CLINICAL MONITORING

(a) ***To describe in detail the measurement of electrocardiogram including calibration, sources of errors and limitations.***

Electrocardiogram (ECG) → the vector sum measurement of all electrical currents at the body surface that are generated by the electrical activity of the heart

Technique of ECG:

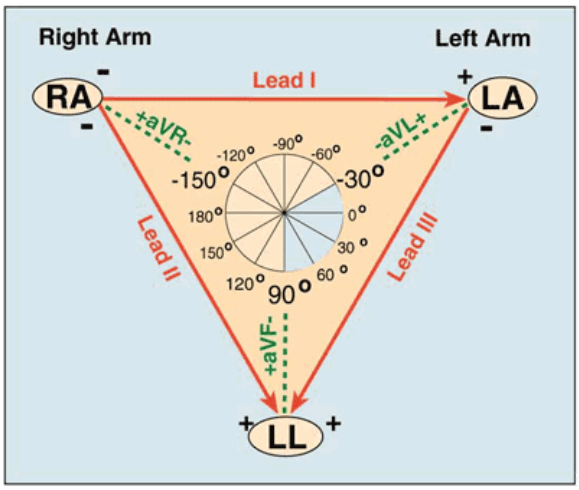
- Standard ECG involves placement of 12 electrodes on the body surface → detect small potentials (0.5-2 mV) at skin generated by spread of electrical activity of the heart through body tissues
- Electrodes made of Ag/AgCl → separated from skin by a foam pad soaked in a conducting gel
- ECG signals detected by these electrodes → send to electronic device that filters out noise and boosts the signal → then displayed on oscilloscope

12 lead ECG system:

- Standard limb leads (6x leads)
  - Bipolar limb leads – Connecting one limb to another → 3x limbs are used (RA, LA, LL) with RL used as "earth" to minimise interference
    - Lead I: RA (-) to LA (+) at 0°
    - Lead II: RA (-) to LL (+) at 60°
    - Lead III: LA (-) to LL (+) at 120°
  - Unipolar limb leads – Consists of unipolar leads from 3x limbs (RA, LA, LL)
    - aVR: RA (+) at -150°
    - aVL: LA (+) at -30°
    - aVF: LL (+) at 90°
- Chest leads (6x leads) → consists of unipolar leads on chest wall
  - V1: R sternal margin at 4th ICS
  - V2: L sternal margin at 4th ICS
  - V3: Midway b/t V2 and V4
  - V4: Intersection of 5th ICS and L MCL
  - V5: Intersection of L MAL and horizontal line through V4
  - V6: Intersection of L MAL with horizontal line through V4/V5

Principles of ECG:

- Based on "Einthoven's Triangle" → electrical activity of the heart is at the centre of an equilateral triangle formed by the shoulders and pubic symphysis (with electrodes on both arms and the left foot approximating the corners of the triangle → standard 6x limb leads)

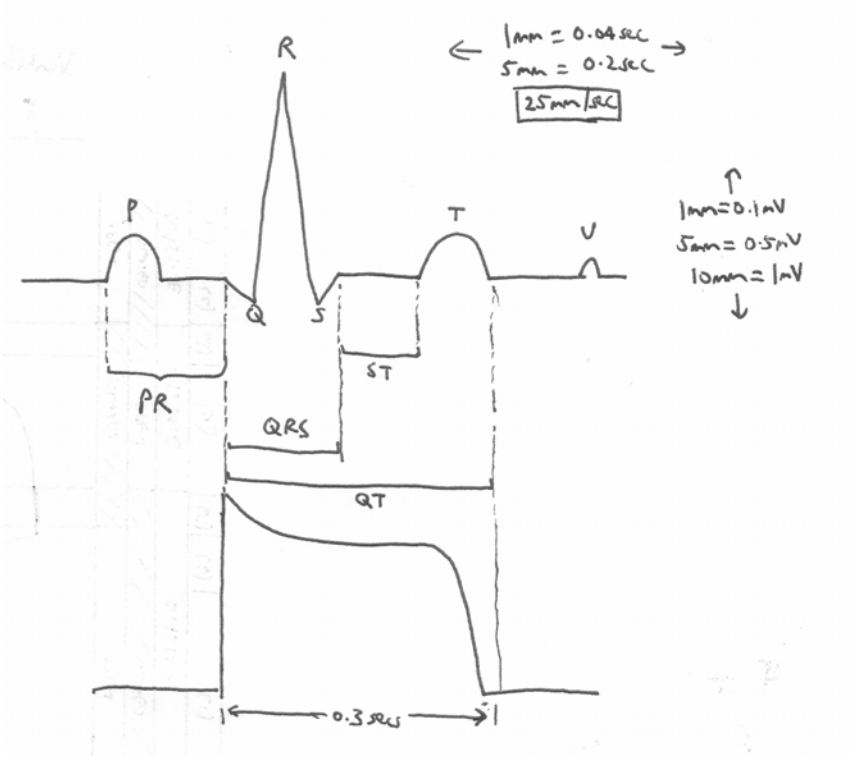


- "+ve deflection" in ECG occurs when wave of cardiac depolarisation travels TOWARDS electrodes, while "–ve deflection"

Important to note – ECG has characteristic waveform in lead II is b/c:

- (i) Atrial depolarisation commences in SAN and spreads down and to left to AVN → +ve deflecting P-wave
- (ii) Ventricular depolarisation starts in interventricular septum and spreads down and to right → -ve deflecting Q-wave
- (iii) Left ventricle depolarises first at the apex and epicardially → +ve deflecting R-wave
- (iv) Then remaining ventricles (RV, base and endocardium) → -ve deflecting S-wave
- (v) Ventricles repolarise from epicardium to endocardium → +ve deflecting T-wave

ECG waveform:



Calibration:

- Vertical calibration → 1 mV signal produces a vertical deflection of 10 mm (2x large square or 10x small squares) → 0.1 mV per mm (or small square)
- Horizontal calibration → paper speed is 25 mm/s → 0.04 s/mm (or small square)

Waves, intervals and segments:

- P-wave
  - Smooth and rounded deflection preceding QRS complex
  - Represents SA node and atrial depolarisation
- PR-interval
  - From start of P wave to start of QRS complex (usually Q-wave rather than R-wave) → 0.12-0.2 sec
  - Represents electrical conduction from SA node through atrial to AV node, then to ventricles via bundle of His → a good estimate of AV nodal function
- QRS-complex
  - Usually the largest deflection on ECG with "spiky" shape (starts from Q-wave to end of S-wave) → -ve deflection (Q-wave), followed by +ve deflection (R-wave), then another –ve deflection (S-wave) → < 0.12 msec with axis -30° to 90°
  - Represents ventricular depolarisation and spread of electrical activation through ventricular myocardium (Nb. atrial repolarisation also occurs here)
- ST-segment

    - From end of S-wave to beginning of T wave
    - Represents continued ventricular myocardial depolarisation
- T-wave
    - Broad and rounded wave following QRS complex
    - Represents ventricular repolarisation
- QT-interval
    - From beginning of Q-wave to end of T-wave
    - Corrected for HR as confounding factor → Corrected QTc = QT/√RR = 0.36-0.44 sec
    - Represents the duration of ventricular depolarisation
- U-wave
    - Broad and rounded wave following T-wave
    - Represents slow repolarisation of papillary muscles → caused by hypokalaemia, digoxin toxicity, bradycardia, ischaemia

Other features:
- "Sinus rhythm" → when every P-wave followed by QRS, every QRS preceded by P-wave, and P-wave upright in leads I-III
- Regularity → determined by PP-interval (atrial) and R-R interval (ventricular)
- Rate → 60-100 bpm

<u>Use of ECG in anaesthesia</u>:
- 3- or 5-lead ECG is used instead of standard 12-lead:
    - Lead II → best views of P and R waves → ideal for detecting arrhythmias and inferior wall ischaemia
    - CM5 (RA electrode on manubrium; LA electrode on V5, indifferent lead on left shoulder) → ideal for detecting ST segment changes due to LV ischaemia
    - CB5 (RA electrode over centre of right scapula and LA electrode over V5) → best view of P and QRS waves during cardiothoracic anaesthesia → ideal for detecting arrhythmias and ischaemia
- Two ECG modes exist:
    - (i) Monitoring mode:
        - Narrow frequency response range ~ 0.5-50 Hz → significantly reduces noise/interference but obscures ECG details (Ie. P and T-wave morphology and ST-segments)
        - High frequency limit of 50 Hz → ↓ artefact from muscle movement, electrical interference from equipment
        - Low frequency limit of 0.5 Hz → ↓ artefact from respiratory and body movement
    - (ii) Diagnostic mode:
        - Wider frequency response range ~ 0.05-100 Hz → allows monitoring of ST-segment and analysis of QRS, P and T-wave morphology, but introduces more noise/interference
        - High frequency limit of 100 Hz → allows QRS morphology and tachyarrhythmia assessment
        - Low frequency limit of 0.05 Hz → allows representation of P/T-wave morphology and ST segment analysis

<u>Sources of error</u>:
- ECG are easily affected by noise and interference as they measure very tiny electrical potentials at the skin (0.5-2 mV) → caused by:
    - (i) Electrical interference by any device using AC current (esp high-frequency diathermy) → minimise by ECG filters, shielding of leads/cables, differential amplifers, Etc.

- (ii) Movement or shivering → minimised by placement over bony prominences and use of ECG filters
- (iii) High skin impedance → minimised by degreasing skin with EtOH and use of conducting gel with electrodes
- (iv) Incorrect electrode placement relative to heart

(b) ***To describe and to compare the methods of measuring blood pressure.***

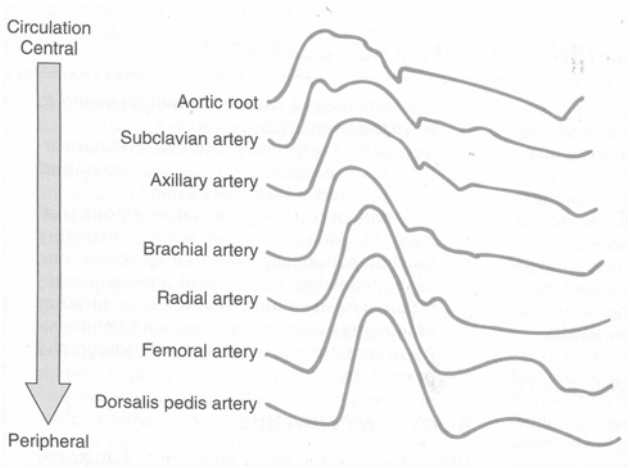
(I) Overview of blood pressure measurement:

Definition of blood pressure:

- "Blood pressure" is the pulsatile pressure in the arterial system caused by ejection of blood into the vascular system by rhythmic left ventricular contraction
- Types of BP measured:
    - (i) Systolic BP → peak pressure generated during systolic contraction
    - (ii) Diastolic BP → trough pressure generated during diastolic relaxation
    - (iii) Pulse pressure → difference b/t SBP and DBP
    - (iv) Mean arterial pressure → time-weighted average of arterial pressure during pulse cycle → where MAP = DBP + 1/3 (SBP – DBP)

Variations in blood pressure:

- Arterial BP varies within the arterial tree → as the pulse moves more peripherally:
    - Arterial BP waveform becomes narrower and increases in amplitude → exaggerates SBP and pulse pressure → due to changes in vessel diameter, vessel elasticity, reflection of wave pattern from vessel walls
    - Loss of dicrotic notch (which is present due to intra-aortic vibrations)



- Arterial BP varies with respect to level of measurement site relative to the heart → due to gravity-dependent effect on BP (Ie. falsely ↑ BP if manometer below level of heart)

Basis for measuring blood pressure:

- Adequate O_2 delivery to tissues needs to be maintained → BUT it is impractical to measure organ-specific perfusion and oxygenation during anaesthesia
- As a result → arterial BP is measured instead as it is directly related to flow:

$$\text{Flow} = \frac{\text{Pressure}}{\text{Resistance}}$$

- Note – Arterial BP is an indicator of tissue perfusion (rather than a direct measure) → b/c vascular resistance is not known (Ie. if R is ↑, then flow remains ↓ despite a ↑ BP)

(II) Non-invasive blood pressure (NIBP) measurement:

All NIBP measurement (except arterial tonometry) involves an inflatable cuff connected to a manometer:

Inflatable cuff:

- Properly positioned on extremity being measured (usually arm) → with centre of bladder over artery (usually brachial artery)
- Cuff width should be 20-50% greater than diameter of extremity → as a narrow cuff will overestimate BP (as it needs more pressure to occlude an artery), and a wide cuff will underestimate BP (as it needs less pressure to occlude an artery)
- Cuff, tubing and connections should be free of leak

Manometer:

- Hg-type → must read zero before use and kept vertical during measurement
- Aneroid gauge → more portable and less toxic, but requires more frequent calibration
- Electronic (pressure transducer)

Methods of NIBP measurement:

(1) Palpation

BP measured	SBP only
Principle	Blood flow is restored in a peripheral artery when a BP cuff is deflated below SBP → produces a palpable pulse that correlates with SBP
Method	- Palpable peripheral pulse is located first → then BP cuff is placed proximal to it and inflated to a pressure above the expected systolic BP → causes occlusion of blood flow and loss of pulse - ↓ cuff pressure by 2-3 mmHg per second until pulse palpable again → pressure when this happens is measured as the SBP
Advantages	Simple and inexpensive
Disadvantages	- (i) Tend to underestimate SBP (due to insensitivity of touch and delay in flow under cuff and distal pulsation) - (ii) Does not measure MAP or DBP - (iii) Issues with cuff (positioning, size, leak) and manometer (calibration, positioning)

(2) Doppler probe

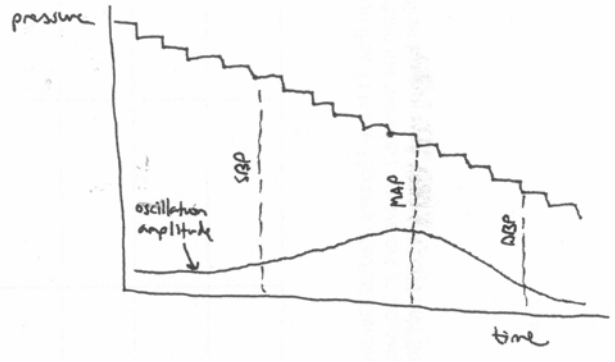
BP measured	SBP and DBP
Principle and method	- Doppler effect → shift in frequency of sound waves when source moves relative to observer - Restoration of blood flow in a peripheral artery when BP cuff is deflated below SBP is detected by Doppler frequency shift of RBC flowing in artery → measures SBP - Lateral arterial wall movement due to intermittent opening/closing of vessel walls between SBP and DBP → measures SBP and DBP
Advantages	Greater sensitivity than palpation technique (esp in obese, paediatric and shocked patients)
Disadvantages	- (i) Probe needs to be kept directly over artery - (ii) Interference due to movement artefact and diathermy - (iii) Need to apply gel between skin and probe - (iv) Issues with cuff (positioning, size, leak)

(3) Auscultation

BP measured	SBP and DBP (SBP is more accurate)
Principle	Turbulent flow is produced when a peripheral artery is partly collapse when a BP cuff is inflated to a pressure between SBP and DBP → audible by stethoscope
Method	- Palpable peripheral pulse is located first → then BP cuff is placed proximal to it and inflated to a pressure above the expected systolic BP - ↓ cuff pressure by 2-3 mmHg per second until Korotkoff sounds (indicating turbulent flow) are audible by stethoscope: o 1st Korotkoff phase (snapping tone) → indicates SBP o 2nd Korotkoff phase (murmurs)

	○ 3rd Korotkoff phase (thumping) ○ 4th Korotkoff phase (muffling) ○ 5th Korotkoff phase (loss of all sound) → indicates DBP
Advantages	Simple and inexpensive
Disadvantages	- (i) Hypotension, movement, marked peripheral vasoconstriction → difficult to auscultate Korotkoff sounds - (ii) Auscultatory gap (esp in HTN patients) → Korotkoff sounds cannot be heard → leads to inaccurate DBP readings - (iii) Issues with cuff (positioning, size, leak) and manometer (calibration, positioning)

(4) Oscillometry

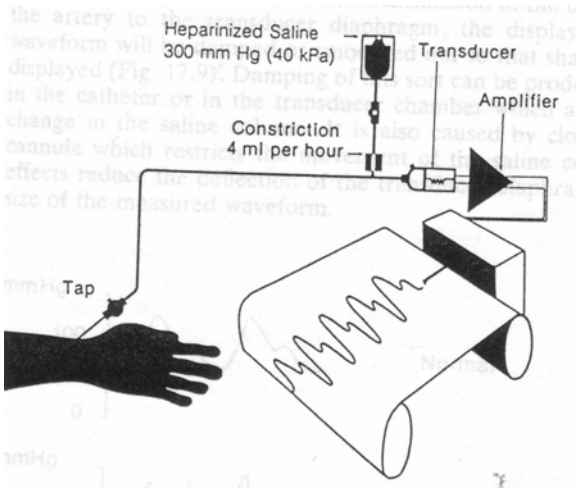
BP measured	MAP (most accurate) > SBP >> DBP (least accurate → some machines calculate it from measured MAP and SBP)
Principle	Based on oscillometry → arterial pulsations cause oscillations in cuff pressure which is then measured by a pressure transducer within the cuff: - Point of maximal pressure oscillation amplitude → MAP - Point of significant rise in amplitude of pressure oscillation → SBP - Point of significant fall in amplitude of pressure oscillation → DBP - Frequency of pressure oscillation → HR
Method	- Palpable peripheral pulse is located first → then BP cuff is placed proximal to it and inflated using air pump to a pressure above the expected systolic BP - Cuff pressure is then ↓ by 2-3 mmHg per second via a bleed valve and held briefly → pressure transducer within cuff measures the oscillations in cuff pressure caused by arterial pulsations → oscillations above a baseline level are recorded → this process is repeated multiple times until cuff is fully deflated - Characteristic pattern of cuff pressure oscillation is demonstrated: ○ Above SBP and below DBP → small oscillations in pressure ○ At SBP → significant rise in amplitude of pressure oscillation ○ At MAP → maximal amplitude of pressure oscillation reached ○ At DBP → significant fall in amplitude of pressure oscillation - HR → determined by frequency of oscillations  - Subsequent NIBP measurement → cuff pressure is inflated to 25 mmHg above last SBP measurement
Advantages	- (i) Simple and inexpensive - (ii) Portable and versatile - (iii) Fast response time and accurate
Disadvantages	- (i) DBP is derived → inaccurate - (ii) Movement artefact - (iii) Arrhythmias (esp AF) → inaccurate results as BP varies with each ventricular contraction → machines needs identical consecutive pulse waves for measurement confirmation - (iv) Hypotension (esp SBP < 50 mmHg) → inaccurate results - (v) Cannot do frequency readings (max 1x/min) → if used consistently, can impede blood flow in extremity! - (vi) Cannot be using during cardiopulmonary bypass - (vii) Issues with cuff (positioning, size, leak)

(5) Arterial tonometry

BP measured	Continuous pulse recording → tracing similar to IABP waveform
Principle	Measures beat-to-beat BP by sensing pressure required to partially flatten a superficial artery supported by bony structure (Eg. radial artery)
Method	Consists of several independent pressure transducers applied to skin over artery → contact stress b/t transducer over artery and skin reflects intraluminal pressure
Advantages	Continuous pulse recording (like IABP)
Disadvantages	Need for frequent calibration, and inaccuracies due to movement artefact

(III) Invasive blood pressure measurement:

Components of invasive arterial BP:



- (1) Intra-arterial cannula
  - Short and narrow cannula is inserted into a peripheral artery (usually radial artery) → connected to a fluid-filled tubing system
- (2) Fluid-filling tubing
  - Acts as a column of non-compressible, bubble-free fluid between arterial blood from cannula and the pressure transducer → permits "hydraulic coupling"
- (3) Infusion system
  - Pressured bag (300 mmHg/40 kPa) of heparinised saline is attached to the fluid-filling tubing via a "flush system" → provides a continuous slow infusion at < 4 mL/hr to maintain cannula patency and prevent clotting
  - "Fast fluid flush" can be performed → (i) assess natural frequency and damping of system, and (ii) keep the tubing system clear
- (4) Pressure transducer
  - Movement of pressure transducer's diaphragm caused by arterial pressure changes in tubing fluid is converted into an electrical signal by either stretching or compressing "strain gauges" within a "Wheatstone bridge circuit"
- (5) Microprocessor
  - Electrical signal from the transducer is processed, amplified and displayed as a pressure waveform over time on a screen

Principles of invasive arterial BP:

- Pressure waveform of arterial pulse at cannulated artery is transmitted to a column of fluid within the tubing system, which then transmits it to a pressure transducer (via "Hydraulic coupling") → converted into electrical signal using strain gauges within a Wheatstone bridge → sent to microprocessor
- Since arterial waveform consists of many sine waves of varying amplitudes, frequency, wavelength, and phases → microprocessor uses "Fourier analysis" to break down the

arterial pressure waveform into component sine waves → then reconstructs it from a fundamental wave and at least 8-10 harmonic waves of higher frequency

> For example → with a HR of 60-180/min, fundamental frequency (F_O) of fundamental wave is b/t 1-3 Hz → to reconstruct an arterial waveform, harmonic frequencies of 8-10 Hz (at HR 60/min) up to 24-30 Hz (at HR 180/min) are required

Accuracy of invasive arterial BP measurement:

(1) "Static accuracy" → easily achieved by calibrating the catheter-transducer system via:
- (a) Zeroing
  - $P_{ATMOSPHERIC}$ must be excluded from arterial pressure measurement → done by exposing transducer to $P_{ATMOSPHERIC}$ and calibrating this pressure reading to zero
- (b) Levelling
  - Transducer must be set at an appropriate level to the patient (Ie. level of the heart), otherwise error due to $P_{HYDROSTATIC}$ exerted by a column of fluid above (or below) the transducer being measured is added to the arterial BP measurement

> Note → 10 cm deviation of the transducer = 7.4 mmHg error:
> - Transducer too low → arterial BP falsely elevated (as it includes $P_{HYDRSOSTATIC}$ of fluid column above the transducer)
> - Transducer too high → arterial BP falsely depressed (as pressure measured is less $P_{HYDROSTATIC}$ of the fluid column below the transducer)

(2) "Dynamic accuracy" → more difficult to achieve as the catheter-transducer system is influenced by certain mechanical parameters (Eg. elasticity, mass, friction of system)
- (a) Resonant (natural) frequency of the system
  - Defined as the frequency at which the system oscillates freely
  - Most IABP systems have a high resonant frequency of 100-200 Hz to avoid signal amplification and distortion → this is because:
    - If the resonant frequency of the system lies close to the frequency of any sine wave component of the arterial waveform → system will resonate (Ie. system's oscillation will superimpose on oscillation of arterial waveform) → cause excessive signal amplification and distortion characterised by falsely ↑ SBP, ↓ DBP and widened pulse pressure
    - To avoid this, resonant frequency of system must be at greater than the 8^{th} to 10^{th} harmonic frequency of the fundamental frequency → thus, to keep the system accurate for HR up to 180/min (F_O = 3 Hz), resonant frequency of system must be > 24-30 Hz
  - The system's resonant frequency can be increased by:
    - (i) ↓ its length (Ie. shorter cannula and tubes, avoiding 3-way taps)
    - (ii) ↓ its compliance (Ie. stiffer tubes)
    - (iii) ↓ the density of the fluid within the system
    - (iv) ↑ the diameter of the tubing and cannula
  - System's resonant frequency is assessed by "Fast flush" test (Ie. system flushed with high-pressure saline) → generates undershoot and overshoot of waves that resonate at the system's resonant frequency → this frequency is calculated by dividing the screen speed by the wavelength of the wave produced
- (ii) Damping of the system
  - Defined as the tendency of an oscillating system to lose its energy → attenuates the amplitude of oscillations towards baseline as a result of viscous and frictional forces within the system
  - Levels of damping:

    - (i) Overdamping (DC > 1.0) – System does not oscillate freely, does not overshoot its resting point, lacks high frequency oscillations, and is very

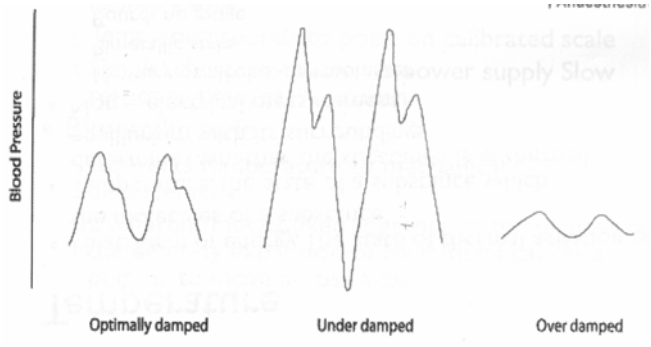
slow to respond → causes falsely ↓ SBP, falsely ↑ DBP and loss of fine details of waveform (Eg. dichrotic notch)

- (ii) "Critical damping" (DC = 1) – Minimal amount of damping needed to prevent any overshoot of oscillation; system slow to respond

- (iii) "Optimal damping" (DC – 0.64) – Provides a compromise between the speed of the system with its accuracy (minimises overshoot of oscillations, phase and amplitude distortion, and provides maximal frequency response)

- (iv) Underdamping (DC < 0.7) – System oscillates freely, overshoots its resting point, has very high frequency oscillations, and is quick to respond → causes falsely ↑ SBP and falsely ↓ DBP

- (v) Lack of damping (DC = 0) – System oscillates at its resonant frequency with no decrement in oscillation over time



- The system's damping is often caused by:
  - (i) Addition of 3-way taps
  - (ii) Bubbles and clots within the system
  - (iii) Arterial vasospasm
  - (iv) Kinking of the tubing or cannula
  - (v) Narrow, long or compliant tubing system
- "Damping coefficient (DC)" is measured by "Fast flush test" → amplitude ratio of 2 consecutive resonant waves (smaller wave to larger one)

Important to note:
- "Static calibration" → determines accurate measure of MAP only (physiologically important as it determines perfusion pressure of tissues)
- "Dynamic calibration" → determines accurate measure of SBP, DBP and pulse pressure only (less physiologically important)

Advantages and disadvantages of invasive arterial BP:

- Advantages:
  - (i) Gold standard of arterial BP measurement – High accuracy (esp with low BP, such as shock) and high reliability (esp with fluctuating CO, such as AF)
  - (ii) Continuous beat-to-beat BP measurement is useful for close monitoring of patients with labile BP (Eg. shock, MI)
  - (iii) Useful where NIBP is not practical (Eg. burns, obesity, reduce risk of tissue injury with frequent NIBP in prolonged cases)
  - (iv) Permits arterial blood sampling
  - (v) Waveforms can be analysed to provide info regarding CV status ("pulse contour analysis")
- Disadvantages:
  - (i) Risk of arterial damage (including thrombosis and haematoma)
  - (ii) More costly to manage
  - (iii) Requires technical skill to set up

(c) ***To describe and to compare the methods of measuring temperature.***

Heat:

- Heat is a form of kinetic energy → being a state of "thermal agitation" of molecules in a substance
- It can be transferred by:
  - (i) Conduction (through a substance)
  - (ii) Convection (by movement of a surrounding medium, such as liquid or gas)
  - (iii) Radiation (by electromagnetic waves) → Nb. this can occur through a vacuum and does not require direct contact cf. other heat transfer mechanisms
- Units for heat:
  - SI unit → Joules (J)
  - Non-SI units → calorie (where 1 calorie = 4.186 J → raises temperature of 1 g of H_2O from 14.5°C to 15.5°C); Calorie (where 1 Calorie = 1000 calories = 4186 J)

Temperature:

- Temperature is a measure of a physical property of a substance that determines the tendency for heat to flow from one object to another → heat energy is transferred from a region of higher temperature to a region of lower temperature
- Units for temperature:
  - SI unit → Kelvin (K), which is 1/273.16 of absolute temperature of "triple point of H_2O" (where H_2O exists in equilibrium as a solid, liquid and gas → occurs at 0.01°C)
  - Non-SI unit → Celsius (°C), where 1°C is $1/100^{th}$ the difference between the freezing and boiling point of H_2O

$$K = °C + 273.15$$

Specific Heat:

- Specific heat of substance is the amount of heat energy required to ↑ temperature of 1 g of substance by 1°C
- SI unit → J/kg (Eg. 4.2 kJ/kg per °C for H_2O)

Measurement of temperature:

Non-electrical measurement of temperature:

(1) Mercury thermometer

Technique	- Consists of a uniform evacuated glass capillary tube connected to a Hg reservoir → heating of reservoir cause Hg to expand and moves up the capillary tube → the top of the Hg column rests at unique position for a given temperature → temperature is read from the scale on the side of capillary tube - Notable features o Constriction at bottom of capillary tube above reservoir → maintains position of Hg column so temperature value does not change after removal from measurement site o Capillary tube is small (enhances sensitivity) and uniform (allows linear scale) o Size of Hg reservoir is of an appropriate size → large enough to provide sensitivity but small enough to allow rapid response o Capillary tube is positioned at focal point of a parabolic mirror on the back of thermometer → allows visualisation of small capillary tube and minimises error in reading temperature from the scale
Advantages	- (i) "Gold standard" measurement of temperature - (ii) Accurate and reliable measurement → linear expansion response within a large temperature range (- 40 °C to 357 °C) - (iii) Readily made and easy to use → easily incorporated into thermostat and

	no calibration needed - (iv) Cheap - (v) Reusable with sterilisation
Disadvantages	- (i) Slow response (needs 2-3 mins to reach thermal equilibrium) - (ii) Cannot be made small → unsuitable for certain orifices or remote readings - (iii) Readings cannot be connected to an electronic recorder for easy display - (iv) Does not allow continuous readings (only intermittent) - (v) Thermometer is fragile → if broken, Hg is toxic

(2) Alcohol thermometers

Technique	Similar to mercury thermometer
Advantages	Similar to mercury thermometer EXCEPT: - It is cheaper - Can be used at very low temperatures (as Hg freezes at -39°C) - Alcohol is less toxic
Disadvantages	Similar to mercury thermometer EXCEPT: - It is not suitable at high temperatures (as alcohol boils at 78.5°C) - Less accurate and reliable → b/c alcohol has a less linear expansion response

(3) Bimetallic strips

Technique	Two dissimilar metals are welded together in a spring that is coupled to a needle gauge with a pointer over a temperature scale → Δ in temperature causes each metal expands at a different rate, thereby causing a Δ in coil of spring and movement of needle gauge/pointer
Disadvantages	- (i) Requires calibration - (ii) Low accuracy - (iii) Corrosion of metals is an issue

(4) Bourdon gauge

Technique	Hollow metal tube rolled in a spring and attached to pressure dial at one end, and attached to a sensory element at the other end → tube is filled with a volatile liquid (Eg. freon) that expands with ↑ temperature
Advantages	- (i) Rapid response - (ii) Suitable for remote recordings - (iii) Accurate (to 0.3°C)
Disadvantages	- (i) Pressure dial needs calibration - (ii) Small temperature range in which it can be used

Electrical measurement of temperature:

(1) Resistance thermometer

Technique	Thermal-sensitive resistor (metal wire made of Pt, Cu or Ni) → electrical resistance ↑ linearly with temperature
Advantages	- (i) Linear response over a wide temperature range - (ii) Accuracy can be improved when incorporated into a Wheatstone bridge - (iii) Allows multiple readings to be taken
Disadvantages	- (i) Slow response time - (ii) Bulky (limiting use in certain places) - (iii) Only allows intermittent readings

(2) Thermistor

Technique	- Solid-state thermometer composed of a thermal-sensitive resistor (made of small bead of heavy metal oxide (Co, Ni, Hg, Zn)) within an electrical circuit → incorporated into a small measuring tip - Electrical resistance changes with temperature in a non-linear manner: o (i) Most are –ve temperature coefficient → resistance ↓ exponentially with temperature o (ii) Few are +ve temperature coefficient → resistance ↑ with

	temperature
Advantages	- (i) Rapid response (quick to reach thermal equilibrium) - (ii) Very sensitive due to non-linear response (Ie. large change in resistance required for temperature change) - (iii) Very accurate → improved further when incorporated into Wheatstone bridge - (iv) Small and can be use remotely (Ie. PA catheter, oesophageal probe, Etc.) - (v) Allows continuous readings - (vi) Readings can be connected to a electronic recorder for easy display
Disadvantages	- (i) Requires zeroing and calibration - (ii) Narrow temperature reference range (need different thermistors for different temperature ranges) and non-linearity of response - (iii) Demonstrates hysteresis - (iv) Cannot undergo sterilisation (as resistance changes with heat exposure) - (v) Needs recalibration over time (due to ↑ oxide resistance) - (vi) Single use only (due to issues with sterilisation and need for recalibration over time) → expensive

(3) Thermocouple

Technique	- Circuit is made from two dissimilar metals (Cu + Constantan (60% Cu/40% Ni)) → contains two junctions → one junction kept at a "constant reference temperature", the other used as a "measuring junction" - Based on Seebeck effect → size of electrical potential difference that develops between the junctions is dependent on the temperature difference between them → 40 uV per °C
Advantages	- (i) Rapid response - (ii) Small and can be used remotely (like thermistor) - (iii) Highly accurate (to 0.1°C)

(4) Infrared

Technique	Optical thermistor that focuses infrared detector onto a point (usually tympanic membrane) → senses radiation emitted and converts this into an electrical signal that is made to produce a linear output voltage related to temperature
Advantages	- (i) Fast response - (ii) Non-invasive
Disadvantages	- (i) Presence of wax/dirt → gives false readings - (ii) Inability of human eye to detect focused point of sensor - (iii) Corrections required as tissue surfaces do not work as ideal black body

(d) ***To describe and to compare the methods of measuring humidity.***

Definition of humidity:

- Absolute humidity:
  - Defined as the mass of water vapour (g H_2O) present in a given volume of air (m^3) → expressed as g H_2O/m^3 or mg H_2O/L
  - Varies between zero (dry air) and a maximum amount (humidity at saturation)
  - Temperature-independent → EXCEPT when air is saturated with maximum amount of water vapour

> Note – ↓ temperature causes ↓ absolute humidity of fully saturated air 2° to a ↓ in SVP → fully saturated air at 0 °C contains 4.8 mg/L; at 20 °C contains 17 mg/L; at 37 °C contains 44 mg/L

- Relative humidity:
  - Defined as the ratio of the mass of water vapour in a given volume of air (absolute humidity) to the mass required to fully saturate that volume of air at a given temperature (humidity at saturation) → expressed as %

$$\text{Relative humidity} = \frac{\text{Absolute humidity}}{\text{Humidity at saturation at that temperature}} \times 100\%$$

> Aside: Since mass is directly proportional to # moles present, then as per "Ideal gas equation" (at a constant temperature) → Relative humidity = (actual vapour pressure of H_2O) / (saturated vapour pressure of H_2O)

  - Temperature-dependent → this is b/c humidity at saturation varies with temperature (such that ↓ temperature causes ↓ absolute humidity of fully saturated air 2° to ↓ in SVP) → thus relative humidity ↑ with ↓ temperature

> Note:
> - Water content → defined as the total amount of water present per unit volume of gas (either water vapour and/or fine suspended droplets) → expressed as mg/L
> - Dew point → defined as the temperature to which air must be cooled before water condenses from it (Ie. at dew point, vapour pressure of H_2O = SVP)

Measuring humidity:

(1) Hair hygrometer

Measurement	Relative humidity
Principle	Hair length (at a constant tension) elongates in a linear fashion with a ↑ in relative humidity
Technique	Hair is coupled to a needle gauge with a pointer moving over a humidity scale
Advantages	Simple and cheap
Disadvantages	Accurate only over 30-90% humidity range, slow, difficult to couple with electrical circuit, needs calibration against an external standard

(2) Wet and dry bulb hygrometer

Measurement	Relative humidity
Principle	Rate of evaporation is inversely related to humidity
Technique	- Two mercury thermometers are mounted side-by-side and exposed to airflow – one is kept dry, and the other has a wet wick around its bulb - Temperature of wet bulb ↓↓↓ due to evaporation → airflow that is less humid causes greater evaporative cooling → larger temperature difference between the two thermometers (cf. more humid air causes less evaporative cooling → smaller temperature difference between the thermometers)

	- Reference table of temperature differences → determine humidity
Disadvantages	Not as accurate as Regnault's method

(3) Regnault's (dew point) hygrometer

Measurement	Absolute and relative humidity
Principle	Condensation occurs when air is fully saturated at a given temperature (Dew point)
Technique	- Hygrometer consists of a silver test tube with ether → temperature of ether monitored with thermometer - Gas flow over the top of the test tube causes evaporation of ether → causes evaporative cooling of ether → results in cooling of silver test tube at the same rate as ether (due to high thermal conductivity of silver) - At dew point temperature, air layer on outside of tube is fully saturated with water vapour so dew condenses on outside of silver test tube - Noted dew point temperature (as measured by temperature of ether) is referred to a standard table to determine absolute humidity - Relative humidity → determined by (SVP at dew point) / (SVP at ambient temperature)
Advantages	Accurate and calibration not required

(4) Transducers

Measurement	Absolute humidity
Principle	Change in resistance or capacitance in an electrical transducer when its absorbs moisture from the environment
Advantages	Sensitive and rapid response
Disadvantages	Hysteresis (↓ accuracy)

(5) Mass spectrometry → measures absolute humidity on breath-by-breath basis

(6) Light absorption technique (using UV light)

(e) ***To explain in detail the principles of pulse oximetry including calibration, sources of errors and limitations.***

Beer Lambert Law:

- Beer's Law → absorption of radiation by a given thickness of solution of a given [ ] is the same as that of twice the thickness of solution of half the [ ]
- Lambert's Law → each layer of equal thickness absorbs an equal fraction of radiation that passes through it (Ie. process shows exponential decay)

Therefore:

$$I_T = I_I e^{-A}$$

I_T = Light intensity transmitted
I_I = Light intensity shone
A = Absorbance

Where $A = C.d.E$

C = [ ] of solution
d = Distance through medium
E = Extinction coefficient (specific for solute at a given wavelength of light)

Note:

- In a mixture of solutes → $A_{TOTAL} = C_1dE_1 + C_2dE_2 + \ldots = d(C_1E_1 + C_2E_2 + \ldots)$
- Hence, in a mixture of two unknown solutes → 2 wavelengths (λ_1 and λ_2) are needed to measure the C_1 and C_2 of solutes → solve simultaneous equations:

$$C_1E_{\lambda1} + C_2E_{\lambda1} = (A_{\lambda1}/d) = (\ln [I_I/I_T]_{\lambda1})/d$$
$$C_1E_{\lambda2} + C_2E_{\lambda2} = (A_{\lambda2}/d) = (\ln [I_I/I_T]_{\lambda2})/d$$

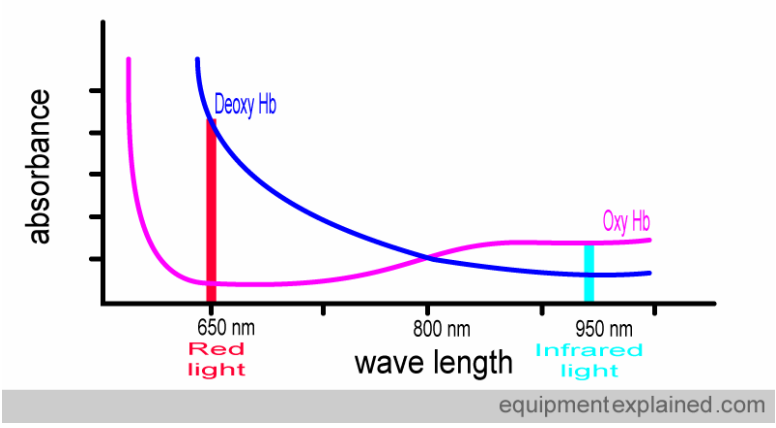
Pulse Oximetry:

Overview:

- Non-invasive method of measuring Hb saturation (SpO_2) of arterial blood using light signal transmission through perfused tissue (Eg. finger, ear lobe) → combines principles of (i) oximetry and (ii) plethysmography

Principle:

- (1) Oximetry → spectrophotometric technique
  - Based upon HbO_2 and RHb having different absorption patterns at 2 different wavelengths → RHb absorbs more light in red band (660 nm), while HbO_2 absorbs more light in IR band (940 nm)



Nb. Isobestic points (where HbO_2 and RHb absorb same absorbance) → at 590 nm and 805 nm

- Using Beer-Lambert Law → relative contents of HbO_2 and RHb in arterial blood are determined by their relative absorbance of light at these 2 different wavelengths → leads to determination of SpO_2

$$SpO_2 = \frac{HbO_2}{(RHb + HbO_2)}$$

- (2) Plethysmography → detects arterial pulsations
  - Corrects for light absorption by nonpulsating blood and tissue → divides light absorbance signal received by photodetector into 2 components:
    - Variable (ac) component → due to pulsatile arterial blood
    - Fixed (dc) component → due to tissue + capillary blood + venous blood + non-pulsatile arterial blood
  - At each wavelength, oximeter determines ac/dc fraction → then "ratio" (R) is calculated:

$$R = \frac{(\text{ac absorbance/dc absorbance})_{RED}}{(\text{ac absorbance/dc absorbance})_{IR}} = \frac{A_{660\ NM}}{A_{940\ NM}}$$

  - Using "calibration curve" (determined from experimental data from volunteers) → R value is then used to determine SpO_2

SpO_2 100% at R = 0.4
SpO_2 85% at R = 1.0
SpO_2 0% at R = 3.4

Technique:
- Pulse oximeter probe is placed on perfused tissue that can be illuminated (Eg. finger, ear lobe, Etc.) → the probe consists of
  - 2x high intensity monochromatic LED photodiodes on one side of probe → emit 2 wavelengths of light (660 nm (red light) and 940 nm (IR light)) through tissue
  - Single photodetector on other side of probe → reads transmitted light intensity through tissue → sends signals to electronic processor to produce pulsatile waveform → calculates SpO_2
- Photodiodes emit light signals at 480-500 Hz cycles in following pattern – Red light only → then IR light only → then both lights off (so ambient light only is detected by photodetector) – this is done to reduce interference caused by ambient light

Calibration:
- Oximeter does NOT require repeated calibration → b/c it uses a predetermined "calibration curve" (derived form experimental data from volunteers) for each patient

Accuracy:
- Accuracy is +/- 2% for SpO_2 70-100% and +/- 3% for SpO_2 50-70%
- Accuracy is not known for SpO_2 < 50% → this is b/c calibration curve at these SpO_2 is derived by extrapolation (Ie. unethical to desaturate volunteers!)
- Finger probes are less accurate and have slower responsiveness than ear probes
- SpO_2 trends are more accurate than absolute values

Sources of error and limitations:
- (1) Presence of other light absorbing Hb in arterial blood
  - CO-Hb → absorbs same amount of light as HbO_2 at 660 nm but little at 940 nm → oximeter mistakes CO-Hb as HbO_2 → gives falsely elevated SpO_2 (> 90%)
  - Met-Hb → high light absorbance at 660 nm and 940 nm → ↑ both A_{660} and A_{940} so R-value ~ 1.0 → gives SpO_2 ~ 85%

    - HbF and HbS → light absorbance profile similar to HbA → does not affect SpO_2
- (2) IV dyes
    - Methylene blue → high extinction coefficient at 660 nm → gives falsely low SpO_2
    - Indocyamine green (ICG) → gives falsely low SpO_2 (intermediate effect)
    - Indigo carmine → gives falsely low SpO_2 (small effect)

> Nb. Bilirubin does NOT affect SpO_2!

- (3) Nail polish → gives falsely low SpO_2
- (4) Dark skin → gives falsely low SpO_2
- (5) Ambient light → gives falsely elevated SpO_2

> Nb. This is minimised by emitting light signals at 480-500 Hz cycles (red → IR → no light) to filter out ambient light, and by covering sensor with opaque material

- (6) Motion artefact → gives erroneous SpO_2

> Nb. This is minimised by increasing signal average time → but response time is also increased

- (7) Probe variability errors → LED wavelength varies up to +/- 10 nm from specified value → produces probe-probe variation in accuracy
- (8) Signal-to-noise ratio → gives poor signal detection
    - Low S:N ratio occurs when ac component is < 1% of dc component → due to:
        - ↓ ac component (Eg. weak peripheral pulse, shock, low CO state, probe malposition, hypothermia, vasoconstricted state, hypotension)
        - ↑ dc component (Eg. nail polish, ambient light, dark skin)
        - Pulsatile component added to ac component (Eg. motion artefact, diathermy, venous pulsations due to TV incompetence)
    - Oximeter minimises this by increasing light intensity (as part of "automatic gain control") → ↑ amplifies low signal strength by up to 10^9
    - BUT this causes both signal and noise to amplify → gives erroneous results as noise produces equal values of A_{660} and A_{940} → produces R-value ~ 1 (SpO_2 85%) → most oximeters fail to read signal at this point and displays "poor signal"
- (9) Low SpO_2 < 70% → ↓ accuracy b/c calibration curve at these SpO_2 is derived by extrapolation
- (10) Risks of use:
    - Excessive compression of digits (esp when tapes used on sensors)
    - Burns by excessive heating (esp when wrong sensor connected to machine)

(f) ***To explain the principles of gases using ultraviolet or infra-red absorption, paramagnetic analysis, gas chromatography, mass spectrometry and Raman scattering.***

Sampling of anaesthetic gas:

- (1) Mainstream analysis → analyser attached directly to airway and samples gas within respiratory circuit
    - Gas analysed – Limited to O_2 and CO_2 only
    - Advantages – Quick response time and more reliable
    - Issues – Cannot analyse other anaesthetic gases, introduces dead space, need to heat sample close to patient, machinery weight
- (2) Side-stream analysis → sample continuously aspirated from respiratory circuit which is then fed through an analyser (gas then returned to circuit or scavenged)
    - Gas analysed – Most anaesthetic gases (CO_2, O_2, N_2, N_2O, He, volatiles)
    - Advantages – Analyse most gases, more portable/light weight, less dead space
    - Issues – Cost (esp for aspiration system), lag time (esp if sampling tube blocked, such as by H_2O vapour), contamination of circuit gas (as sample is returned to it), mixing of gas in sample tubing (can blur sharp changes)

Volatile gas analysis:
- (i) IR absorption
- (ii) Photoacoustic spectrometry
- (iii) Mass spectrometry
- (iv) Raman scattering analysis
- (v) Piezoelectrical crystal resonance

O_2 gas analysis:
- (i) Paramagnetic analysis
- (ii) Photoacoustic spectrometry
- (iii) Mass spectrometry
- (iv) Raman scattering analysis
- (v) Fuel cell

CO_2 gas analysis:
- (i) IR absorption
- (ii) Photoacoustic spectroscopy
- (iii) Mass spectrometry
- (iv) Raman scattering
- (v) Chemical analysis

Mass spectrometry:

Uses	CO_2, O_2, N_2O, N_2, volatile agent, and monoatomic gas analysis
Principle	Fractional composition of a gas mixture is determined by ionising molecules within a gas sample, and then separating them in magnetic field based upon their mass/charge ratio
Technique	- Small of gas sample enters ionising chamber through a molecular sieve → gas molecules are bombarded by an electron beam → molecules are split into smaller units and gain +ve charge (Eg. $CO_2 \rightarrow CO^+$; $N_2O \rightarrow NO^+$) - Using an electrical field, these ionised particles are accelerated and focused into a beam → then directed through a strong magnetic field that separates them by deflecting them according to their mass/charge ratio (Ie. heaviest ions deflect the least and travel farthest) - Most machines will have 7-8 collectors positioned at specific locations (so 7-8 gases can be measured simultaneously): o Each collector collects a specific ion → voltage generated at each collector is proportional to amount collected o Sum of all voltages from all collectors is 100% → so the portion of voltage of any collector can be expressed as a % - Partial pressure of a specific gas = (% voltage at collector) x ($P_{EXPIRED\ GAS} - P_{H2O}$)
Advantages	- (i) Multiple anaesthetic gases can be accurately measured simultaneously - (ii) Gas analysis from multiple operating theatres can be done - (iii) Rapid analysis (assuming sampling lines to machine are not long)
Disadvantages	- (i) Large and expensive machine → one machine per theatre complex and is remote - (ii) Lack of flexibility (Ie. if machine breaks down, all theatres lose gas analysis) - (iii) Results can be delayed due to long sampling lines to the machine - (iv) Measures only the proportion of a gas within the mixture (Ie. fractional composition) → partial pressure has to be calculated - (v) Only identifies agent it was set for → presence of other gases in significant levels can produce erroneous readings - (vi) Requires periodic calibration

	- (vii) Gases in measuring chamber need to be emptied after deionising them - (viii) Machine will tolerate only minimal movement

Raman scattering:

Uses	CO_2, O_2, N_2O, N_2, volatile agent analysis
Principle and technique	- High intensity laser beam of a single frequency is applied to gas → this is absorbed by gas molecules → causes a changes its vibrational and rotational energy to an "excited state" - Energy is then released from the gas molecule → light is re-emitted at a lower frequency and intensity → such that: o (i) Frequency of scattered light → identifies type of molecule present o (ii) Intensity of scattered light → determines # of molecules present - Nb. frequency of laser beam can be altered to analyse a specific type of gas in the sample
Advantages	- (i) Accurate measurements of gas - (ii) Rapid response time - (iii) Multiple gas analysis can be done simultaneously
Disadvantages	Monoatomic gases (He, Xe, Ar) cannot be measured

Infrared radiation (IRR) absorption:

Uses	CO_2, N_2O, volatile agent analysis
Principle	- Gases with > 2 different atoms will absorbs IRR → each gas has a peak absorbance at a specific IR wavelength and this is used to distinguish between different gases: o CO_2 → 4200-4400 nm o N_2O → 4400-4600 nm (and less at 3900 nm) o Volatile agents → 3300 nm and 9000-12000 nm - Amount of IRR absorption at a specific wavelength is measured → as per Beer-Lambert's Law, the degree of IRR absorption is directly proportional to the # of gas molecules present (and the [ ] or partial pressure of gas) - Nb. only molecules with different charge distributions can absorb IR → non- polar molecules (Eg. Ar, He, O_2, N_2 and Xe) do not absorb IRR
Technique	- Hot wire heated to 1500-4000 K → provides radiation source - Radiation is passed through sapphire window (glass absorbs IR) → then a filter which selects a desired wavelength - Two chambers exist – one for "sample gas" and another for "reference gas" → separate radiation beams are passed through each chamber - IR detector separately measures the amount of radiation passing through each chamber → electronics then calculate, amplify and display result
Advantages	- (i) Accurate measurements of gas - (ii) Rapid response time
Disadvantages	- (i) Response time of machine o Lag time → period it takes for gas to reach sensor (usually seconds) → factors: ▪ (a) Method of sampling – Mainstream analyser (a/w minimal lag) vs Side-stream analyser (a/w ↑ delay) ▪ (b) Sampling flow rate ▪ (c) Diameter and length of sampling tube (incl blockages of tube) ▪ (d) Presence of filter ▪ (e) Respiratory rate o Rise time → speed at which sensors can detect change (usually milliseconds) - (ii) Interference from other gases o (a) Overlapping absorption spectra between gases (N_2O and CO_2,) → correct for the interfering gas by either measuring its content by a different wavelength or using algorithms o (b) Collision broadening → gases that do not absorb IRR (Eg. O_2, N_2, Ar, He, Etc.) collide with molecules of interest (Eg. CO_2) → ↑↑↑ the IR absorption

	band of gas being measured o (c) H_2O vapour absorbs highly (so sample needs to be dried and heated) - (iii) Cannot distinguish b/t volatile agents using a single wavelength (3300 nm) as all agents peak at that level → thus, 2-3 additional wavelengths are needed (b/t 9000-12000 nm) for analysis - (iv) Cannot measure certain gases (O_2, N_2, H_2, Xe, Ar)

Photoacoustic spectrometer:

Uses	CO_2, O_2, and volatile agent analysis
Principle and technique	- Single IR beam of a certain frequency is filtered using a chopper wheel → beamed into sample chamber - Gas molecule absorbs IRR → expands and contracts according to frequency of pulsed beam → produces sound waves whose amplitude is proportional to its partial pressure
Disadvantages	Cannot distinguish between volatile agents

Ultraviolet absorption:

Uses	Old method to analyse halothane
Principle and technique	Similar to IRR absorption except using UV light
Advantages	Cheap
Disadvantages	- (i) Delay in initialising analysis (takes 20-60 mins for warm up) - (ii) Analysis produces toxic gases → cannot be returned to circuit - (iii) Needs frequent calibration

Piezoelectric crystal resonance technique:

Uses	Volatile agent analysis
Principle and technique	- Two quartz crystals → one coated in silicone oil, the other uncoated - Gas dissolves in silicone oil in proportion to oil:gas partition coefficient (as per Henry's law) → alters resonant frequency of silicone oil-coated crystal → magnitude of change dependent on [ ] of gas present - Resonant frequency of uncoated crystal → used as a reference
Disadvantages	- (i) Cannot distinguish b/t volatile agents → user needs to specific which agent is being used - (ii) Interference from H_2O vapour (so sample needs to be dried and heated) - (iii) Does not measure other anaesthetic gases (Eg. CO_2, O_2, N_2O, Etc.)

Paramagnetic analysis:

Uses	O_2 analysis
Principle	O_2 is "paramagnetic" (due to unpaired electrons in outer shell) → attracted to magnetic field
Technique	- Tubes of sample gas and reference gas (Ie. air) pass through a rapidly changing magnetic field - Each stream of gas will have differing content of O_2 molecules → so stream with larger content of O_2 will be held by the magnetic field (due to its paramagnetic nature) → thus result in ↑ pressure within that tube - Pressure differential between the tubes is measured by a pressure transducer → converted to partial pressure of O_2
Advantages	- (i) Rapid - (ii) Accurate
Disadvantages	- (i) Cannot be used to measure other anaesthetic gases (only O_2) - (ii) Interference from H_2O vapour (so sample needs to be dried and heated)

	- (iii) Requires periodic calibration

Fuel cell analysis:

Uses	O_2 analysis
Principle	O_2 dependent battery that measures partial pressure of O_2 according to current flow between electrodes
Technique	- Cathode – Gold mesh covered with membrane permeable to O_2 $O_2 + 4e^- + 2H_2O \rightarrow 4\ OH^-$ - Anode – Pb wire in KOH gel $Pb + 2\ OH^- \rightarrow PbO + H_2O + 2e^-$ - e^- move from anode to cathode → current flow is proportional to PO_2 - Since current is temperature-dependent (like Clarke electrode) → thermistor is placed in within the circuit to compensate for temperature variation
Advantages	Accurate (until the fuel cell expires)
Disadvantages	- (i) Slow response time (30 secs) - (ii) Lacks external power source (cf. Clarke electrode) - (iii) Fuel cells need to be capped when not in use → b/c fuel cells expire with ongoing usage of O_2

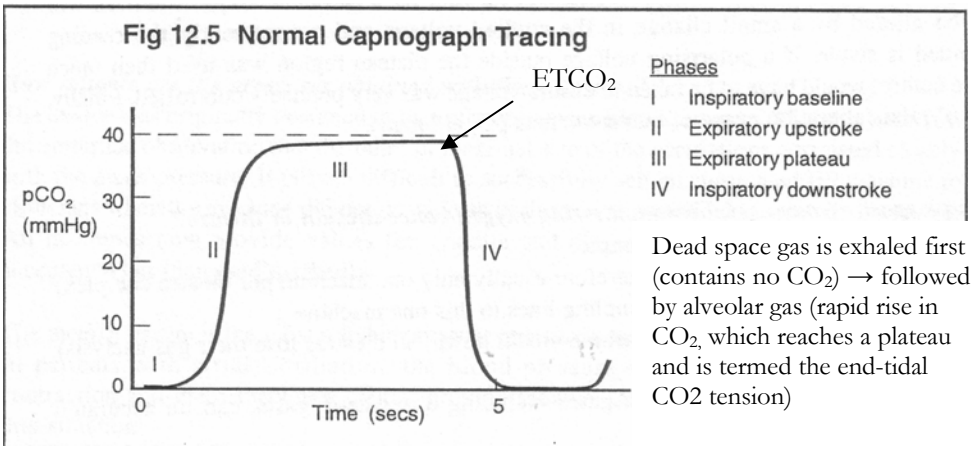
Gas-liquid chromatography:

Principle	Gas sample is separated into its components within a column according to its differential solubility between two phases – stationary and mobile phase
Technique	- Gas and/or liquid sample injected into sample port → heated to vapourise entire sample → sample then separated into its components as it passes through a column that contains a "stationary phase" (fine silica-alumina with PEG or silicone oil) and "mobile phase" (Ar, He, N_2 carrier gas) → components then leave the column and enters a detector - Speed at which the components passes through the column and reaches the detector is determined by differential solubility between the two phases - Temperature of system is kept constant (as solubility varies with temperature) - There are 3 types of detectors: o (i) Flame ionisation detector → detect organic gas vapour ▪ Gas enters into H_2/air flame that contains ionised particles → resistance of flame ↓↓↓ in presence of organic gas vapour ▪ As a constant potential (150 V) is applied across the flame → thus, current flow ↑↑↑ in presence of organic gas vapour o (ii) Thermal conductivity detector (katharometer) → detect inorganic gas vapour (respiratory gases and N_2O) ▪ Heated electrical resistance wire is placed in main stream of gas flow → as thermal conductivity of gas differs with each type of gas, temperature of gas flow will vary → causes change in current in wire o (iii) Electronic capture detector → detect halogenated gas vapours (volatile agents) ▪ Polarising voltage applied across ionising chamber → electrons released by radioactive cathode are captured by halogenated compounds ▪ This effectively ↓↓↓ the current flow reaching the anode
Advantages	Sensitive → can measure very low [ ] of gas
Disadvantages	- (i) Continuous analysis is not possible - (ii) Prior knowledge of content of gas sample required

(g) ***To explain in detail the principles of capnography including calibration, sources of errors and limitations.***

Overview of capnography:

- Capnography is the continuous graphical measurement of expired CO_2 tension from airway (in gas phase) against time → permits monitoring of end-tidal CO_2 tension



Dead space gas is exhaled first (contains no CO_2) → followed by alveolar gas (rapid rise in CO_2, which reaches a plateau and is termed the end-tidal CO2 tension)

- End-tidal CO_2 as part of capnography is an excellent non-invasive estimate of $PaCO_2$:
  - $ETCO_2$ is normally 2-5 mmHg less than $PaCO_2$ → due to alveolar dead space ventilation
  - This difference is ↑↑↑ if there is V/Q mismatching 2° to ↑ alveolar dead space (Eg. ↓ CO, hypotension, PE, PPV/PEEP, Etc.)

Causes of ↑ $ETCO_2$	Causes of ↓ $ETCO_2$
↓ alveolar ventilation (↓ RR or TV or ↑ equipment dead space)	↑ alveolar ventilation (↑ RR or TV)
↑ CO_2 production (fever, hypercatabolic state)	↓ CO_2 production (hypothermia, hypocatabolic state)
↑ inspired PCO_2 (rebreathing, external source of CO_2, CO_2 absorber exhaustion)	↑ alveolar dead space (↓ CO, hypotension, PE, PPV/PEEP)
Sampling error (loss of machine calibration)	Sampling error (loss of machine calibration, leak in breathing system or sampling line, inadvertent FGF sampling, long tubing to analyser, sampling site far from trachea, sample line blockage (esp due to H_2O)

Methods of capnography:

- CO_2 in gas phase can be measured by:
  - (1) Infrared (IR) absorption → MOST commonly used
  - (2) Raman scattering
  - (3) Photoacoustic spectroscopy
  - (4) Mass spectrometry
  - (5) Chemical analysis (Eg. Lloyd-Haldane apparatus)

Note: All above methods (EXCEPT chemical analysis) allows breath-by-breath analysis of CO_2 → as these measuring systems have a rapid response time (~ 100 msec) and provide an accurate and reliable assessment from a small sample of gas

Note: See above for in-detail description of each method of CO_2 measurement

Sources of error and limitations with capnography:

- (1) Issues related to method of measuring PCO_2 in gas phase (see issues relating to IRR absorption, Raman scattering, mass spectrometry, photoacoustic spectrometry, Etc.)
- (2) Loss of calibration of machine (PCO_2 can vary)
- (3) Leak in breathing system or sampling line (underestimates PCO_2)
- (4) Malfunctioning non-rebreathing valve (overestimates PCO_2)
- (5) Inadvertent FGF sampling (underestimates PCO_2)
- (6) Long tubing to analyser (underestimates PCO_2)
- (7) Sampling site far from trachea (underestimates PCO_2)
- (8) Blockage of sampling line, such as due to H_2O (underestimates PCO_2)

(h) ***To describe and compare the methods of measuring gas flow.***

Overview of gas flow, velocity and volume:

- "Gas flow" is the volume of gas passing a point per unit time → measure in L/sec
- "Velocity of gas flow" is the distance travelled by the gas per unit time

> Relationship between gas flow, velocity and time:
> - Gas flow = (velocity of gas flow) x (cross-sectional area)
> - Gas flow = (gas volume) / (unit time)

- So:
  - "Gas flow" → determined from either (i) velocity of gas flow and CSA of measuring system, or (ii) gas volume and time
  - "Gas volume" → determined from gas flow rate → by integrating gas flow rate over a specified period of time (as gas volume = (gas flow) x (time))

Measurement of gas volume:

(1) Spirometry
- (a) Wet spirometer
  - Consists of an inverted bell in a container of water → bell connected via a pulley to a counter-weight and pen that writes on a rotating drum
  - Respiration causes vertical movement of inverted bell → causes movement of pulley system and pen → changes in lung volume recorded on rotating drum
- (b) Dry spirometer (Vitalograph)
  - Consists of a wedge-shaped bellow connected to a pen
  - Expiration causes bellow expansion and movement of the pen → activates a motor that drives paper recorder to move at a fixed rate → tracing of changes in lung volume recorded
  - Cheap but requires ↑ flow inertia (meaning inaccurate at low flow rates, and causes backpressure to patient)

(2) Gas meters (Douglas bag, water displacement)
- Consists of internal chambers of known volume
- Lung volume is determined by measuring the # of times each chamber is filled

(3) Anemometers
- (a) Wright respirometer
  - Cylinder with 10x tangential slots that direct gas flow onto a twin-bladed rotor → gas flow causes rotor to spin → activates a gearing system that converts flow velocity measured by spinning rotor into a volume shown on a clockface-type dial
  - Advantages – Ideal for normal TV breathing with accuracy 5-10%
  - Disadvantages:
    - (i) Responds to gas flow in one direction only
    - (ii) Overestimates at high TV and flow rates (due to inertia of spinning rotor) and underestimates at low TV and flow rates (as rotors fail to spin)
    - (iii) Very fragile (damaged easily if dropped)
    - (iv) Discrepancy in flow rates when N_2O used → produces greater readings than air for a given flow rate
    - (v) H_2O vapour condensation and wearing of parts affect rotor spinning
- (b) Drager volumeter → similar to Wrights respirometer, except it consists of 2x twin-lobed rotors that can respond to flow in either direction
- (c) Pneumotachograph (see below) → volume is derived from integration of flow rate over a period of time

(4) Inductance/impedance body plethysmography → indirectly measure lung volume from chest wall movement

Measurement of gas flow:

(1) Fixed orifice flowmeter:
- (a) Pneumotachograph
  - Principle:
    - Gas flow enters into a circuit with a constant and known resistance (generated by a fixed orifice) that produces a small pressure drop (1-2 cmH_2O) → several variants exist:
      - (i) Fleisch type → parallel bundle of small bore tubes arranged in series with gas flow
      - (ii) Lilly type → perforated wire or plastic gauze
      - (iii) V-shaped flap

      Nb. Each type of resistance is designed to encourages laminar flow
    - Gas flow across resistance is heated (esp Fleisch type) → prevents condensation of H_2O droplet that would affect gas flow
    - Pressure drop is sensed by differential pressure transducer → converts pressure change into electrical signal → electronic device calculates flow rate on assumption that in presence of laminar flow, gas flow rate is directly proportional to pressure drop (as per Poiseuille's Law)

$$\text{Poiseuille's Law} \rightarrow \text{Flow} = \frac{\Delta P}{R} = \frac{(\Delta P \pi r^4)}{(8nl)}$$

  - Advantages:
    - (i) Fast response flowmeter for both continuous or intermittent flows → allows breath-to-breath analysis
    - (ii) Total resistance of system is small → can be used with spontaneous breathing
  - Issues:
    - (i) Gas flow needs to be laminar for accurate reading → b/c flow and pressure are no longer directly related in presence of turbulent flow

      Turbulent flow occurs with:
      - ↑ gas flow rate
      - ↑ diameter tubing (Ie. adult size tubing for a child)
      - ↑ density or ↓ viscosity gas
    - (ii) Temperature and humidity → heating element prevents inaccuracy caused by temperature variations, and H_2O droplet condensation on resistance elements
    - (iii) Obstruction of gas flow through resistance elements (Eg. H_2O condensation, dirt, mucous, Etc.)
    - (iv) Differing viscosity between gas measured and gas used for calibration
    - (v) Very low gas flow rates → pressure drop too small to be measured
- (b) Bourdon gauge
  - Principle of gas flow measurement similar to pneumotachograph (Ie. measure pressure drop across a constant resistance), EXCEPT the fixed orifice is either → (i) a linear constriction where pressure drop is proportional to flow rate, OR (ii) an orifice where pressure drop is proportional to the square of flow rate

(2) Variable orifice flowmeter:

- (a) Rotameter
  - Variable orifice, constant pressure flowmeter → used to measure steady gas flow in anaesthetic machines
  - Principle:
    - Gas flows up a vertical tube causes the bobbin to rise
    - Glass tube is shaped as inverted cone → as bobbin rises, space b/t outside of bobbin and inside of tube increases → "variable orifice"
    - Weight of bobbin is constant → exerts downwards pressure against gas flow → "constant pressure drop"
    - As gas flow is varied, bobbin rises up (or down) until it comes to rest at a unique position → flow rate is read from top of bobbin on a scale on tube

    Nb. Rationale for variable sized orifice
    - Glass tube shaped as inverted cone so that with increased flow rates, the orifice size increases as the bobbin rises → this allows the bobbin to lie at a unique position at a given flow rate
    - Glass tube with parallel walls (Ie. fixed sized orifice) → constant clearance around bobbin → thus, no stable position in tube that is unique to a particular flow rate

  - Accurate to +/- 2.5-5% → factors that can reduce accuracy:
    - (i) Different gas being measured from that used for calibration (as rotameter calibration is gas-specific)
    - (ii) Rotameter is not vertical → causes friction b/t bobbin and tube wall
    - (iii) Static electricity b/t bobbin and tube wall
    - (iv) Presence of dust or contaminant within tubing
    - (v) Incorrect bobbin and tube are used together
    - (vi) Bobbin is not freely rotating (Ie. due to contaminant)

  Aside: Difference b/t bobbin and ball flowmeters
  - (i) Flow read from middle of ball
  - (ii) Flow control is downstream from ball
  - (iii) Less accurate but more robust and portable → used in transport/wards (such as portable O_2 cylinders) rather than anaesthetic machines

- (b) Wright peak flowmeter
  - Air flow into apparatus via mouth piece → causes centrally-pivoted vane to rotate against a light spring → vane opens up sections of annular orifice and permit air to escape → final position of vane depends on flow rate → ratchet prevents return of vane when air flow ceases, allowing flow rate to be read from front dial
  - Issue – Underestimates flow rate cf. pneumotachograph

(3) Others:

- (a) Gas meter (Douglas bag, water displacement)
  - Sequential filling of internal chambers of known volume → # of times each chamber filled is recorded to determine gas volume → gas flow then determined by dividing gas volume over collection time
  - Issues – Cumbersome collection, and system has a large resistance
- (b) Hot-wire flowmeter
  - Gas flow through an electrically-heated Pt-wire alters its resistance → if current is held constant, then Δ wire resistance by gas flow results in a Δ voltage being proportional to gas flow rate
- (c) Fluidic flowmeter
  - Series of fixed vanes cause gas flow to swirl and spin a rotor in the gas path → optical sensor using IR light senses spinning rotor → calculates gas flow rate

(i) ***To explain the principles involved in the electronic monitoring of depth of sedation and anaesthesia, including the use of EEG analysis.***

Definitions:

- "Anaesthesia" is defined as a reversible state of drug-induced unconsciousness in which the patient neither perceives nor recalls noxious stimulation → unresponsive unconsciousness
- "Sedation" is defined as a drug-induced state of altered consciousness (includes reduction of anxiety, stress, irritability or excitement)

Monitoring depth of sedation and anaesthesia:

(1) Electroencephalography (EEG):
- Use – Confirm adequacy of cerebral oxygenation during cerebrovascular surgery
- Principle – EEG is a recording of electrical potentials generated by neurons in the cerebral cortex
- Technique:
    - A full 16 lead/8 channel EEG involves placing electrodes on the scalp according to the International 10-20 system → electrodes can be:
        - (i) Silver disks with conductive gel (most ideal)
        - (ii) ECG electrodes
        - (iii) Needle electrodes placed in scalp (traumatic and high impedance, but can be sterilised and used in surgical fields)
    - The potential differences between combination electrodes are filtered, amplified and displayed on oscilloscope
- Issues:
    - (i) Limited space to place equipment in OT
    - (ii) Difficult placement in surgical field
    - (iii) Problems with interpreting EEG – Difficult to read, generates large amount of data, data can be inaccurate (esp if previous brain injury, such as a CVA) and non-specific (Eg. ischaemic changes can be mimicked by hypothermia, electrolyte imbalance, hypocapnoea, anaesthetic agents) → thus, any change in EEG trend should prompt a more thorough review

(2) Bispectral index (BIS):
- Use – (i) Prevent awareness during anaesthesia, and (ii) Minimise the use of anaesthetic agents, as possible (thus, more cost-effective, fewer drug side-effects, and faster offset leading to earlier recovery and discharge)
- Principle:
    - A continuous and highly processed EEG that generates a numerical value that correlates with the patient's state of hypnosis → value is derived from over 30 EEG readings averaged every 2-5 seconds
    - Levels of hypnosis:
        - 100: Fully awake
        - 60-85: Light hypnosis/sedation (usually aware)
        - 40-60: Moderate to deep hypnosis associated with GA (no awareness)
        - 0: Isoelectric EEG
- Technique:
    - A specialised BIS electrode is attached to patient's forehead → measures influence of cortical EEG by neuronal activity of subcortical structures responsible for awareness
    - The "biocoherence" (Eg. harmonic and phase relationships) of EEG signals is assessed using Fourier transformation analysis to produce a numerical value correlating with the patient's state of hypnosis

    - This assessment is based upon regression analysis of the biocoherence signal of EEGs from thousands of subjects in various states of wakefulness, sedation and anaesthesia (Eg. EEG is low-amplitude, high-frequency when awake; EEG is high-amplitude, low-frequency when asleep or anaesthetised)
- Issues:
    - (i) High cost of machine/electrode
    - (ii) Patients can still be aware despite BIS < 65
    - (iii) BIS values can be inaccurate in the event of hypothermia, hypoxaemia or cerebral ischaemia
    - (iv) BIS is influenced by forehead muscle activity (Ie. if patient not paralysed)

(3) Entropy:
- Use – Similar to BIS
- Principle:
    - Entropy is the measure of "disorder" in a system (0 is completely ordered, and 1 is completely disordered)
    - Using this principle, the patient's level of hypnosis can be determined by (i) Measuring the level of disorder in the cortical EEG (Ie. highly disordered when awake; ordered when anaesthetised), and (ii) Detecting facial muscle activity
- Technique:
    - Electrodes are placed on the patient's temple and two measurements are made:
        - (1) State entropy (SE)
            - Calculated over frequency range 0.8 to 32 Hz
            - Similar to BIS, it analysis cortical EEG to reflect a *static level of hypnosis* provided by the anaesthetic agent
            - Generates a value 0 to 91 (< 60 suggests anaesthesia)
        - (2) Response entropy (RE)
            - Calculated over frequency range 0.8 Hz to 47 Hz
            - The electrode measures activation of facial muscle (using a Frontalis EMG) – Nb. Facial muscles are quite resistant to effects of muscle relaxants. Furthermore, eye movements and blinking detected by this EMG are rejected during analysis
            - RE has a faster response time than SE, and can thus provide an *early warning of arousal and emergence from anaesthesia*
            - Generates a value 0 to 100 (< 60 suggests anaesthesia)
    - The monitoring system normalises RE and SE such that they are equal when EMG power (sum of spectral power between 32-47 Hz) is equal to zero – During stable periods of anaesthesia, RE and SE are similar. However, RE rises suddenly when there is lightening of anaesthesia

(j) ***To describe the principles involved in ultrasound imaging in echocardiography.***

- See "Principles of Measurements" (To describe the basic physics of ultrasounds and the Doppler principle.)