PHYSICS AND ANAESTHESIA

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INTRODUCTION

For the safe & efficient use of anaesthetic apparatus, the anaesthetist must have a clear concept of the physical aspects of the equipment in use. Understanding of basic concepts may avert unnecessary accidents & near misses.

Physics is the world in measurable terms and the physical laws apply to all states of matter (i.e. solids, liquids and gases). As anaesthesiolgists we deal with liquids & gases under pressure at varying temperatures and volumes. These inter-relationships are simple, measurable and their understanding ensures a safe outcome for the patient.

1. Gas Laws. Basic Concepts

The relationship between the three variables,

1. Volume
2. Pressure
3. Temperature is explained by the gas laws

<u>Volume</u>: Space occupied by a substance measured in three dimensions,

- Units,
- cubic cm,
- cubic mm etc.

<u>Pressure:</u> Force / unit area $P = \frac{F}{A}$

- Units, I Barr= I Atmosphere=100kpa=760mmHg=760 torr=14.7psi = 1000cm H_2O
- Gauge Pressure = Content Pressure & Atmospheric Pressure
- Absolute Pressure = Content pressure

<u>Temperature</u>: measures heat, a form of energy, kinetic energy which comes from movement of the molecules

- Units = O ^{O}C = 32 ^{O}F = 273 ^{O}K
- STP = Standard Temperature and Pressure T = O ^{O}C P = 760mmHg
- Absolute Temp. O ^{O}K = -273 ^{O}C

According to gas laws if one of the variables is kept constant the other two have a definite relationship.

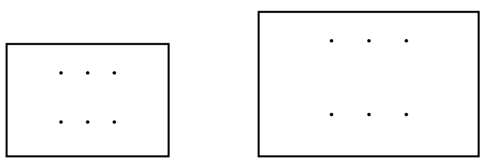
I. Boyle's Law

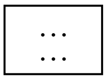
a. **Definition.**

At "CONSTANT TEMPERATURE" the "VOLUME" of a mass of gas varies "INVERSELY" with "ABSOLUTE PRESSURE"

$V \;\alpha\; \frac{I}{P}$ or VP= Constant or $V_1 P_1 = V_2 P_2 = V_3 P_3$

b. **Clearing Concepts**





V_1P_1 V_2P_2 V_3P_3

Same number of molecules at the same temperature occupying different volumes will exert different pressures. However, their product will be the same.

c. **Application in Anaesthetic practice**

Gaseous Cylinders

Medical gases are stored in large amounts under pressure (P_1) in small volumes (V_1). These gases are delivered to patients at atmospheric pressure (P_2)

P_1 = Gauge pressure of cylinder
V_1 = Physical volume of cylinder
P_2 = Atmospheric pressure
V_2 = Actual amount of gas stored in the cylinder

d. **Example**

An oxygen cylinder made of molybdenum steel and of any physical volume (V_1) can safely withstand a gauge pressure (bordon gauge) of 138 bars (P_1). How much oxygen gas is stored in this physical volume (V_1) of the cylinder can thus be calculated.

Let us assume a physical volume V_1 of 10 liters.
$P_1 \times V_1 = P_2 \times V_2$
138 Bars x 10 litres = 1 Bar x O_2 stored in the cylinder
Ans = 1380 L

The content (gas stored) of any GASEOUS cylinder depending on its physical capacity and the pressure showing on the bourdon gauge can thus be calculated.

II. Charles Law / Gay Lussacs Law

a. Definition

At "CONSTANT PRESSURE" the "VOLUME" of mass of a gas varies "DIRECTLY" with the ABSOLUTE TEMPERATURE

$V \alpha T$

b. Application

i. Respiratory gas measurements of tidal volume & vital capacity etc are done at ambient temperature while these exchanges actually take place in the body at 37 ^{O}C.
ii. One way of heat loss from the body is that air next to the body surface gets warmer and moves up and thus our patient loses heat this way (esp. important in paediatric anaesthesia).

III. 3rd Gas Law

a. Definition

At "CONSTANT VOLUME" the "ABSOLUTE PRESSURE" of a mass of gas varies "DIRECTLY" with the "TEMPERATURE"

$P \alpha T$

b. Application

i. Medical gases are stored in cylinders having a constant volume and high pressures (138 Barr in a full oxygen / air cylinder). If these are stored at high temperatures, pressures will rise causing explosions.
ii. Molybdenum steel can withstand pressures till 210 bars. Weakening of metal in damaged cylinders are at a greater risk of explosion due to rise in temperature.

IV. Ideal Gas

V. Law & Universal Gas Constant

a. Definition

Combining the 3 perfect gas laws gives the "IDEAL GAS LAW" and the combination of ideal gas law with the Avogadros hypothesis and the concept of mole gives us the UNIVERSAL GAS CONSTANT = R.

$PV = K_1$ $\frac{V}{T} = K_2$ $\frac{P}{T} = K_3$

Which means

$\frac{PV}{T}$ = Constant

For one mole of any gas (molecular weight expressed in gms)

$PV = n\,RT$

R = Universal Gas Constant, UGC

n = Number of moles

b. Application

The bourdon gauge or the pressure gauge acts as a content gauge for gases since all other variables are constant (i.e.) R = UGC, volume in the cylinder capacity and temperature is the same at all times in an operation theatre.

2. FLOW OF FLUIDS – BASIC CONCEPTS

Fluids are gases or liquids. Flow is the quantity passing a point in a unit time represented by Q.

Flow can be laminar or turbulent. Flow changes from laminar to turbulent and is halved when the Reynold's number which is a product of certain factors crosses the value of 2000.

Reynolds number = $\frac{vpd}{\eta}$

V = Velocity

P = Density

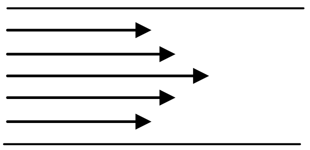
D = Diameter

η = Viscosity

Rough surfaces, sharp bends, type of gases all affect the type of flow.

i. **Laminar Flow**

A steady flow greatest at the centre and slowest at the periphery of tube. Physical property effecting laminar flow is viscosity to which it is inversely proportional.



<u>Law Applicable – Hagen – Poiseuille's Law</u>

Definition

Laminar flow through tubes (blood vessels, ETT) is directly proportional to the pressure gradient (P) & fourth power of the radius and inversely proportional to viscosity & length

Hagen – Poiseuille's, Law takes into account all the factors effecting LAMINAR FLOW.

$$Q = \frac{\Pi (P_1 - P_2)\, r^4}{\&\, \eta\, l}$$

$P_1 - P_2$	=	Pressure difference across the tube
r^4	=	Radius to the power of four
η	=	Viscosity
L	=	Length
Π and 8	=	constant

ii. **Turbulent Flow**

When the flow rate of fluids through a tube (blood vessel, breathing circuits, ETT) exceed a certain velocity (Reynolds number) laminar flow changes into turbulent flow producing eddies and reducing the flow to half. Turbulent flow is facilitated by corners, irregularities and sharp angle etc.

Physical property of gas effecting turbulent flow is density, to which it is reversely proportional

<u>Law Applicable to Turbulent Flow</u>

i- Tubes $Q = \frac{\sqrt{\Delta P}}{\sqrt{LP}}$

ii- Orifices $Q = \frac{r^2\sqrt{\Delta P}}{\sqrt{P}}$

P	=	rho (density)
L	=	length
ΔP	=	Pressure gradient
r^2	=	Radius

Application:

1- Using an undersized ETT may cause a tremendous decrease in the flow of gases
2- Every piece of anaesthetic equipment; because of diameters & shape of connectors, number & arrangement will effect FGF. Wide bore & curved rather than sharp angles should be preferred.
3- In respiratory tract obstruction, oxygen – helium mixtures are given to reduce density and improve the flow.
4- Laminar flow during quiet breathing is changed to turbulent during speaking & coughing leading to dyspnea.
5- In the flow meter at low flows, Hagen – Poiseuille's Law applies because the flow is laminar while at higher flows, the law applicable to turbulent flow is applicable.
6- Numerical value for critical flow in liters per minute for the anaesthetic gas mixture of $O_2 + N_2O$ is the same as the internal diameter in millimeters (e.g for an ETT of 8mm, it is 8L/min; in breathing circuit it is 22L/min). At these flow rates the flow changes to turbulent from laminar.

i. **Bernoulli's Principle**

Flowing fluid possesses two forms of energy, kinetic energy and potential energy. If there is a constriction in the tube, kinetic energy increases and potential energy (pressure) falls, since the total energy must remain the same.

ii. Venturi Apparatus

Any apparatus containing a tube with a constriction and an opening at the constriction will suck in air / fluid due to low pressure at that site (Bernoulli's principle). Such an apparatus is known as **Venturi apparatus**.

Application

Suction apparatus, nebulizers and fixed performance venturi masks are such devices.

iii. Coanda Effect

If such a constriction occurs at bifurcation because of increase in velocity and reduction in the pressure, fluid (air, blood) tends to stick to one side of the branch causing maldistribution.

Application

1. Mucus plug at the branching of tracheo-bronchial tree may cause maldistribution of respiratory gases.
2. Unequal flow may result because of atherosclerotic plaques in the vascular tree.
3. Fluid logic used in ventilators employs this principle to replace valves or mobile parts.

3 SPECTROPHOTOMETRY– BASIC CONCEPTS

a. Definition

Radiation is of different wave lengths. If radiation is passed through a solution, different wavelengths are absorbed by different substances. Two laws apply to this phenomenon

b. Beers Law

Absorption of radiation by a given thickness and concentration of a solution is the same as twice the thickness with half the concentration.

c. Lamberts Law

Equal thicknesses absorb equal amounts of radiation.

Both laws say that the absorption of radiation depends on the amount of a particular substance. This fact has been utilized in pulse oximetry.

d. Pulse Oximetry

Principle

Spectrophotometry & Plethysmography

Light absorbed by the blood depends on the quantities of Haemoglobin and DeoxyHb and the wavelengths of the light. Absorbance of oxyHb at a wavelengths of 660 nm (red light) is less and that of DeoyHb is less in 940nm (blue light).

Two diodes, one emitting red light 660 nm and the other a blue light (940nm) is shown through the finger. The output processed electronically on the other side of the finger gives us the oxygen saturation depending on the relative amount of each type of Hb present in the pulsating arterial blood.

4 DIFFUSION – BASIC CONCEPTS

All states of matter are formed of molecules. In liquids and more so in gases molecules are free to move and this process is known as diffusion.

Factors governing this process and the laws applicable are :

1. State of matter ……… Liquid or Gas
2. Molecular size ………. Graham's Law
3. Concentration gradient ……… Fick's Law
4. Tension gradient / partial pressure …… Modified Fick's Law
5. Solubility co-efficient
6. Membrane area & thickness

1. State of matter

Molecules move more easily in gaseous state than the liquid state.

2. Molecular size – Graham's Law

"Rate of diffusion is inversely proportional to the square root of its molecular size". Heavier the gas the longer it takes to diffuse.

Application

a) Flow Meters. Each gas with its own physical property (density / molecular weight) must pass through its own calibrated flow meter. Error in reading flows will result otherwise.
b) Rate of Diffusion is slower in liquids and thus local anaesthetics, if not injected in close proximity to the nerve fibre will not be effective.
c) Helium, a lighter gas is used in airway obstruction to improve diffusion and gas exchange.

3. Concentration gradient - Fick's Law

"Rate of diffusion of substance across unit area is α to the concentration gradient / partial pressure across a membrane".

4. Tension gradient / Partial pressure - Modified Fick's Law

Rate of diffusion of a substance across a membrane is $\boldsymbol{\alpha}$ to the tension gradient / partial pressure.

Application

1. Alveolar capillary membrane – CO TRANSFER TEST
2. Anaesthetic vapour diffusing into breathing circuits and later acting as Vaporizer at the time of discontinuation of anaesthetic.
3. N_2O diffusion into the cuff of Endotracheal tube.
4. Diffusion of N_2O into air filled cavities e.g. pneumothorax, intestinal distension, middle ear cavity, air embolism.

5. Solubility co-efficient

Higher the solubility coefficient, easier it is for the gas to diffuse. e.g. Carbon dioxide is 20 times more diffusable than oxygen and thus diseases affecting gas exchange in alveoli affect oxygenation rather than CO_2.

6. Membrane area & thickness

Diffusion is inversely proportional to the thickness of membrane and directly proportional to the membrane area across which diffusion has to take place.