By Adam Hollingworth

Monitoring

Respiratory Monitoring

Pulse Oximetry

- = non invasive way of measuring O_2 saturation (SpO_2) from a light signal transmitted through tissue, taking into account pulsatile nature of blood flow
- based on spectrophotometry

History

- until 1980's non invasive oximeters were large, cumbersome & expensive
- modern oximeters are smaller, less expensive, can differentiate absorption of incident light by pulsatile arterial component from static components
- ASA introduced requirements:
    - 1st Jan 1990 = intraop monitoring
    - 1st Jan 1992 = PACU

Physiology Revision

- adult blood contains 4 types of Hb:
    - HbO_2 = oxyHb
    - Hb = reduced Hb or deoxyHb
    - MetHb = Fe^{3+} - usually in v low conc
    - COHb = carboxyHv - usually in low conc - can be higher in smokers up to 5%

Functional O2 Saturation (SaO2)

- = ratio of HbO_2 to all functional Hbs (ie those which have reversible binding with O_2)

$$SaO_2 = \frac{HbO_2}{HbO_2 + Hb} \times 100\%$$

Fractional oxygen saturation (%HbO2)

- = ratio of HbO_2 to sum of all Hb species present ie whether available for reversible binding to o_2 or not

$$\%HbO_2 = \frac{HbO_2}{HbO_2+Hb+MetHb+COHb} \times 100\%$$

- for pts with low dysHb levels the difference between fractional & functional is small
    - ↳ ∴ if ↑dysHbs then pulse oximter is unlikely to agree with true value for either

O2 Transport

- Hb must load & unload O_2 at physiological tensions
- sigmoid OHDC dictates:
    - loading of O_2 in lungs = blood fully saturated over large range of tensions
    - unloading in periphery = large amount of O_2 released with only small drop in O_2 tension
        - ↳ ∴ maintaining driving gradient for ongoing unloading

Structure of Oximeter

- summary:
    - probe
    - electrical cable
    - black box
    - display

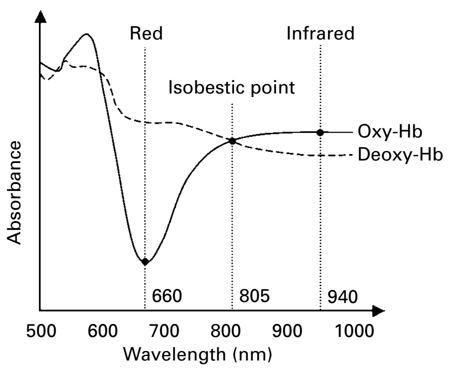
Probe

- = sensor in direct contact with pt
- contains
  - 2 (or more) LEDs that emit light at specific wavelengths
  - photodetector directly opposite
- enclosed in casing which excludes ambient light & keeps probe in contact with tissue
- LEDs give out monochromatic light at constant wavelength
- light is partially absorbed & modulated as passes through tissue ⟹ detector which converts light received into an electrical signal
- signal passed up to black box console

PhotoSpectrometry

- = measurement of quantity of radiation absorbed by a sample
- 2 laws used:
  - Beer's law = amount of light absorbed is proportional to the concentration of the absorbing substance
  - Lambert's law = amount of light absorbed is proportional to the length of the path light has to travel in the absorbing substance
- Pulse Oximeters measure pulsatile signals across perfused tissue at 2 discrete wavelengths:
  - 660nm (red light) = absorbed mostly by deoxyHb (why arterial looks looks red ie ↓absorption)
  - 940nm (infrared light) = absorbed mostly by HbO2
- isobestic point (805)
  - = point where absorbances for 2 forms of Hb (oxyHb & deoxyHb) are identical
  - = dependant only on the conc of Hb
  - of historical interest - used to be impt in calculation of old probes
- light:
  - is absorbed by all tissues ie arterial blood, venous, capillary, tissue beds
  - but oximeter distinguishes between absorption of light by pulsatile art blood compared to all other components by considering change in transmitted light caused by inflow of arterial blood
    - pulsatile expansion of arteriolar bed causes
      - ↑path length
      - ↑absorbance
    - transmitted light signal during diastole serves as baseline references
- oximeter pulses LED on/off:
  - both in turn and includes a time when both are off
  - frequency several hundred times/second
  - ∴ rapid sampling ⟹ precise recognition of times of peak & trough of each pulse wave (creating arterial pressure curve)
  - time when both lights off allows for correction for ambient light
  - data from several sequences averaged to calculate saturation

Haemoglobin absorption spectra



- calculates ratio of pulse added absorbances:

$$R = \frac{660}{940}$$

- calibration curves:
  - then used to determine saturation from the absorbance ratio
  - curves are based on experimental data from normal human subjects who voluntarily apnoiec
    ↳ ie lose accuracy with ↓ing Spo2
- info displayed on console:
  - SpO2 (p = ie from pulse oximeter)
  - pulse rate & rhythm
  - plethysmograph waveform
  - audible tone which changes in pitch with change in SpO2

Effects of Different Hb's

MetHb

- = iron in Fe3+ (ferric state) bound to Hb
- usually <1% total Hb
- = non functional Hb
- diagnosis confirmed with multiwavelength oximetry ie not detected by standard blood gas
- has same absorption coeffiecient in red (660nm) & infrared (940nm) wavelengths
- oximetry readings compared with:
  - functional saturation:
    - if sats >85% ⟹ will see false low value
    - if sats <70% ⟹ will see false high value
    - ↳ ie see a trend to 80-85% sats reading - which increased as MetHb level rises >40%
  - fractional saturation:
    - oximeter will give false high values

CarboxyHb

- has an absorption spectrum similar to HbO2
- ∴ oximeter will give false high level

Fetal Hb (HbF)

- does not affect accuracy of oximetry to clinically significant degree

HbS (sickle cel

- no sig effect

Hyperbilirubinaemia

- no effect on oximeter reading
- may cause elevation of MetHb + HbCO using in-vitro cooximetry

Anaemia

- pulse oximetry less accurate at low saturations

Applications

- monitoring oxygenation
- controlling O2 administration - norm SpO2 = 97-99% ie 100% ≈ hyperoxygenaemia
- monitoring circulation
- determining SBP - inflate cuff until waveform lost
- monitoring vascular volume:
  - hypovolaemic ≈ poor signal trace
  - variation in amplitude of pulse waveform during IPPV similar to 'swing on A line'

Advantages

- cheap
- accurate +/- 3% when SaO_2 >70%
- non invasive
- independent of anaesthetic circuit/vapours
- fast response - compared to transcutaneous oximetry
- easy to use
- fast start time
- tone modulation
- low failure rate <2%
- continuous real time monitoring

Limitations

- readings unreliable when lose periph pulses
- inaccurate with ↑ed venous pressure
- erratic performance with arrhythmias
- artifact:
  - ambient light,
  - low perfusion
  - motion
- interference from exogenous dyes:
  - methylene blue
  - indocyanine green - CO measurement
  - flurosceine
- nail polish - esp dark colours
- sensitive to elec interference
- lag times to detect hypoxic events - ↑ed in:
  - distal location of sensor
  - poor perfusion
  - venous obstruction
  - periph vasoC
  - cold
  - motion artifact
- false alarms:
  - motion artifact
  - poor signal quality
  - sensor displacement
  - electrocautery interference
- false high reading:
  - mal positionned sensor
  - HbCO
  - probe too large

Capnography

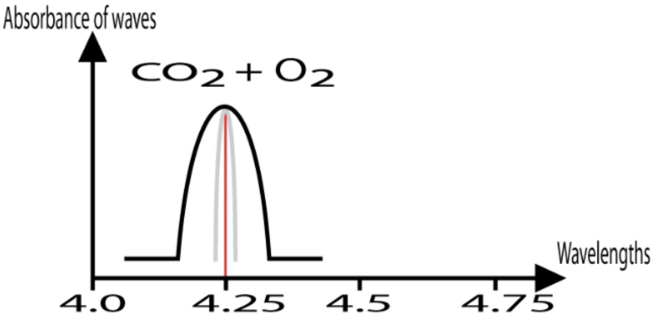
- = comprehensive measurement & display of CO_2 including:
  - end tidal CO_2
  - inspired Co2
  - CO_2 waveform (= capnograph)
- capnography depicts all components of resp:
  - metabolism
  - transport
  - ventilation
- capnometry = measurement and display of CO_2 in numeric form only

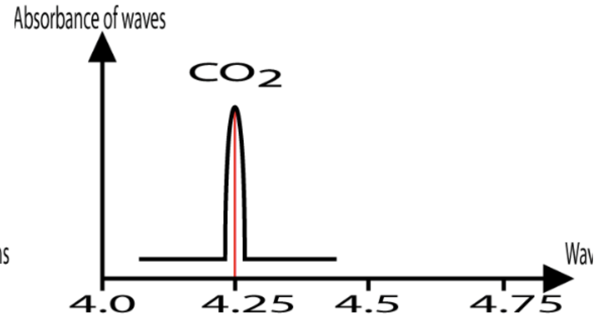
Mechanism

- different methods exist:
  - infrared - see below
  - Raman spectrography -
    - laser to shine light beam at CO_2 sample
    - the sample changes the wavelength of some of the beam of light
    - changes in wavelength used to measure CO_2
  - photo-acoustic spectrography:
    - CO_2 sample is bombarded with pulses of IR waves
    - ⟹ CO_2 sample rapidly expand & contract ⟹ sound waves
    - sensitive microphone picks up sound waves which vary according to amount of CO_2 present
  - mass spectrography:
    - = bulky device measures the charge:mass relationship of the measured substance
    - not common

Infrared Mechanism

- infrared mechanism - akin to measuring volatiles
- infrared can be used as CO_2 has 2 or more atoms
  ↳ unable to be used to measure O_2
- Beer Lambert Law applied: 'amount of infrared absorbed is proportional to the concentration of the infrared absorbing substance'
- beam of infra-red passed across gas sample to fall on sensor:
  - max absorption of CO_2 at 4.3um
    ↳ NO_2 = 3.9um; volatile 3.3um
  - presence of CO_2 ⟹ ↓light falling on sensor ⟹ change in voltage of circuit
- analysis is rapid and accurate
- collision broadening:
  - a source of error
  - occurs when unpure gases are passed through sampling chamber
    ↳ clinically = all gases as never will expire 100%CO_2
  - see a broadening of absorption wavelengths when trying to measure only CO_2
  - occurs when O_2 or N_2O combined with CO_2
  - simple explanation: other gas molecules collide with CO_2 molecules ⟹ alter way absorb IR waves ⟹ broader absorption pattern
    ↳ collision broadening:





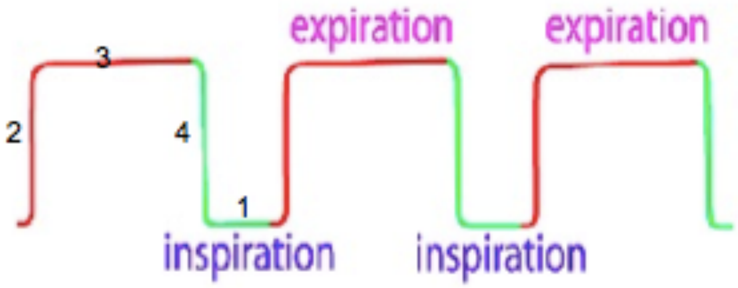
Types of Sampling

- named after position of infrared sampling device:
  - mainstream:
    - placed directly at airway
    - gases pass directly across IR light path
    - adv:
      - fast response time
      - no need for water trap
  - sidestream:
    - IR sensory located away from airway
    - ∴ needs continuous gas sample to be aspirated from breathing circuit
      ↳ long thin sample line & pump eg at 150ml/min
      ↳ sample line returns gas to anaesthetic circuit so not to waste volatile agent
- Response time = delay in sensing of CO2
- response time = transit time + rise time
  - transit time:
    - = time for CO2 to travel to sampling end
    - obviously only a problem in sidestream monitoring
    - can be minimised by:
      - short tube
      - narrow sampling tube
      - high suction flow rate
  - rise time:
    - = how quickly analyser able to respond to CO2 in analyser
    - = time takes for displayed value to rise from 10% to 90% max value
    - usually ~ 0.2seconds
    - can make rise time quicker by using smaller measuring chamber

Water Vapour

- need to remove otherwise will cause errors
- mainstream - electrically heat analyser to minimise condensation
- sidestream:
  - water vapour can condense in sample line
  - use water trap prior to entry into sample chamber

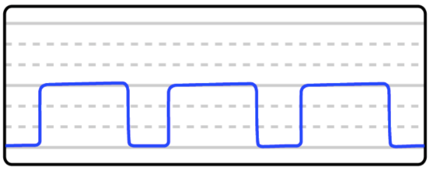
Phases of Capnograph



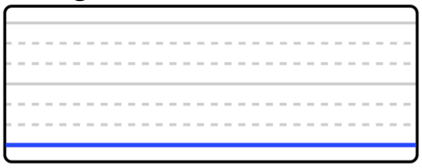
- notes:
    - early expiration - trace remains at baseline - as no CO2 in resp deadspace
    - rapid upstroke: = transition from dead space gas to alveolar gas
    - plateau - ongoing expiration
    - downstroke = inspiration: start of inspiration of O2. represents washing out of CO2 from sample chamber
    - trough = ongoing inspiration
    - x axis defines length of phases:
    - I:E ratio usually 1:2

Sample Waveforms

normal:

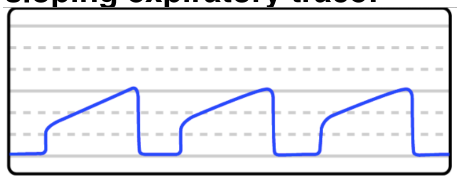


straight line:



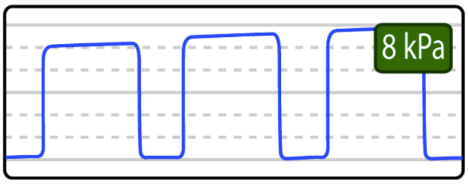
- causes:
    - equipment failure - should have checked preop!
    - complete obstruction of lungs - severe bronchospasm
    - complete obstruction of airway eg tracheal tube obstruction
    - complete obstruction of sample tubing
    - resp arrest
    - cardiac arrest - no CO2 being delivered to lungs
    - oesophageal intubation - although often initially see some ETCO2

sloping expiratory trace:



- causes:
    - partial obstruction of lungs eg brochospasm, COPD
    - partial obstruction of airway eg tracheal tube secretions, kinking

high exp tracing:

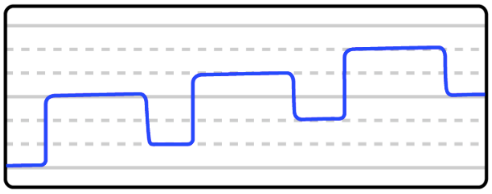


- causes:
  - inadequate ventilation - lung has to ‘pack’ more CO_2 into each breath
  - $\uparrow$ed CO_2 production:
    - MH

low exp trace:

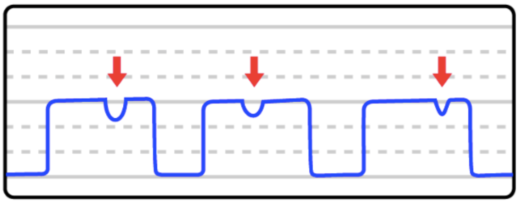
- causes:
  - hyperventilation

re-breathing:



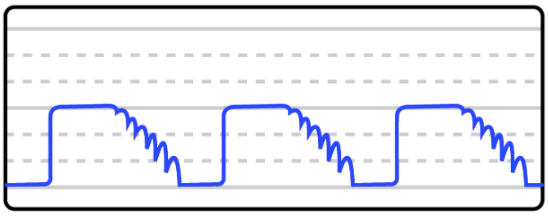
- causes:
  - failing CO_2 scrubbing

relaxant notches:

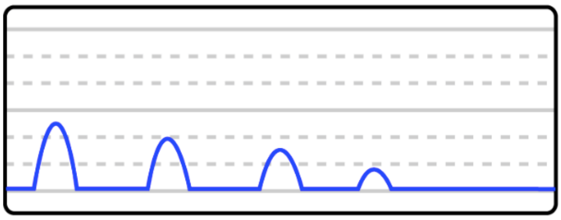


- aka curare cleft
- causes:
  - mm relaxants wearing off $\Longrightarrow$ diaphragm spont active during expiration
  - surgeons pushing on diaphragm/chest wall

cardiac notches:



oesophageal intubation:



- dont be fooled by initial CO_2!!

CVS Monitoring

Blood Pressure

- = surrogate index of tissue perfusion
- = one of primary determinants of brain & coronary blood flow ∴ DO2
- relatively easy to measure

Measurement

- non invasive:
    - occlusive:
        - Riva-Rocci bp cuff
        - DINAMAP
    - non occlusive:
        - Penaz
        - arterial tonometry
- invasive

Non Invasive Measurement

Occlusive

- A cuff (Riva-Rocci type) is used to occlude the pulse
    - width should any of:
        - 40% of arm circumference
        - 40% of arm length
        - 20% of upper arm length
- diff ways to then detect the return of the pulse or blood flow:
    - palpation - finger or finger photoplethysmograph
    - auscultation -
        - audible range - Korotkoff sounds
        - ultrasound range (5Mhz) eg arterisonde
        - subaudible range (10-40MHz) eg infrasonde
    - oscillometry -
        - von Recklinghausen's oscillotonometer
        - DINAMAP
- korotkoff sounds:
    - originally:
        - systolic (1st sound) = point where 1st pulse sounds returned
        - 2nd sounds = murmurs between systolic & diastolic
        - 4th = thumping & muting 10mmHg above diastolic
        - 5th (diastolic) = point where disappearance of sounds
    - AHA modified it = point where muffling of sounds occurs
- causes of errors in bp measurement:
    - incorrect cuff size ie too small ⟹ false ↑bp
    - mal position of cuff - ie middle of bladder should be over artery
    - improper calibration of aneroid manometer
    - other:
        - deflating cuff too fast ie ⟹ false ↓bp
            ↳ deflate at 2mmHg/sec
        - variability in hearing sounds
        - placement of stethoscope

DINAMAP

- = Device for Indirect Non-invasive Automatic Mean Arterial Pressure measurement
- uses oscillometry to determine:
    - systolic
    - diastolic
    - mean pressures
    - HR

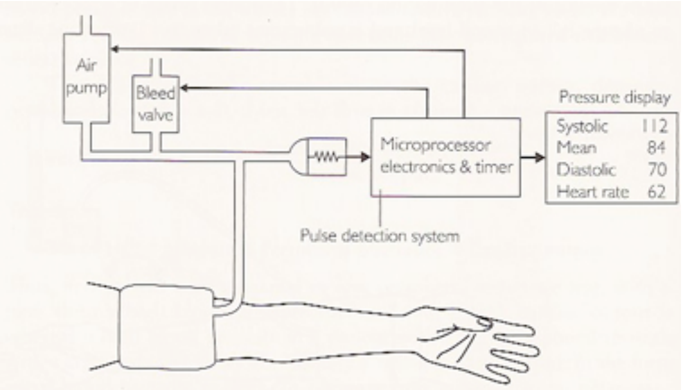


Figure 17.4 Principle of automatic blood pressure measurement

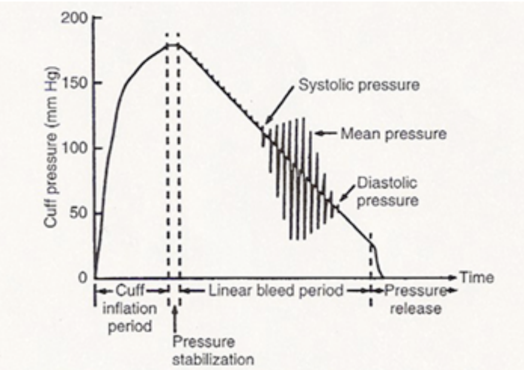
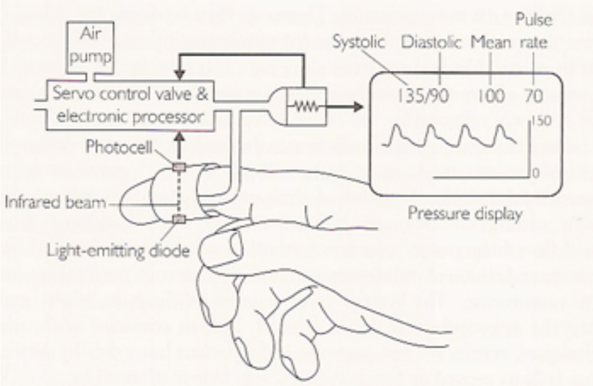


Figure 30–15 Noninvasive blood pressure measurement. Using the signal from the arterial pulse, oscillometric blood pressure measurements are obtained by determining the point at which the signal is first detected, its maximal amplitude, and the signal decay rate.[8] (Adapted from Ehrenwerth J, Eisenkraft J: Anesthesia Equipment: Principles and Applications. St Louis, Mosby–Year Book, 1993.)

- only uses one cuff which = occluding & sensing cuff
    - ↳ von Recklinhausen's system had 2 cuffs
- cuff inflation system is adaptive = each time will inflate to 50mmHg above last systolic bp
- MAP equal to either:
    - point of max oscillations OR
    - electronic averaging - line drawn through mean point of bp pressure wave which divides curve area above & below equally
- adv:
    - cuff application is not critical
    - non sensitive to diathermy
- disadv:
    - sensitive to motion artefact ie processor must have good noise cancelling capability
    - MAP is most accurate figure. DBP least accurate

Non Occlusive

Penaz method



Penaz technique for the continuous measurement of blood pressure

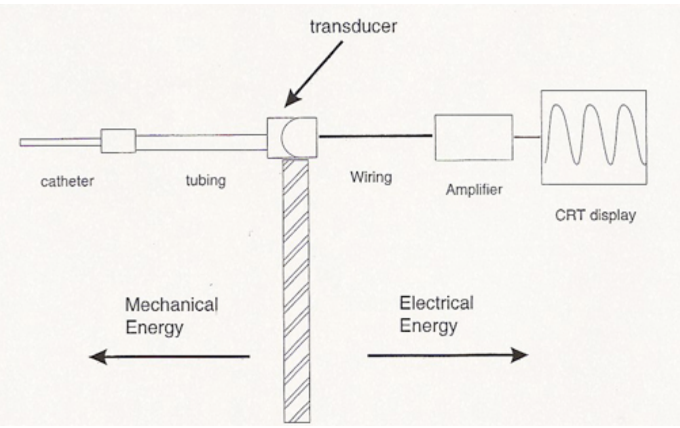
- gives continuous measurement of finger bp
- method:
  - cuff :
    - placed around finger + attached to transducer to measure bp
    - air pump with servo control valve
    ↳ similar to electronic oscillometric technique
    ↳mean bp = point of max oscillation
  - infrared LED + photocell at cuff which acts as photoplethysmograph
  ↳ ∴ cuff and photoplethysmograph system together work to:
    - servo mechanism continuously inflate & deflate cuff to maintain photopleth output around a set point according to MAP
    - ⟹ continuous tracing of arterial pressure
    - some perfusion of finger still occurs despite continuous inflation of cuff

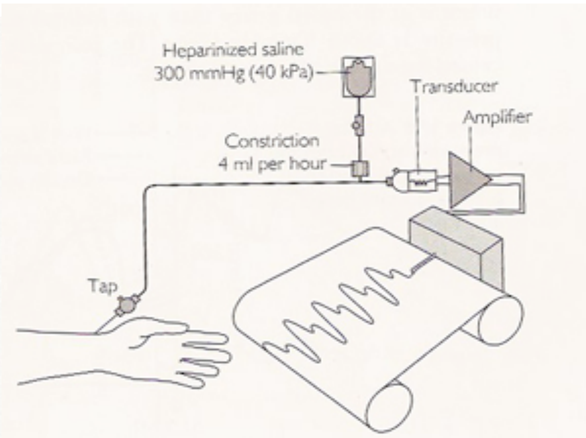
Arterial Tonometry
- uses a plethysomographic method on the eg finger
- measures periph arterial tone
- this can be correlated to peripheral blood pressure

Invasive BP Monitoring
- methods include:
  - arterial line
  - central venous catheters
  - pulmonary artery catheters
- advantages of invasive:
  - continuous/realtime information
  - trends are more obvious
  - sustained accuracy over whole of bp range ie very highs & very lows
  - visual analysis of pressure wave yields additional information

Arterial Lines
- indications:
  - failure of oscillometry eg
    - CPB,
    - AF
    - obese arm
  - critical perfusion eg

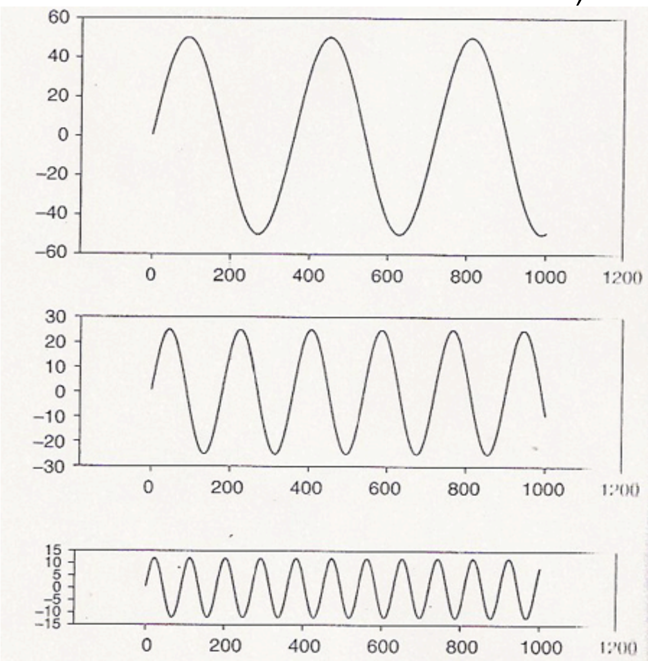
    - critical CVS disease
    - use of vasoactive drugs
  - frequent sampling:
    - ABGs
    - expected large blood loss
- complications:
  - haematoma
  - arterial damage - do an Allens test 1st :
    - elevate hand, make a fist for 30sec;
    - occlude ulna & radial arteries ⟹ release hand - should look pale
    - release ulnar pressure - norm = return of colour in 7 secs
      ↳ if >7 secs ?patency of ulnar artery ∴ avoid radial art
  - infection
  - thrombosis - 20-30%
  - pain
  - embolisation - clots, bubbles, catheter fragments
- generally use radial artery:
  - ulnar artery = predominant blood supply to hand (deep & superficial palmar arches
  - radial = usually only supplies deep
  ↳ do Allens test to assess risk
- Components:
  - Cannula - standard cannula to special A-line catheters
  - IV tubing - providec mechanical coupling. need 3 way tap
    - errors: bubbles ,kinking, blood clots, excessive length
  - transducer - a strain gauge with wheatstone bridge
    - errors from bubble, dome, drift, alinearity
  - electric cable
  - black box amplifier
    - erros: erros of frequency response
  - display





Physical Principles
- mean pressure = easy to measure accurately
- phasic pressure changes = difficult to measure accurately esp rapid changes
- intra-arterial pressure wave has a basic periodicity which is equal to the heart rate
- basic or fundamental frequency (f) = first harmonic:
  - HR 60/min ⟹ f = 1Hz ie 1/sec
  - HR 120 ⟹ f = 2Hz
- analysis of frequency components which make up the complex wave:
  - allow reproduction of shape of pressure wave

- fourier analysis is used =
  - complex wave reduced to number of sine and cosine waves of diff frequencies
  - add these together ⟹ complete wavw
- in A waves - can reduce to sine/cosine waves of frequencies equal to 1xf - 10xf (ie up to tenth harmonic or 10Hz for HR of 60/min)



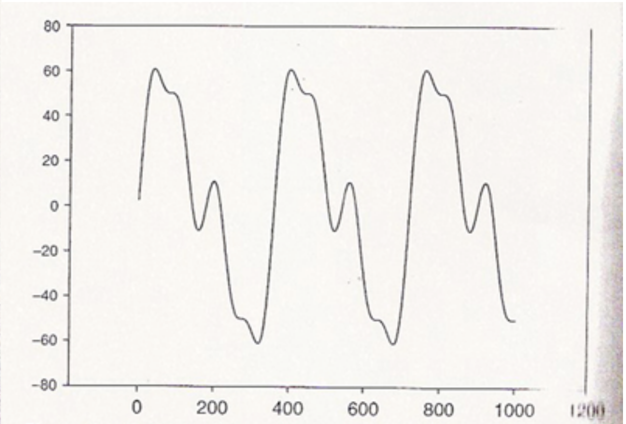


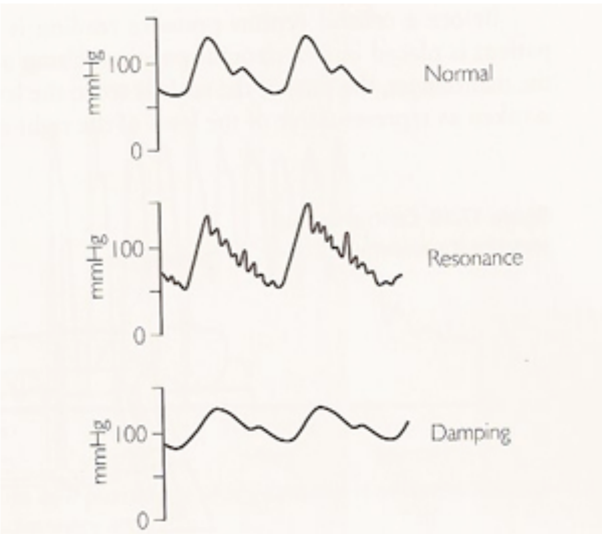
Figure 30–6 Fourier series. This pseudoarterial waveform was generated by adding the three sine waves with the following characteristics: y = 50 sin x, y = 25 sin 2x, y = 12 sin 4x.

- to create correct shape (pressure & time) frequency range of component sine waves (up to 10th harmonic) is relayed from artery to display unit preserving:
  - amplitude of each component wave
  - temporal relationship of various waves - need to be added up correctly to form original wave

  ↳ ∴ need frequency range of 1-10Hz recorded, transmitted, displayed with none of:
    - amplitude distortion
    - phase distortion - phase lag = tendancy of high frequency components to travel more quickly than low freq components
- resonance & damping cause errors in amplitude & phase distortion
- errors lead to ↓ed:
  - dynamic accuracy (most)= correct peaks & troughs ∴ representing accurate systolic & diastolic pressures
  - static accuracy (least) = represents MAP. less error
- resonance =
  - process whereby amplitude amplification occurs when frequency of oscillating signal approaches the natural resonant frequency of measuring system (*fo*)
  - natural resonant frequency =
    - feature of all systems oscillating in simple harmonic motion when disturbed
    - as applied frequency (measured) is ↑ed ⟹ amplitude ↑s to maximal at the *fo* of measuring system
    - ∴ ideally to prevent error:
      - *fo* should be as high as possible so that it is beyond the measured frequency range
      - this means f0 >100Hz to keep measured frequencies linear
      - but is impossible to achieve in practise for catheter/transducer system
      - when f0 is too low ⟹ higher frequencies of signal get amplified

        ↳ = upstroke phase ⟹ overshoot of wave ⟹ false high SBP
    - strategies to ↑ f0:

        - short, wide bore cannula
        - shortest, widest possible manometer tubing
        - diaphragm of transducer is as stiff as possible
        - no compression or expansion components in system eg bubbles
- Damping:
    - = force due to inertia & frictional resistance within an oscillating system which has a tendancy to decrease movement within system ie a brake
        ↳ another definition = any effect that tends to reduce the amplitude of oscillations of an oscillatory system
    - extremes of damping:
        - critical or excessive =
            - ↓s ability to record rapid oscillations ie takes to long to reach target that mean miss oscillation
            - would eventually record perfect amplitude (if that variable is constant)
        - under-damped = effects of resonance are obvious & target amplitude is overshot
        - optimal damping =
            - 64% and is best compromise of extremes
            - still see <5% overshoot but is accepted
            - general rule is must be >5th harmonic
    - generally in fluid filled systems: damping cannot be adjusted and results in ~70% of fully damped



Optimal damping

Underdamped

Over-damped

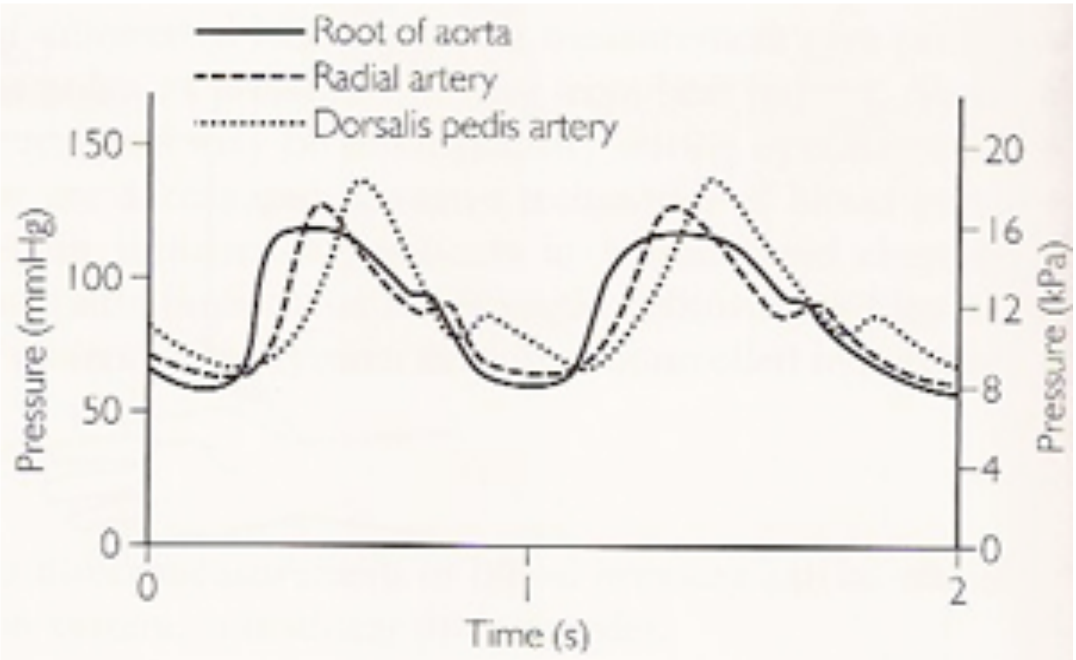
- dynamic accuracy of recording system= interaction between natural resonant frequency (f0) & damping coefficient
    - to achieve best dynamic accuracy::
        - damping cannot be adjusted ∴ aim for high as possible resonant frequency (f0)
        - undamped system = need ~100Hz
        - damped system (70%) = only need f0 ~ 30Hz
        ↳ to achieve linearity without distortion up to 20Hz (10th harmonic for 120/min pulse rate)
        - f0 = 30Hz is possible to achieve (than 100Hz) if no error source (bubble, stiff diaphragm, short wide cannula)

Summary

- static accuracy
    - = ability of system to measure stationary or extremely slowly varying events
    - ie:
        - no baseline or sensitivity drift regardless of time or temp

- linearity between input/output voltage over physiological range & no hysteresis
  - v impt for accurate MAP
  - easy to achieve by carefully zero system & height of transducer
- dynamic accuracy:
  - = ability of system to faithfully record changing events & is governed by dynamic response to amplitude & phase
  - dynamic accuracy is determined by interaction between resonant frequency & damping coefficient
  - better dynamic accuracy ⟹ more faithful representation of SBP & DBP & wave shape
    ↳ NB MAP remains accurate as dependant on static calibration
  - = hardest criteria to attain
- physiological reactance =
  - ie measuring system should have no effect on the event being recorded
  - v diff to achieve in practise due to eg catheter impeding blood flow in the vessel

Variation of A line Contour trace in Arterial Tree

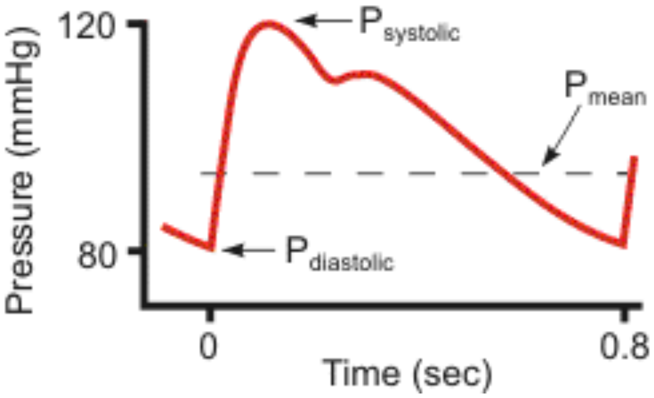


- Comparing radial vs aortic curve:
  - Delayed:
    - due to time taken to travel down the arterial tree.
      - Faster if low compliance, eg elderly, atherosclerotic disease
  - Distorted shape: due to
    - reflection
    - resonance
    - damping
    - different conduction speeds of the different pressure components
      ↳ high pressure components travel faster.
  - Taller: due to lower compliance, ⟹ resulting in higher systolic P
  - Narrower at its peak: due to higher velocity of the higher pressure peak.
  - Diastolic hump instead of an incisura:
    - loss of incisura due to damping of high pressure components
    - Resonance and reflection in the arterial tree causes the diastolic hump

    - slight drop in MAP - radial MAP 5% lower than aoritc
    - diastolic pressure tends to ↓ towards periphery
    - ↑pulse pressure towards periphery - radial pulse pressure 40% higher than aorta

- In elderly radial trace will look less different to aortic: = due to lower vascular compliance which causes the pressure wave to travel faster and be less distorted.
- Changes to **<u>Aortic</u>** contour with ageing:
    - slower upstroke (decreased contractility)
    - Higher peak due to lower aortic compliance

Information which can be obtained from A Line Trace



- myocardial contractility = The slope of the upstroke (dp/dt) ie steep upstroke = strong LV
- Stroke volume:
    - by measuring the area from start of upstroke up to incisura
    - (if multiply SV with HR, an estimate of CO can be derived)
- SVR = The slope of downstroke
    - steeper the slope= the faster the arterial run-off (ie low SVR)
    - Position of incisura/dicrotic notch (diastolic hump in peripheral artery) on the down slope:
        - Sitting high up = high SVR vs
        - sitting low down = low SVR
- haemodynamic significance of arrhythmias - bp & pulse contour following abnormal beats indicate degree of impairment of cardiac pumping
- index of myocardial demand (tension time index, TTI) = Area under systolic part
- index of O2 supply to heart (diastolic P time index, DPTI) = Area under diastolic part
    - ∴ Endocardial viability ratio (EVR) = DPTI / TTI
    - high ratio = ↑ed O2 supply to heart
- Vascular volume status (preload):
    - In ventilated pts see “arterial swing” (change in systolic peaks):
        - during single cycle of +ve pressure vent ⟹
            - inspiration: 1st +/- 2nd beat see ↑ SV **then** following beats see ↓SV
              ↳ due to superadded ↑ITP & mobilisation of central blood
            - expiration: ↑ing SV due to ↓ITP allowing ↑preload
        - during spont vent: see complete opposite
    - **delta down** = ↓SV in inspiration during +ve pressure vent
        - rate of decline during inspiration can be calculated by software averaging.
        - = a good indicator of LV preload: better than PCWP
    - delta up = ↑SV in expiration during +ve pressure vent
        - gives an indication of afterload
          ↳ although less accurate than what delta down is for preload

- Pressure:
  - Systolic,
  - diastolic,
  - MAP - calculated by
    - integrating pressure signal over pulse duration.
    - MAP = integral divided by time
- High peak (high systolic) may be due to low arterial compliance.
- Rate, rhythm

(A succinct summery can be found in Miller's Anesthesia under "Systolic Pressure Variation")

Cardiac Output Monitoring

- methods:
  - non invasive:
    - clinical - finger on pulse
    - ultrasound
    - NiCO
    - transthoracic impedance
    - arterial pulse contour analysis
  - invasive:
    - fick priniciple
    - dilutional methods - dye & temperature
    - angiography/cardiac catheterisation
    - electromagnetic flow measurement
    - MRI

Non invasive

Clinical

- eg feel pulse, cap return, UO, LOC etc
- often overlooked in exams as very basic but instinctive in theatre
- finger on pulse:
  - principle is compliance ie change volume/change in pressure
  - are actually feeling a change in pressure not volume:
    - change in pressure = change in volume (or CO) / compliance
    - can assume compliance is constant for that pt ∴ change pressure ~ change in volume

↳ but eg elderly who has ↓ed arterial compliance ⟹ ↑change in pressure for given change in volume ie will over-estimate CO!

- advs:
  - non invasive
  - costs nothing
  - rapid
- disadv:
  - very crude
  - depends on arterial compliance ie when feeling pulses

Ultrasound

- TTE: use to estimate LVEF
- TOE with doppler:
  - align probe down long axis of ascending aorta
  - can measure velocity of column of blood expelled from heart using doppler
  - if also measure cross sectional area of a. aorta ⟹

  - velocity (m/s) x cross sectional area (m^2) = CO (m^3/s)
  - then averaged out over a period of time ⟹ average CO
- can also be down with aortovelography = probe in suprasternal notch directed towards cardiac outflow tract

NiCO (Non invasive Cardiac Output measurement)

- essentially applying Fick prinicple to measure CO
- it uses CO2 substance produced instead of O2 consumed

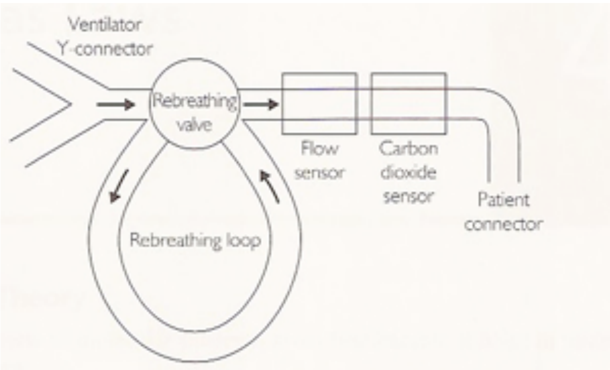
$CO = V_{CO2} / Cv_{CO2} - Ca_{CO2}$

V_{CO2} = rate of CO2 elimination,
Cv_{CO2} = mixed venous concentration of CO2,
Ca_{CO2} = arterial CO2 concentration

- has been shown that mixed venous CO2 does not change significantly throughout a 50sec breathing period:

$CO = V_r - V_n / a_n - a_r$

Vr = mixed venous CO2 in rebreath circuit
Vn = mixed venous CO2 in normal breathing
an & ar = arterial CO2 conc in normal & rebreath circuit



Principle of a noninvasive cardiac output measurement technique

- every 3mins the pts inspired & expired gases are automatically diverted through rebreating loop for 50sec period
- at any time VCO2 (elim of CO2) = expiratory flow x fraction of CO2 present in this flow
- VCO2 product is averaged over breathing cycle
- endtidal CO2 is used to estimate arterial CO2 (ie accurate only if minimal alveolar dead space)
- applying Fick principle as above:
  - CO acquired represents flow that participates in gas exchange
  - ∴ need method to adjust for shunt flow:
    - take FiO2 in equipment and compare it to expected O2 sat with measured O2 sats via pulse oximetry

Transthoracic impedance

- can measure across externally applied electrodes
- impedance changes with the cardiac cycle via changes in blood volume
- rate of change of impedance = reflection of CO
- useful in estimating changes but not for absolute measurements

Pulse Contour Analysis

- not strictly non-invasive as it is commonly combined with transpulmonary thermodilution
- = an indirect method as CO is computed from a pressure pulsation based on modelling
- origin of method is based on Windkessel model as described by Otto Frank in 1899:
  - Windkessel Effect:
    - distension of aorta when blood is ejected from LV
    - aorta recoils & smooths out pressure & blood flow

- this helps perfuse coronary arteries by pushing blood back to coronary art openings

- model related an arterial pressure or pressure difference to a flow or volume change
- commercially available systems =
    - PiCCO - calibrated by transpulmonary thermodilution
    - PulseCO - calibrated by transpulmonary lithium dilution
    - Modelflow - calibrated by averaged conventional thermodilution

↳ calculate pulse contour beat to beat but present data in 30sec windows

Invasive Methods

Fick principle

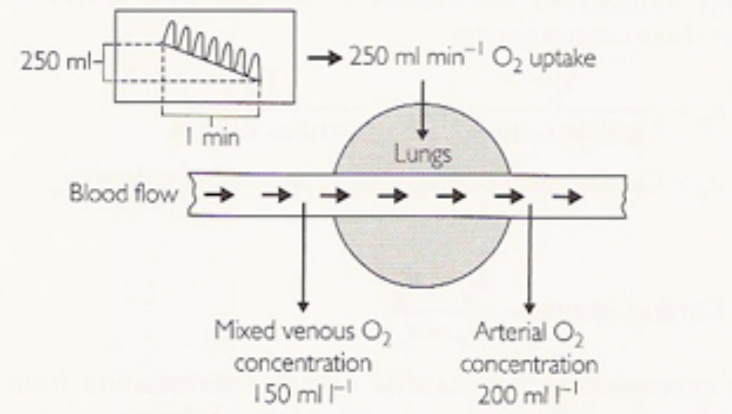
- = gold standard
- = rate at which a substance is removed or taken up is equal to blood flow to the organ, multiplied by the difference between arterial & venous concentrations to & from that organ

Ie : $Vx = Q(c_{ax} - c_{vx})$

Vx = rate substance x is added or removed from blood,
Q = flow to the organ,
c_{ax} = arterial content of x, and c_{vx} the venous content

thus; $Q = Vx / (c_{ax} - c_{vx})$

- gold standard for CO measurement =
    - calculating total pulmonary blood flow by measuring the uptake of O2 in lungs
    - pulmonary flow = CO - shunt flow



Fick principle

- pt rebreathes O2 into a Benedict Roth spirometer through a soda lime absorber
- rate of O2 uptake (VO2) is determined
- catheter is placed in RA or pulmon artery ⟹ obtain mixed venous blood for analysing oxygen content
- arterial o2 content is measured from any arterial sample
- disadv:
    - invasive - PA catheter
    - time consuming

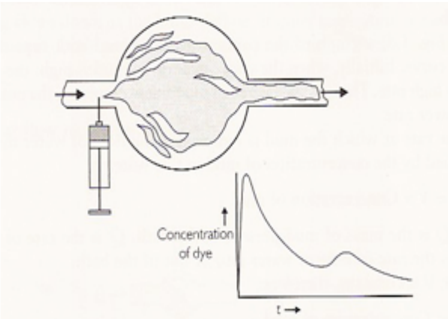
Dilutional Methods (wash out)

Dye Method

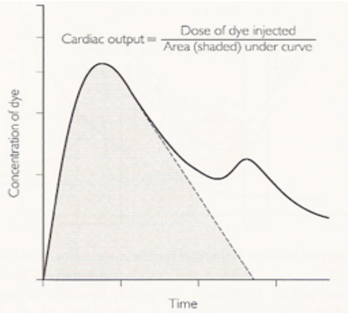
- principle = conservation of mass
- CO determined by means of wash out curves for a given indicator injected into heart eg indocyanine green
- method:
    - known amount (m) of dye injected into R heart

- chambers initial high conc (c) of dye is washed out exponentially by new blood entering
- higher CO = faster washout of dye
- conc of dye is plotted against time ⟹ washout curve
- cardiac output = amount of dye injected / area under curve x time
    - ↳ calculus equation Stewart-Hamilton equation = complicated!

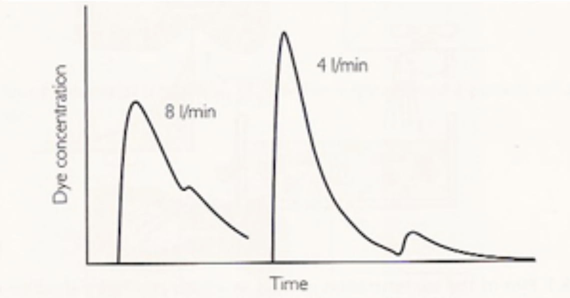
- ∴ smaller AUC = higher CO



Use of a washout curve to measure cardiac output



Plot of a washout curve on semilogarithmic graph paper

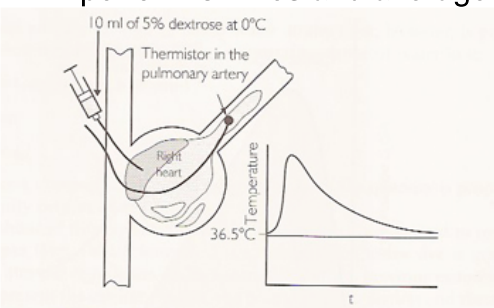


Washout curves for a high (left) and low (right) cardiac output

- hump on the curve = dye returning back to heart = recirculation hump
- is adjusted for on semi-log paper ⟹ straight interrupted line making downslope straight
- disadv:
    - invasive - need PA catheter
    - time consuming
    - recirculation hump
    - intracardiac shunts/TR

Thermal Dilution

- same principle as dye washout but amount of heat (or cold) is used instead of dye
- dilution is then reflected by change in temp:
    - temp = concentration
    - amount of heat (cold) = amount of dye
- method:
    - PA catheter with 2 channels inserted into R heart
    - injection end placed at junction of SVC & RA
    - other end has thermistor and guided into PA
    - 10ml of cold 5% fluid at close to 0 deg injected in
    - change in temp of blood leaving RV measured by thermister in PAC
    - plot temp vs time ⟹ washout curve ie cooled blood exponentially warmer towards norm
    - perform 3 times and average out



Thermal dilution technique for the measurement of cardiac output

- temp scale is inverted ie colder up: for easy comparison to dye technique
- adv:
    - recirculation is less evident
    - repeat measurements can be done

- averaged measurement makes it more accurate
- disadv:
    - intracardiac shunts/TR
    - measured injected volume or temp is inaccurate
    - speed of injection varies
    - thermistor is against a vessel wall

Angiography/Cardiac Catheterisation
- invasive but allows estimation of LV volume as well as ejection fraction
- similar can be achieved with radioisotope scanning

Electromagnetic flow measurement
- probe is placed around root of aorta
- obviously limits its use to open thoracic/cardiac surgery

MRI
- velocity encoded phase contrast MRI
- detects changes in phase of proton precession

↳ this proportional to velocity of movement of protons through a magnetic field with known gradient
- result is 2 sets of images for each time point in cardiac cycle:
    - 1 anatomical - to measure cross sectional area of vessel
    - 1 velocity encoded

  ↳ then multiply them together to get flow
- flow can be plotted against time
- AUC for 1 cardiac cycle = stroke volume
- length of cardiac cycle ie HR is known ∴ CO = SV x HR
- disadv:
    - only used as part of clinical cardiac MRI examinations
    - unable to use in emerg/ICU setting
- adv: less variable than fick & thermodilution!

Depth Of Anaesthesia Monitoring

Awareness

- explicit =
  - conscious recall of events during GA
  - extreme = awake but paralysed
  - other examples:
    - auditory (most common)
    - feeling the surgery but without pain
    - pain
    - intubation
    - panic
- implicit =
  - no conscious recall but information retained in memory
  - may display symptoms of PTSD ie dreams, insomnia, flashbacks, anxiety

Incidence

- varies by surg:
  - general surgery = 0.2% (if relaxant used) vs 0.1% with no relaxant
  - C section = 0.4%
  - cardiac surgery 1.15-1.5%
  - major trauma surgery: 10-40%
- insurance claims from USA suggest:
  - F:M 4:1
  - <60yrs = 90%
  - ASA1-2 = 70%

Causes

- pharmacologic:
  - very low volatile
  - N2O/narcotic + relaxant used
- technique:
  - induction:
    - too little IV induction agent
    - no premed
    - prolonged intubation
    - RSI
    - drug error
    - dilution of volatile based on flows
  - maintenance:
    - deliberate - major trauma, ASA4/5, obstetrics
    - inadvertent -
      - machine errors - empty volatile, inaccurate flow meter, disconnection & spont vent
      - TIVA
      - inappropriate use of MRs
    - emergence - terminating anaesthetic too soon
- patient:
  - interindividual variability
  - highly anxious pt
  - chronic substance abuse

Prevention Strategies

- vigilance
- meticulous equip check
- amnesic premed
- generous induction dose
- avoid paralysis unless completely required
- add amnesic when used light anaesthetic (trauma, ASA3-5)
- check anaesthetic delivery - vaporiser, analyser, TIVA
- monitors for awareness detection - BIS
  ↳ although no proof that these prevent awareness

Depth of Anaesthesia Monitoring

- performed by either:
  - clinical
  - monitors
  - measuring:
    - end tidal volume conc
    - TCI effect site conc

Clinical

- signs & symptoms of light anaesthesia ≈ signs of ↑SNS activity
  ↳ lacrimation, ↑HR, ↑bp, sweating, dilated pupils, movmt
- ∴ if see movement then deepen (don't paralyse!)
- gold standard for awareness detection = isolated forearm technique:
  - tourniquet inflated on upper arm > systolic
  - THEN give mm relaxant in diff arm
  - look for arm movement (spont or to command) during surgery

Monitors

- primarily anaesthetist is the monitor
- machines are only aids!
- machines:
  - EEG:
    - conventional EEG - big, bulk & diff to interpret with poor correlation between diff anaesthetic agents
    - cerebral function monitor - user friendly but less data than raw EEG
    - power spectral analysis (PSA) - processed EEG displayed in easy to interpret fashion
      ↳ BIS = derivation of PSA
  - evoked potentials -
    - more physiological than BIS
    - similar effects with diff anaesthetic agents
    - auditory evoked potentials (AEPs) are most commonly used
  - oesophageal contractility - effected by smooth mm relaxants & ganglion blockers + diseases eg achalasia
  - EMG:
    - esp of frontalis mm
    - requires concurrent separate monitoring of periph NMJ blockade

Anaesthesia Effect on EEG

(see CNS physiology)

- as anaesthetic deepens ⟹ ↓frequency & ↑amplitude of EEG
- @very deep levels ⟹ burst suppression
  ↳ = burst of electrical activity, then period of v little activity

Processed EEG Monitoring Devices

- there is specific ranges of frequency & amplitude which are impt under anaesthesia
- general idea is to:
  - filters: remove artefact & unwanted frequencies (>20Hz removed)
  - amplifiers: accentuate waves of interest (waves 4-10Hz amplified)
- 2 basic forms of EEG processing:
  - power analysis (PA)
  - bispectral analysis (BA)

Power Analysis

- uses fourier transformation to convert raw EEG into component sine waves of a specific frequency & amplitude
- raw EEG = plot of amplitude / time
- power analysis ⟹ plot amplitude of EEG activity at each frequency at given point in time
- power = amplitude squared ie as a function of frequency
- machine then display data in 2 general forms:
  - compressed spectral array (CSA):
    - x axis = frequency; y axis = power (height of waveform = power at that frequency)
    - z axis = time
  - density spectral array (DSA):
    - x axis = frequency; y axis = time; power is reflected by density of dot at each frequency
- display format provides same data in diff format - user preference
- changes in anaesthesia are reflected by change in amplitude & frequency ∴ easily seen if monitoring right channels
- PA used to detect cerebral ischaemia in risk procedures eg cerebral ischaemia/CPB
- not that widespread as routine depth of anaesthetic monitor

Bispectral Analysis aka coherence

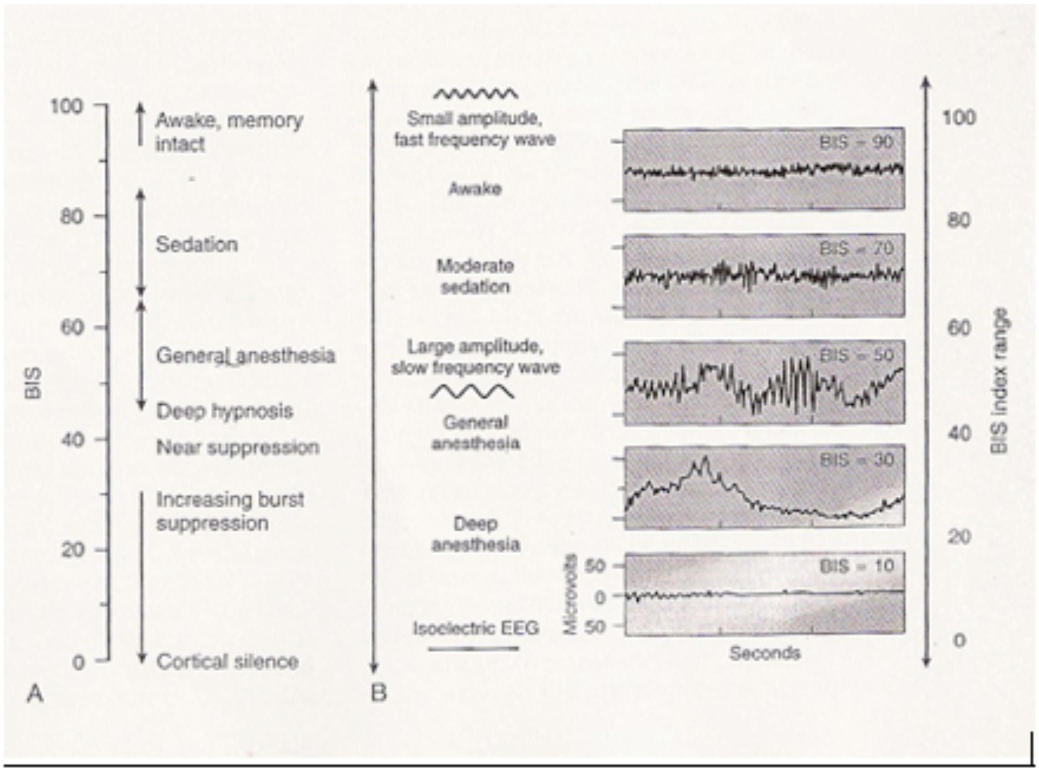
- in addition to PA this also takes account of phase relationships between the individual components of the raw EEG signal
- primary use as monitor of depth anaesthesia
- but diff anaesthetic drugs ⟹ diff EEG patterns
- other factors may also influence EEG:
  - hypoxaemia
  - hypothermia
  - hypotension
  - hypercarbia

Bispectral index (BIS)

- = proprietary processed parameter derived from multiple features generated by bispectral analysis of EEG
- since 1987:
  - used clinical trials to identify features of BA which were predictive of response to stimuli
  - identified response to stimuli under diff anaesthetic agents
  - features combined to form a multivariate index using discriminant analysis
- technical process:
  - EEG processing to remove:
    - high & low frequency artefacts
    - ECG signals

    - pacemaker spikes
    - eye blinks
    - wandering baseline
    - alternating current interference
  - EEG data then analysed by 3 diff approaches:
    - Power analysis -
      - includes fourier analysis of amplitude/power/frequency
    - Bispectral analysis (coherence)
      - in phase = ↑ingly asleep
    - time domain analysis - characterise burst suppression + isoelectricity
- BIS algorithm:
  - takes 3 approaches as above and applies unknown weighting to them
  - used to determine final calculation of BIS value = 0-100
  - multivariate statistical analysis on EEG relative to clinical database gathered from studies (mentioned above)
- BIS number ∴ =
  - complex & dimensionless parameter
  - number generated which can be trended overtime
  - further trials to refine algorithm & determine BIS values which predict:
    - loss of consciousness
    - loss of recall
    - prevention of movmt to surg stimuli
- BIS value has been proven:
  - successfully predict loss of consciousness & recall with different agents
    ↳ **except NO & ketamine** - poorly represented by BIS
  - NOT to predict haemodynamic response or movement to surgical stimuli

Interpretation of BIS



Entropy Monitoring
- another proprietary monitoring system akin to BIS (uses similar forehead probe)
- principle is irregularity within EEG signal ↓s with ↑ing level of anaesthetic drugs
  ↳ ie ↑ing coherence ~ ↑ing unconsciousness
- if irregularity of EEG is related to the entropy within the signal ⟹ assign entropy scale
- monitors produce 2 numbers:
  - RE = response entropy
    - incorporates higher frequencies which include EMG activity
    - gives a faster response than SE number
  - SE = state entropy
- also fail to measure effect of NO & ketamine

Problems with Monitoring Devices
- patient factors:
  - neuro
  - drugs:
    - **no** problematic effect on BIS: propofol, benzo's, thio, volatiles
      ↳ ie work on GABA
    - problematic effect on BIS:
      - opiates - unpredictable
      - ketamine ↑BIS
      - dexmetatomidine or α2 receptor agonists ↑BIS
      - NO - no effect
      - mm relaxants - no effect
      - lignocaine ↓BIS
  - EMG pickup
- sensor issues
- algorithm - generated using healthy adults

Evoked Potentials/Responses
- sensory or nerve stim ⟹ production low amplitude signal within CNS (= evoked response (ER))
- ER can be separated & isolated by computer from underlying spontaneous EEG
- for ER to be seen need intact functional pathway between
  - sensory receptors
  - neural generation of peaks
- primarily used to check integrity of neural structures & diagnose neurophysiological conditions
- ERs are sensitive to anaesthetic drugs ∴ can be used for depth monitoring
- types of stimulation used:
  - SSEPs = somatosensory stim of periph nerves
  - MLAEP =
    - 'midlatency auditory evoked potentials'
    - auditory stimulation using clicks at ear canal
  - visual stim using flashing lights
  - elec stimulation of tooth pulp

MLAEP
- best candidate for depth monitoring
- is significantly affected by anaesthetic/hypnotic drugs in graded, reversible and non specific manner
- monitor:
  - Pa & Nb waves
  - anaesthetic agents ↓their amplitude

- opioids produce minimal changes
- disadvantages:
  - time needed to produce a response 0.5-5min
  - complex set up 5min
  - need intact hearing
  - no univariate parameter calibrated for anaesthetic state
- are newer MLAEP parameters being developed:
  - Auditory Evoked Potential index (AEP)
    - proprietary algorithm
    - simplifies interpretation but still needs sig time for averaging process
  - A line ARX Index (AAI)
    - calculated from fast extracted MLAEP waveform analysis
    - gives a range 0-100 akin to BIS

Comparisons

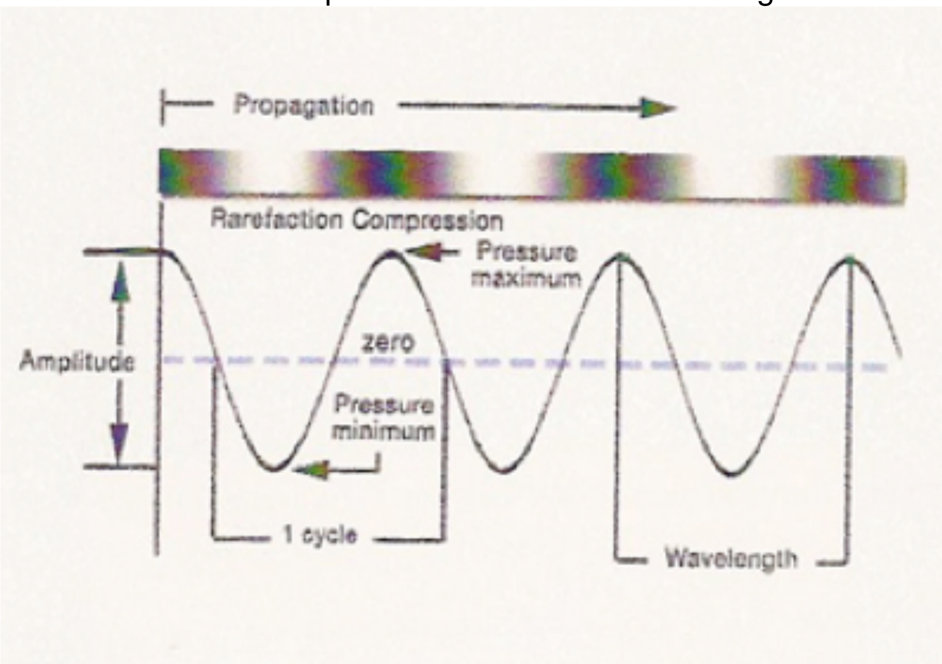
- BIS vs MLAEP:
  - both show changes with ↑ing levels of sedation
  - BIS correlates better with clinical sedation scores
  - MLAEP shows better correlation with plasma drug concs
  - addition of large opioid doses does not affect MLAEP
- BIS vs AAI:
  - with TCI - both good indicators of sedation & loss of consciousness
  - with surg stim - see greater variation in AAI
  - BIS correlates better with propofol effect site conc
  - neither predict reaction to noxious stimuli
  - BIS better discrimination between unconsciousness & awake states

Ultrasonography

- US = relies on transmission of high frequency vibrations & detection of their echoes resulting from their reflection at tissue interfaces

Sound Waves of US

- sound waves used diagnostically frequency >1MHz
    - ↳ audible human range 20Hz to 20Khz
- sound waves are propagated through a medium by vibration of molecules
- within the wave see pressure variations with alternating areas of:
    - compression = correspond to areas of ↑pressure & ↑amplitude
    - rarefaction = low pressure zones where widening of molecules occur



- sound waves = sine waves with diff properties:
    - propagation velocity (v):
        - =speed sound waves move through a medium
        - depends on tissue density & compressibility
        - in soft tissue v = fairly constant @ 1540m/s
            - ↳ this figure assumed by all US machines for all human tissue
    - wavelength (λ)
        - =distance between 2 areas of maximal compression (or rarefaction)
        - penetration of US wave is proportional to wavelength
        - v impt in US:
            - long wavelength ⟹ deeper penetration
            - image resolution = no more than 2 wavelengths
    - frequency (f):
        - number of wavelenghts that pass per unit time at any given point
        - measured as λ' per second = unit Hz
        - = a specific feature of crystal used in specific transducer
            - ↳ can be varied by user within probe limits
        - higher f = better resolution
    - ↳ above variables have a defined relationship:

$v = \lambda \times f$

- ∴ inverse relationship between wavelength & frequency:
    - if need good resolution: high f but ⟹ short λ ∴ shallow tissue penetration
    - inverse is true to look at deep organs
- amplitude:
  - height about baseline which represents maximal compression
  - expressed in decibels in log scale
- acoustic power:
  - = amount of acoustic energy generated/unit time
  - joules/second which = Watts
  - biological effect of US are in the milliwatt range
- intensity:
  - power density or concentration of power/unit area
  - = watts/m^2
  - intensity varies spatially within the beam & greatest in centre
  - in pulsed beam it varies temporally & spatially

Interaction of US with Tissue

- attenuation:
  - =loss of US as a medium is traversed
  - occurs due to absorption of US energy by
    - conversion to heat
    - reflection
    - refractions
    - scattering
  - is ↑ed (∴ penetration of beam reduced) by:
    - ↑distance from transducer
    - heterogenous medium due to ↑acoustic impedance mismatch
    - higher frequency (short λ) transducers
  - NB
    - air forms virtually impenetrable barrier to US
    - fluid offers least resistance
- reflection:
  - US waves are reflected at tissue interfaces & boundaries
  - reflected echoes return to transducer ⟹ basis of imaging
  - amount reflected depends on acoustic impedance between the 2 tissues at the interface
- acoustic impedance (Z):
  - = measure of how US waves traverse a tissue
  - it depends on
    - density of medium (p)
    - propagation through that medium (v)
  - defined as: $z = p \times v$
  - a large difference in Z between tissues = acoustic impedance mismatch
    ↳ ↑ed Z = ↑ed % of US reflected & less transmitted eg soft tissue/bone or tissue/air interfaces
- refraction:
  - US beam encounters media with diff Z's ⟹ proportion of beam (which is not reflected) undergoes refraction (aka bending)
  - explains artefacts such as double image

- diffraction:
  - US bream spreads out with distance from transducer
  - effect to ↓intensity of beam

Transducers

- US waves generated by piezoelectric crystals
- piezoelectric = pressure electric
- generation of sound waves:
  - electrical current applied to a quartz crystal ⟹ change in polarity ⟹ change in shape
  - if use alternating current ∴ ⟹ expansion & contraction ⟹ compression & rarefaction of sound waves
- receipt of sound waves:
  - opposite of generation occurs ie echoes ⟹ expansion & contraction of crystals ⟹ generate electrical current ⟹ converted to display
- ∴ crystals =
  - transmitter - small proportion of time
  - receiver = most of time
- frequency of generated wave is specific to crystal
- types of array:
  - phased array: multiple small crystals fire simultaneously ⟹ individual curved wave fronts combine to form a linear wave front

Near field & Focusing

- near field = near probe where beam = comparable diameter to transducer
- far field = where beam starts to diverge ⟹ ↓ed resolution
- beam focus:
  - possible to cause beam to converge to a given point ⟹ improved lateral resolution
  - achieved either:
    - mechanically ie concave acoustic lens
    - electronically

Resolution

- = ability to distinguish between two objects
- diff types:
  - spatial resolution=
    - ability to distinguish 2 separate objects that are close together
    - subdivided:
      - axial =
        - ability along axis of US beam
        - is improved by higher frequency (shorter wavelength)
      - lateral = perpendicular to axis
  - temporal =
    - ability to accurately locate structures at a particular instant in time
    - esp impt eg in ECHO
    - dependant on frame rate which can be improved by:
      - ↓ed depth
      - narrowing sector of area of interest ie narrow sector angle
      - minimise line density (at expense of lateral resolution)

Lateral Resolution

- lateral resolution:
  - generally poorer than axial

- dependant on beam width:
  - US machine assumes any object visualised originated from the centre of the beam
    ↳ ∴ 2 objects cannot be distinguished unless that are separated by **more** than 1 beam width
- beam width determined by:
  - transducer frequency - ↑width with ↓ing frequencies
  - focusing of beam
  - gain - ↑ed gain ⟹ ↑width ∴ ↓resolution
- ∴ to optimise lateral resolution:
  - use highest frequency (that the depth of structure allows
  - optimise focal zone
  - use minimum necessary gain

Ultrasound Modes

- Amplitude Scan (A scan) =
  - simplest system
  - historical use except for eye surgery to measure depth of orbit
- Movement Scan (M scan):
  - vibrations repeated rapidly
  - ECHOs are capable of detecting movement at tissue interfaces
- B mode:
  - direction of US source is varied
  - produce a 2D tomogram
  - what everyone uses

Doppler Effect

- = increase in observed frequency of a signal when the signal source approaches the observer
  ↳ inverse is true ie as source moves away from the observer: frequency ↓s
- explanation:
  - wave fronts in front of an approaching signal get compressed ie ↓wavelength, ↑frequency
  - humans audibly will hear this as a change in pitch ie change in frequency
    ↳ ambulance siren pitch increases as it moves towards you
    ↳ NB actual frequency emitted has not changed
- principle is used in US to determine velocities of moving substances:
  - flow can be measured by multiplying together :
    - cross sectional area of aorta (m2)
    - velocity of rbcs moving through aorta (m/s)
- Doppler equation:

$$V = \frac{Fd.C}{2Fi \times \cos\theta}$$

Fd = frequency shift
C = Velocity of sound
Fi = initial frequency
cosθ = cosine of angle of transmitted frequency to flow

- angle of measurement (θ) needs to be optimised:
  - >60 deg = calculated velocity less accurate
  - 90 = no doppler shift seen
- BART - Blue Away; Red Towards

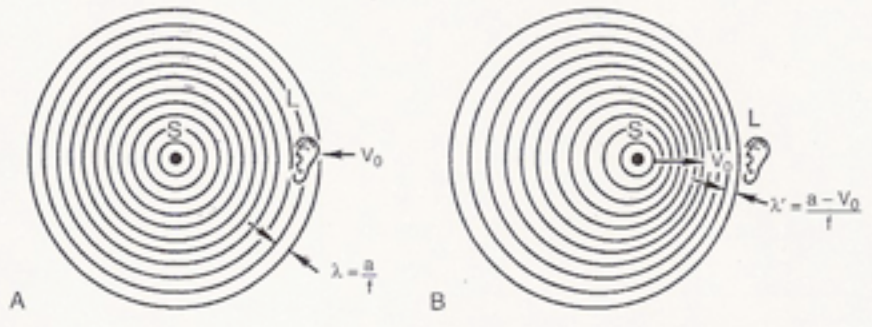


Figure 30–24 Doppler effect. **A,** When a listener is moving toward a stationary sound source, the frequency increases because the listener traverses more waves per unit time than a stationary listener does. **B,** When a sound source is moving toward a stationary listener, the wave fronts "stack up," thereby causing an apparent increased frequency.

Humidity

- absolute humidity = mass of water vapour present in a given volume of air (mg/l or g/m³).
    - ↳ is temp independent
        - ↳ unless sample is saturated, & temp falls ⟹ ↓SVP ⟹ ↓absolute humidity
- the maximum amount of water vapour that can be present in a given volume of air (ie saturated) is determined by the temperature (this relates to relative humidity)
- relative humidity = ratio of mass of water vapour in a given volume of air to the mass required to saturate that given volume of air at the same temperature. (%)
    - ↳ or

$$= \frac{\text{mass water present}}{\text{mass water to saturate}} \quad \text{or} \quad \frac{\text{absolute humidity (actual) in gas}}{\text{absolute humidity (saturated) at that temp}} \times 100\%$$

- saturated vapour pressure (SVP) =
    - vapour is saturated when the number of molecules leaving the liquid phase = number entering liquid phase
    - SVP = pressure exerted by such a vapour ie pressure of a vapour which is in equilibrium with its liquid phase
- effect of temperature (for given volume of air):
    - ↑temp ⟹
        - ↑potential water content of saturated air & vice versa
        - ↓relative humidity (a reflection of ↑SVP)
        - no change in absolute humidity
    - ↓temp ⟹
        - ↓water content of saturated air (and ∴ ↓absolute humidity)
        - ↑relative humidity up to SVP
- boiling point = temperature at which SVP = atmospheric pressure
- evaporation = surface phenomenon where molecules move from liquid to vapour. No bubbles are seen as vapour pressure < atmospheric pressure
- typical values:

Humidity of saturated air at 20 C	17 g/m³
Rel humidity air entering trachea	~ 100%
Humidity at saturation in trachea (34 C)	34 g/m³
Humidity at saturation lung air (37 C)	44 g/m³
Vapour pressure lung air	47 mmHg (6,3 kPa)
SVP water vapour at BTPS	47 mmHg

Measurement of Humidity

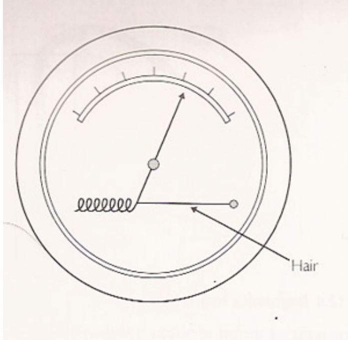
- hair hygrometer
- wet & dry bulb hygrometer
- regnaults hygrometer
- transducers
- mass spectrometer
- light absorption technique

Hair hygrometer

- measures relative humidity
- based on principle that hair gets longer with ↑humidity:
    - blonde hair is best

- 3% ↑length from dry to saturated
- length due to breaking of H bonds which maintain coiled structure of keratin
- bonds reform on drying

- very simple instrument
- disadv:
  - accuracy varies 30-90%
  - slow response
  - difficult to couple to electrical circuit
  - needs calibrating to external standard

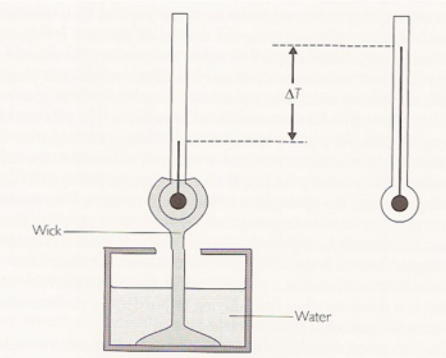


Wet & Dry Bulb Hygrometer

- uses 2 thermometers:
  - 1 = dry & measures ambient temp
  - 1 = surrounded by wet wick - reads lower temp as water evaporates

↳ difference in temp = proportional to ambient humidity - which determines rate of water evaporation

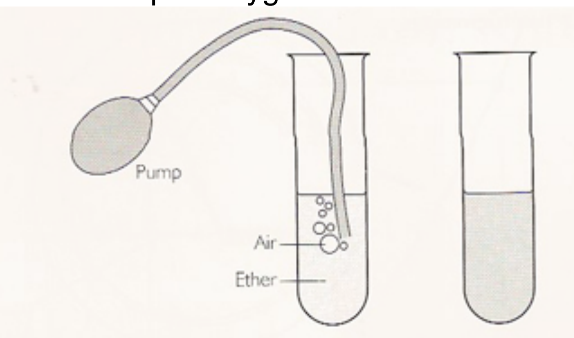
- = standard instrument for measuring climatic humidity



Wet and dry bulb hygrometer

Regnaults Hygrometer

- aka dewpoint hygrometer



Regnault's hygrometer

- method:
  - based on cooling of ether by blowing air through it
  - temp of ether is monitored with a thermometer
  - ether contained by silver tube (silver has high thermal conductivity ∴ it's temp reflects temp of fluid next to it)
  - gas flow over the top of the tube causes evaporation of the ether causing cooling
  - ether cools ⟹ silver lining cools

    - when dew appears on the tube = dew point

$$\text{relative humidity} = \frac{\text{SVP at dew point}}{\text{SVP at ambient temp}} = \frac{\text{actual vapour pressure}}{\text{SVP at that temp}}$$

- to find absolute humidity = look up dewpoint temp in standard table for gas fully saturated at that temp
- common application = chilled mirror hygrometer =
    - air passed through sample chamber which contains a coolable mirror & optical system which measures reflectivity
    - mirror is cooled to dew point & this detected by change in reflectivity & optical output
- adv: is very accurate

Transducers

- =based on change in either electrical resistance or capacitance or a substance as it absorbs water vapour from the atmosphere
- ∴ measures absolute humidity
- disadv: exhibits hysteresis

Mass Spectrometer

- measures amount of water vapour in a given volume of gas

Light Absorption

- ↓of UV light transmitted when water vapour present

Humidifiers

- good humidifier =
    - effective
    - body temp remain unaffected
    - safe
    - no risk infection
    - easy to use & economic
- achieved by:
    - active humidification:
        - based on principle of:
            - larger contact surface
            - adding warmth to ↑evaporation process
    - passive humidification (heat & moisture exchanger - HME)
        - effectively = artificial nose

↳ can combine both to create active heat & moisture exchanger AHME

- Artificial nose:
    - = heat & moisture exchanger (HME)
    - they capture warmth & humidity during expiration
    - release this warmth & humidity during inspiration

Types of Humidifiers

- heated
- artificial nose/HME
- bubble through humidification:
- cold nebulisation
- heated nebulisation

Heated
- eg Fisher & Paykel:
  - heating element in a chamber which is filled with infusion of water through a flutter device
  - flutter has 2 access points:
    - 1 = afferent airflow - air to be humidified. also contains heating wire to warm air to 39 deg
    - 1 = efferent airflow - ie from pt
  - air mixes in heated chamber with high humidity

Artificial nose/HME
- principle is capture warmth & humidity from exp gas & delivering it back during inspiration
- some systems have bacterial/viral filters with effectivity of >99%
- disadv:
  - ↑ed dead space 20-100mls
  - ↑breathing resistance
  - risk of air trapping/auto PEEP

bubble through humidification
- suitable for low gas flows
- deliver relative humidity of 80-95% at room temp
- used for low flow FM or nasal cannula

cold nebulisation
- = short term therapy used with high O2 flows >5L/min
- delivers 100% humidity

heated nebulisation
- short term intensive hydration therapy
- delivers 100% humidity at core body temps