perfusion x extraction

$Q_b = F \int (C_a - C_v) \ dt$

$Q_b = C_b \ Mass_b$

$C_b = C_v \lambda$ (at equilibrium)

$$\frac{F}{Mass_b} = \frac{C_v \lambda}{\int (C_a - C_v) dt}$$

N_2O at low concentration is the tracer used

C_a (arterial concentration) and C_v (venous concentration) are measured continuously at radial artery and IJV until equilibrium

λ is assumed to be 1 for N_2O

Total quantity of tracer in brain (Q_b), total brain blood flow (F) and brain mass ($Mass_b$) don't need to be known to calculate brain blood flow per unit mass.

Result is expressed in ml/100 g/min

Radioactive tracers
    ^{133}Xe, ^{85}Kr as gases
    Organic compounds including ^{11}C, ^{15}O, ^{13}N or ^{18}F
    Detected by scintigraphy, PET, autoradiography
Flow probes
    Doppler, electromagnetic
    MRA
O_2 extraction monitoring
    Jugular bulb oximetry
    Near IR spectroscopy
Hepatic
    Fick principle with indocyanine green
Renal
    PAH clearance

Ultrasound

Physical principles
    Intermittent pulses of sound waves
        2.5 to 7.5 MHz generated by piezoelectric quartz crystals
        ↑ frequency → ↑ resolution (to 1 mm), ↓ penetration (10-25 cm)
    Sound waves passing through tissue of differing densities causes reflection of part of the sound energy
        Loudness of reflection is interpreted as intensity
        Delay of reflection is interpreted as distance from the probe
            Sound assumed to travel at 1540 m/s in tissue at 37°C
A-mode ("Amplitude")
    Brief ultrasound pulses in a single direction
    Amplitude of reflected ultrasound is graphed against time (50-300 μs) for each pulse
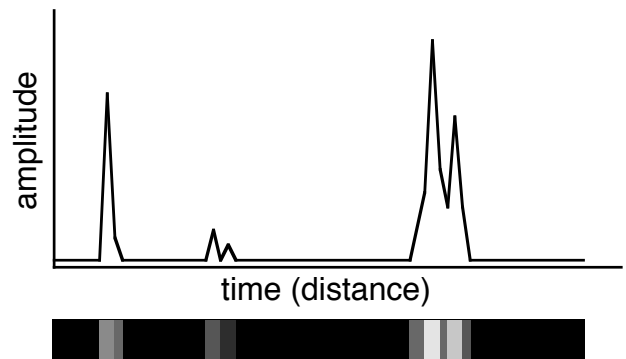   Peaks in amplitude correspond to reflective interfaces
    Time taken before reflection corresponds to distance from the probe
    Used to measure eye axial length ("A-scan")
B-mode ("Brightness")
    Same as A-mode, but one dimensional graphical display with brightness corresponding to amplitude of reflected sound

M-mode ("Motion")
    B-mode scan with repeated pulses graphed against a time-base
    Up to 1000 pulses per second: excellent time resolution
    Provides a one-dimensional image of tissue against a time-base
    Useful for valve motion
2-D
    Multiple crystals (linear or phased-array) or moving crystal
    Sequential B-mode pulses sweeping up to 90° across a plane
    Displayed as a single image
    Up to 30 images per second (dozens of pulses per image)
    Moving in real-time
Pulsed wave Doppler
    Doppler shift is an alteration in the frequency of reflected sound depending on the velocity of the source of the reflection
    Velocity (V) of the source of reflection (e.g. blood cells) can be calculated

$$V = \frac{F_d C}{2F_0 \cos\theta}$$

where F_d is the Doppler shift, C is the speed of sound, F_0 is the ultrasound frequency and θ is the angle between the direction of flow and the sound wave

An area of the 2-D scan is specified and the Doppler shift in reflections from that area is used to provide a graph of velocity versus time

Limitations

If θ is small (<15˚) it can be ignored, if large the results are imprecise

Flow faster than the Nyquist limit (0.4-0.6 m/s) cannot be unambiguously measured because of the intermittent sampling causing "aliasing"

Continuous wave Doppler

Separate crystals are used to emit and receive ultrasound continuously along a single axis

The frequency spectrum of reflected sound is related to the velocity of all interfaces along the axis

A graph of the range of velocities against time is produced

Advantages

Can measure very fast flows

Used to calculate valve gradients (=$4V^2$ where V is peak velocity)

Limitations

θ must be small

No pulses, so no information about location of measured velocities

Colour Doppler

Pulsed wave Doppler used on an area of a 2-D scan

Velocity is depicted as a colour in each pixel of the area

Advantages

Easy visualization of flows across valves or shunts

Limitations

Above the Nyquist limit, colour reversal is seen

Rapid turbulent flow produces "colour jets"

TOE probe

Phased-array 2-D probe with 64 crystals

May be monoplane, biplane (2 arrays) or multiplane (array can rotate)

Mounted on 9 mm gastroscope