Boyle's law

$$PV = K$$

Or

$$V \propto \frac{1}{P}$$

(*at a constant temperature*)

Definition of terms used

P = pressure
V = volume
K = constant

Units

None.

Explanation

Boyle's law (Robert Boyle, 1662) describes one of the characteristics of an ideal gas. It states that if the temperature of the gas is held constant, then pressure and volume are inversely proportional.

An ideal gas is a theoretical gas that obeys the universal gas equation (refer to page 9).

Clinical application/worked example

1. *You are asked to transfer a patient that requires 15 l/minute of oxygen and there is one full E-cylinder of oxygen available. How long will this last?*

Boyle's law can be used to determine the amount of oxygen available from a cylinder (V_2), as follows:

The volume (V_1) of an E-cylinder is 10 l.

The pressure (P_1) inside the cylinder is 13,700 KPa. This is the gauge pressure so atmospheric pressure must be added to make absolute pressure of 13,800 KPa.

The atmospheric pressure (P_2) is 100 KPa.

The temperature is constant in both as long as the gas is allowed to expand slowly.

Boyles law states	$P_1 \times V_1 = \text{constant}$
And thus	$P_2 \times V_2 = \text{constant}$
Therefore	$P_1 \times V_1 = P_2 \times V_2$
So	$V_2 = (P_1 \times V_1)/P_2$
Replacing with values	$V_2 = (13{,}800 \times 10)/100$
	$V_2 = 1{,}380\ \text{l}$

Therefore, if a full E-cylinder of oxygen were being used in these conditions at a flow-rate of 15 l/minute, it would last approximately 92 minutes.

Bear in mind that 10 l will be left in the cylinder when it runs out.

Charles' law

$$\frac{V}{T} = K$$

Or

$$V \propto T$$

(*at a constant pressure*)

Definition of terms used

V = volume
T = temperature
K = constant

Units

None.

Explanation

Charles' law (Jacques Charles, 1780) describes one of the characteristics of an ideal gas. It states that if the pressure of a fixed mass of gas is held constant, then the volume and temperature are proportional.

An ideal gas is a theoretical gas that obeys the universal gas equation (refer to page 9).

Texts differ as to the nomenclature of the second perfect gas law. It was first published by Joseph Louis Gay-Lussac in 1802, although he credited the discovery to unpublished work from 1780s by Jacques Charles.

Clinical application/worked example

1. Spirometry

During pulmonary function testing, a patient will exhale gas at body temperature (37 °C) into a spirometer at room temperature.

Therefore, according to Charles' law, as the temperature drops, the volume of the gas decreases to maintain a constant (K).

For this reason, the terms BTPS and ATPS are used to describe these differing conditions (see box). The volume in the spirometer can be corrected from ATPS to BTPS.

BTPS: Body temperature and pressure, saturated with water vapour
ATPS: Ambient temperature and pressure, saturated with water vapour

2. Heat loss

During anaesthesia, the air around the body is heated by convection. As this happens, according to Charles' law, the volume of the mass of gas increases and therefore rises away from the patient.

Gay-Lussac's law (third gas law)

$$\frac{P}{T} = \mathrm{K}$$

Or

$$P \propto T \text{ (at constant volume)}$$

Definition of terms used

P = pressure
T = temperature
K = constant

Units

None.

Explanation

Gay-Lussac's law (Joseph Louis Gay-Lussac, 1802), often described as the third gas law, describes one of the characteristics of an ideal gas. It states that if the volume of a fixed mass of a gas is held constant, then the pressure and temperature are proportional.

An ideal gas is a theoretical gas that obeys the universal gas equation (refer to page 9).

Clinical application/worked example

1. Describe the 'filling ratio' in relation to nitrous oxide cylinders

The filling ratio is calculated as:

$$\frac{\textbf{weight of the fluid in the cylinder}}{\textbf{weight of water required to fill the cylinder}}$$

Within a cylinder of gas, according to the third gas law, as the ambient temperature rises, the pressure inside the cylinder will also rise.

This is important in the storage of nitrous oxide with its low Critical Temperature. At room temperature, it is stored in a cylinder as a liquid, with vapour on top. As the temperature rises, the pressure exerted by the vapour, the Saturated Vapour Pressure, also rises. If this exceeds the pressure capacity of the cylinder, then it could explode, as the volume is constant.

For this reason, the filling ratio for nitrous oxide in the UK is 0.75, but in hotter climates is 0.67.

2. Apply the third gas law to the hydrogen thermometer

When a constant volume of hydrogen inside the thermometer is heated, its pressure increases. The measured pressure change is directly proportional to the change in temperature.

Avogadro's equation

$$\frac{V}{n} = \mathrm{K}$$

Definition of terms used

V = volume of gas
n = amount of substance of the gas
K = a proportionality constant

Units

None.

Explanation

The equation states 'equal volumes of gases at the same temperature and pressure contain the same number of molecules regardless of their chemical nature and physical properties'.

This number (Avogadro's number) is 6×10^{23} and is described as 1 mole.

1 mole = quantity of a substance containing the same number of particles as there are atoms in 12 g of carbon^{12} = 6×10^{23}.

The mass of gases is different, but the concept of number of molecules, or moles, enables comparison between them.

One mole of any gas at STP occupies 22.4 litres.

STP = Standard Temperature and Pressure

273.15 K = 0 °C

101.325 KPa

Clinical application/worked example

1. Use Avogadro's law to explain how to calibrate a sevoflurane vaporizer.

We know: number of moles = (mass of substance (g)/atomic mass).

The molecular weight of sevoflurane is 200. Therefore, 200 g sevoflurane equals 1 mole and would occupy 22.4 litres at STP.

If a vaporizer contains 20 ml of sevoflurane, this is equivalent to 0.1 mole because the density of sevoflurane is 1 g/ml.

If 1 mole occupies 22.4 litres at STP, then 0.1 mole will occupy 2.24 litres at STP.

If this volume of sevoflurane is fully vaporized in to 224 litres of oxygen, the resulting concentration will be:

$$2.24/224 = 0.01 = 1\%$$

2. How much liquid agent does a vaporizer use per hour?

Ehrenwerth and Eisenkraft (1993) give the formula:

$$3 \times \text{fresh gas flow (FGF) (l/min)} \times \text{volume\%} = \text{ml}$$

Typically, 1 ml of liquid volatile agent yields about 200 ml vapour. This is why tipping is so hazardous, as it discharges liquid agent into the control mechanisms, or distal to the outlet. Minute amounts of liquid agent discharged distal to the vaporizer outlet result in a large bolus of saturated vapour delivered to the patient instantaneously.

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Authors Dr Edward T. Gilbert-Kawai and Dr Marc D. Wittenberg
Excerpt
More information

Universal gas equation

$$PV = nRT$$

Definition of terms used

P = pressure
V = volume
n = the number of moles of the gas
R = the universal gas constant (8.31 J/K/mol)
T = temperature

Units

None.

Explanation

The universal (or ideal) gas equation describes the behaviour of an ideal gas. It is a combination of Avogadro's law (refer to page 7), Boyle's law (refer to page 1) and Charles' law (refer to page 3).

Clinical application/worked example

1. Calculate the contents of an oxygen cylinder.

The universal gas equation may be used to calculate the contents of an oxygen cylinder.

Referring to the equation, in normal circumstances T is constant at room temperature, V is constant as the cylinder has a fixed volume, and R is by definition a constant. These terms therefore may be practically removed from the equation, and so

$$P \propto n$$

The gauge pressure (P) can thus be used to measure the amount of oxygen remaining in the cylinder (n).

2. Calculate the contents of a nitrous oxide cylinder.

In most circumstances, nitrous oxide is stored below its critical temperature of 36.4 °C. It therefore exists in the cylinder as a vapour in equilibrium with the liquid below it.

To determine how much nitrous oxide remains in a given cylinder, it must be weighed, and the weight of the empty cylinder, known as the tare weight, subtracted. Using Avogadro's law (refer to page 7), the number of moles of nitrous oxide may now be calculated.

Using the universal gas equation as above, the remaining volume can be calculated.