Respiratory Scientists' Toolbox

Correction factors, gas laws, mass balance and other key equations and concepts

CRFS Workshop – Brisbane 2010

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What you need to know …

(1, 2 and 3 covered in this talk)

1. Gas laws
   – Boyle’s Law
   – Charles’ Law
   – Avogadro’s Law
   – Dalton’s Law of partial pressures
   – Ideal gas equation
2. The physics of water vapour - why it doesn't behave like an ideal gas
3. Corrections factors
   – Why bother?
   – Range of conditions encountered in respiratory physiology
   – Common correction scenarios
   – Deriving correction factors

4. Other Gas Laws
   – Graham’s Law of gas diffusion
   – Henry’s Law of gas solubility
5. Simple models of the lung
   – Ohm's law with reference to flow resistance through the airways
   – Poiselle's equation with reference to flow through a Fleisch pneumotach
   – Fick's equation and membrane diffusion
   – Boyle's law with reference to plethysmography
   – Mass balance with reference to measurement of lung volume by inert gas dilution

The Gas Laws - 3 historically important laws

$$\text{Boyle's law:} \quad V \propto \frac{1}{P} \quad (\text{constant } n,\ T)$$

$$\text{Charles's law:} \quad V \propto T \quad (\text{constant } n,\ P)$$

$$\text{Avogadro's law:} \quad V \propto n \quad (\text{constant } P, T)$$

Can be combined into a single general equation

Ideal Gas Equation

PV = nRT

V = Volume

P = Pressure

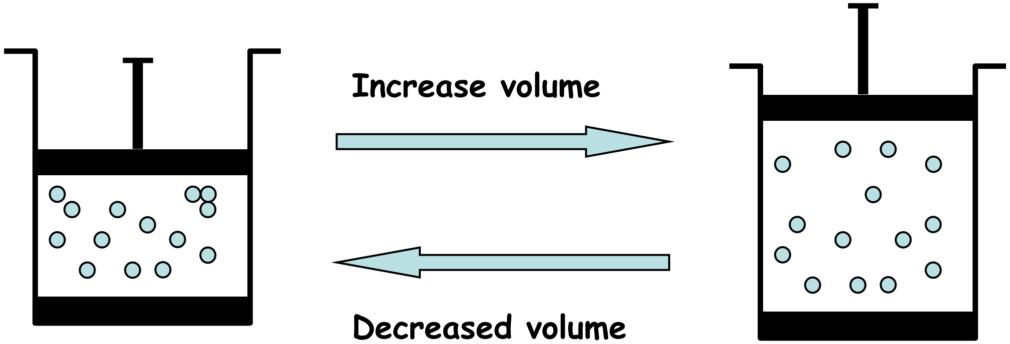
T = Temperature

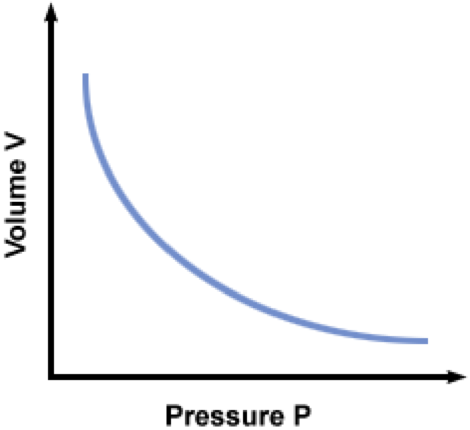
n = amount (moles or number of molecules)

R = Universal Gas Constant

Boyle's Law

$$\text{Boyle's law:} \quad V \propto \frac{1}{P} \quad (\text{constant } n,\ T)$$

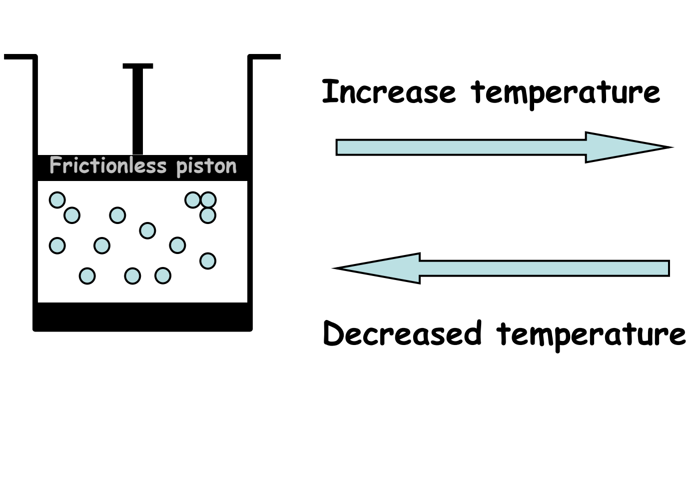


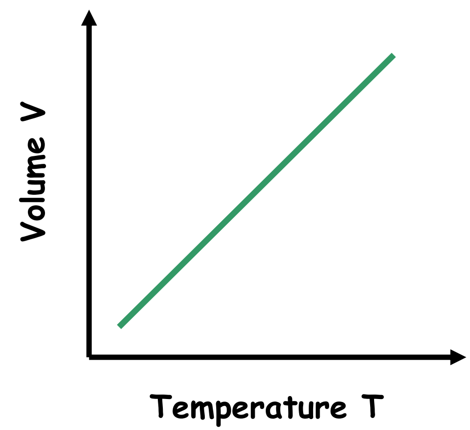


As gas volume decreases, molecules are closer together and more collisions occur. Therefore, pressure rises (and vice-versa).

Charles' Law

Charles' law: $V \propto T$ (constant n, P)

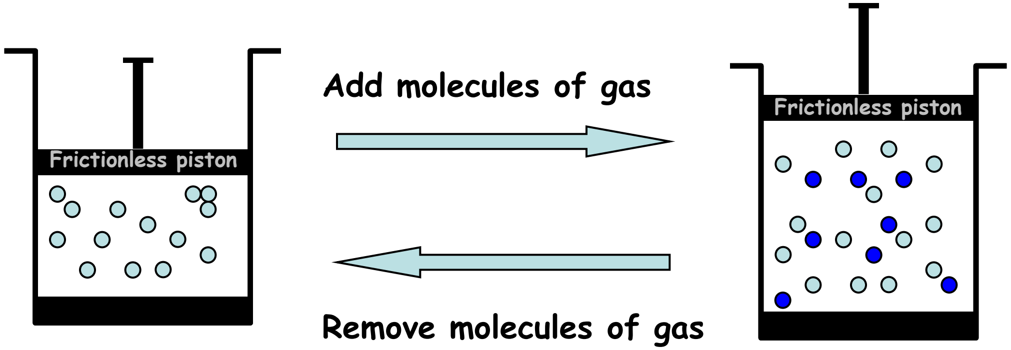


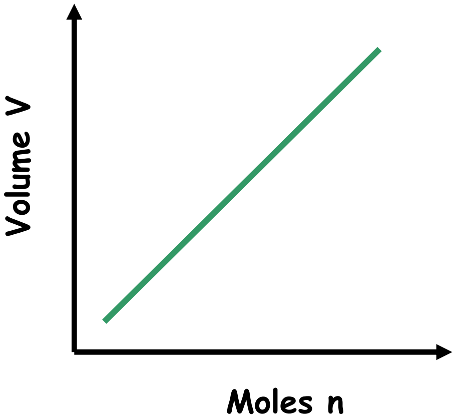


As gas temperature rises, the velocity of molecules and so the force of their collisions increases. Therefore, pressure rises (and vice-versa).

Avogadro's Law

Avogadro's law: $V \propto n$ (constant P, T)





Equal volumes of different gases, at the same temperature and pressure, contain the same number of molecules.

Ideal Gas Equation

$$\left.\begin{array}{ll}\text{Boyle's law:} & V \propto \dfrac{1}{P} \quad (\text{constant } n, T) \\ \text{Charles's law:} & V \propto T \quad (\text{constant } n, P) \\ \text{Avogadro's law:} & V \propto n \quad (\text{constant } P, T)\end{array}\right\} \xrightarrow{?} \boxed{\mathbf{PV = nRT}}$$

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

$$V = R \times \frac{nT}{P}$$

Points to note –

- The value and units of R depend on the units used for P, V, n and T
- Temperature expressed on absolute-temperature scale (°Kelvin = °Celsius + 273)

Ideal Gas Equation – not always ideal!

"Ideal gas" molecules –

1. Occupy negligible volume
2. Do not attract each other
3. Undergo elastic collisions
   (no loss of kinetic energy)

⇨ Insignificant inter-molecular forces

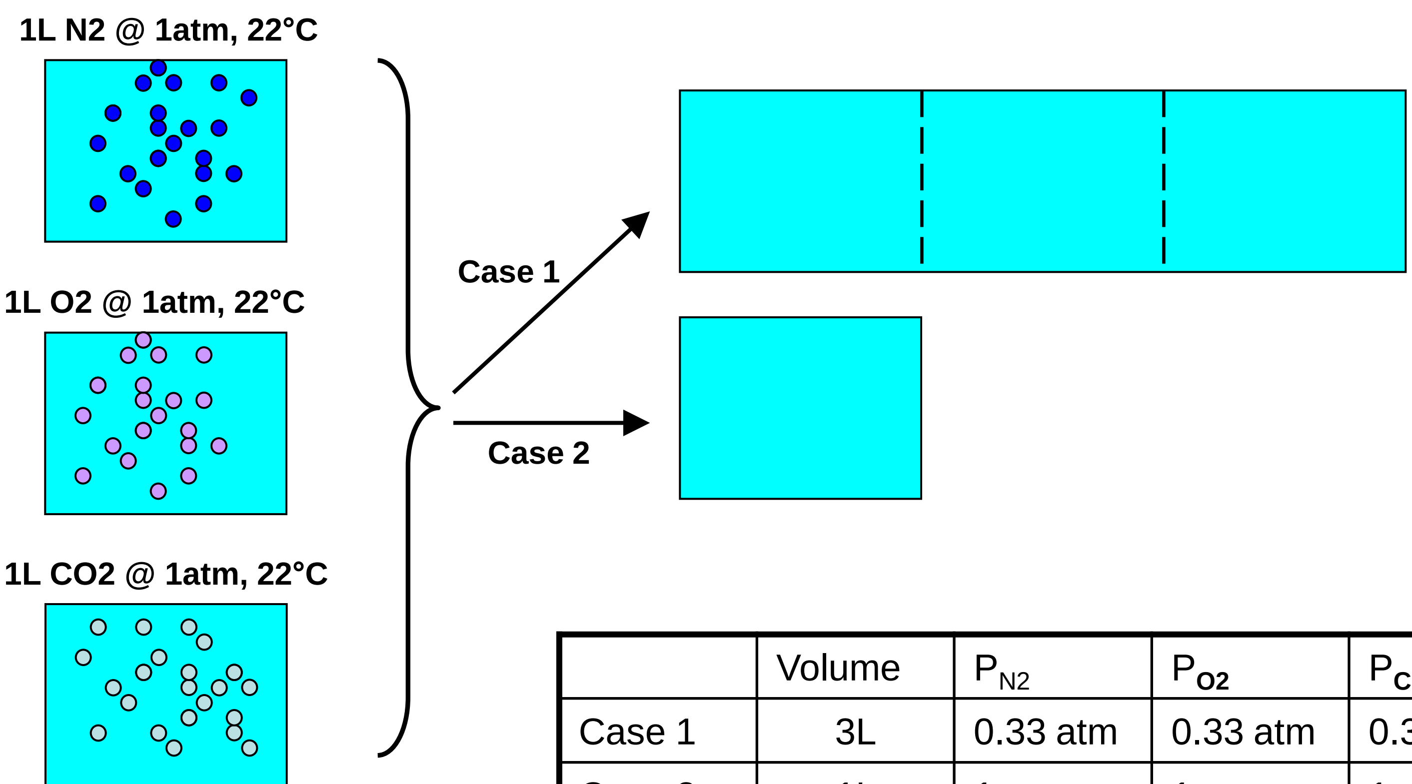
"Real" gases and the ideal gas equation –

- Acceptable accuracy for most respiratory gases at physiological temp's and pressures
- Most accurate for monatomic gases eg Helium
- Ideal gas laws don't explain
  - condensation of gases
  - vapourisation of liquids

Dalton's Law of Partial Pressures

Pressure exerted by a mixture of gases is equal to the sum of the separate pressures that each component would exert if it alone occupied the whole volume.

$$P_{total} = P_1 + P_2 + P_3 + \ldots.. P_n$$



	Volume	P_{N2}	P_{O2}	P_{CO2}	P_{total}
Case 1	3L	0.33 atm	0.33 atm	0.33 atm	1 atm
Case 2	1L	1 atm	1 atm	1 atm	3 atm

A word about water vapour

- Gases in equilibrium with their liquid phase will (appear to) **disobey** the gas laws.

- Water vapour is a gas often in **equilibrium** with its liquid phase (ie water).

    Examples:

    1) in the lungs
    2) inside a water filled spirometer
    3) any situation where there is 100% saturation of a gas with water vapour.

- Water vapour pressure depends **only** **on temperature** (non-linear)

- Ideal gases are also affected by pressure.

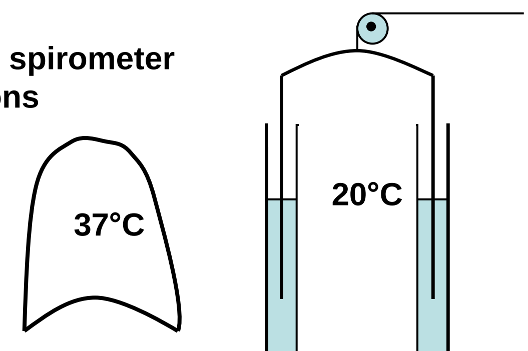
A word about water vapour ….

- Gases in equilibrium with their liquid phase **disobey** the gas laws.
- Water vapour pressure depends **only** **on temperature**, unlike ideal gases.

The lungs at sea level vs altitude

	Pb (mmHg)	PAO2 (mmHg)	Alveolar temp	PAH2O (mmHg)	FAH2O
Sea level	760	106	37°C	47	6.2%
20,000 ft	350	46	37°C	47	13.4%

Lung vs spirometer conditions



	Temp	Pb (mmHg)	Saturated with H2O?	PH2O
Lungs	37°C	760	Yes	47
Spirometer	20°C	760	Yes	18

So far …

1. Gas laws
   - Boyle's Law
   - Charles' Law
   - Avogadro's Law
   - Dalton's Law of partial pressures
   - Ideal gas equation

2. The physics of water vapour and its non-ideal gas behaviour

3. Corrections factors

The nuts and bolts of correction factors (BTPS and others)

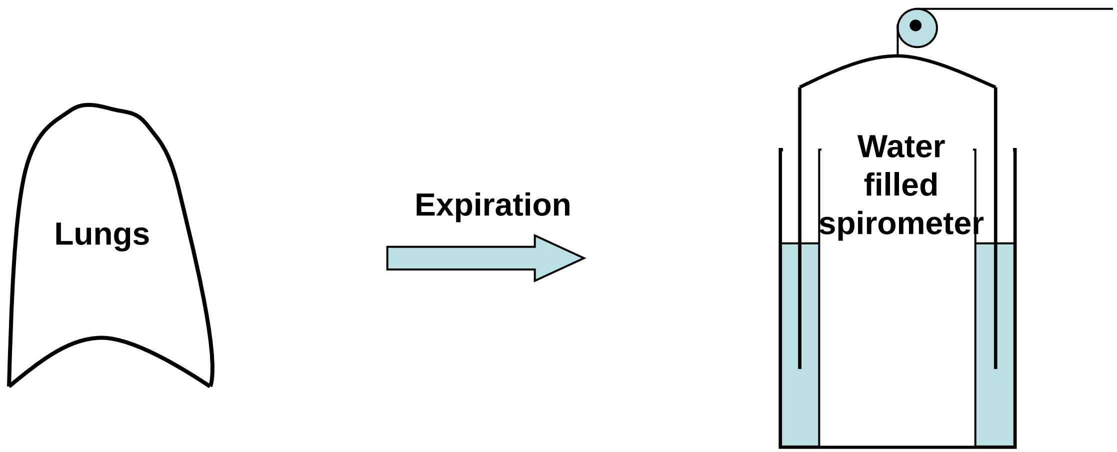
1. Why bother?

2. **Range** of conditions encountered in the respiratory laboratory

3. **Common** correction scenarios

4. How to **derive** a correction factor

1. Why bother ?



Lung conditions

T	**37°C**
P	**Pb**
P H2O	**47 mmHg**

COOLING (Charles' Law) →

PRESSURE (Boyle's Law) →

↓MOLES (Avogadro's Law) →

Spirometer conditions

T	**20°C**
P	**Pb**
P H2O	**18 mmHg**

Actual VC = 4.00L

Measured VC = <u>3.63 L</u>

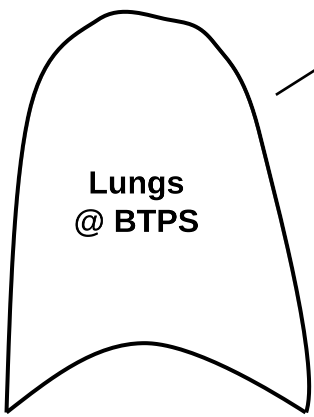
- Measured volumes **vary** with ambient conditions
- Temp and water vapour pressure are the **key** variables
- Volumes and flows (most of them) **are** reported at body conditions by convention (BTPS)

2. Range of conditions encountered in respiratory physiology

	Conditions	Temperature	Pressure (mmHg)	Relative Humidity (%)	P H2O (mmHg)
BTPS	Body	37°C (310°K)	Ambient P	100% (Saturated)	47
ATPS	Ambient	Ambient T	Ambient P	100% (Saturated)	Ambient
ATPD	Ambient	Ambient T	Ambient P	0% (Dry)	0
ATP	Ambient	Ambient T	Ambient P	>0 and <100%	>0 and <47
STP(D)*	Standard	0°C (273°K)	760 mmHg	0% (Dry)	0

***STP = STPD**

3. Common correction scenarios - Spirometry



ROLLING SEAL SPIROMETER

	Exp	Insp
Measure	**ATPS**	**ATPS**
Report	**BTPS**	**BTPS**

HEATED FLEISCH PNEUMOTACH

	Exp	Insp
Measure	**BTPS**	**ATP***
Report	**BTPS**	**BTPS**

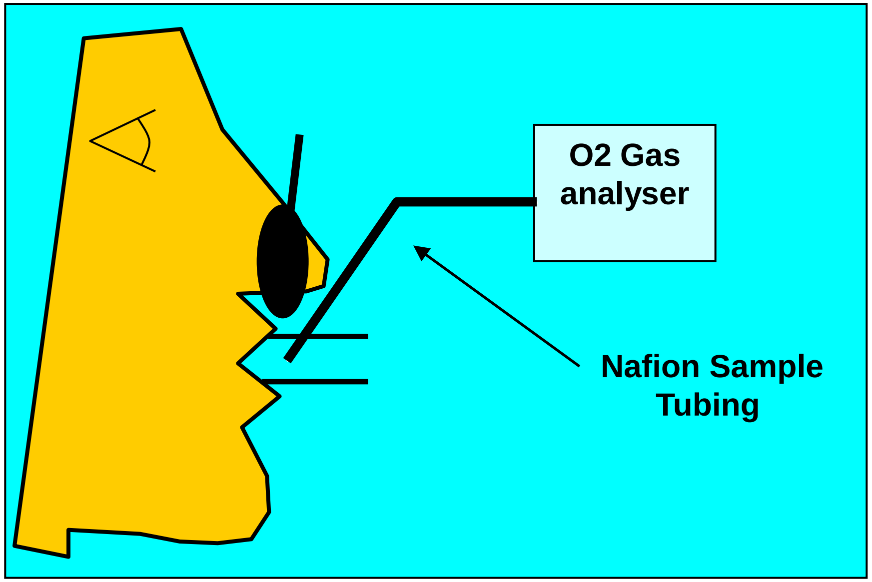
*** Ambient conditions inside pneumotach**

UNHEATED FLEISCH PNEUMOTACH

	Exp	Insp
Measure	**ATPS***	**ATP**
Report	**BTPS**	**BTPS**

*** Ambient conditions inside pneumotach**

3. Common correction scenarios – gas analysis



SCENARIO

- **Report PeO2 at BTPS conditions**
- **Condition in the alveoli is BTPS**
- **Condition in the analyser is ATP**
- **Thus, cooling and drying has occurred**

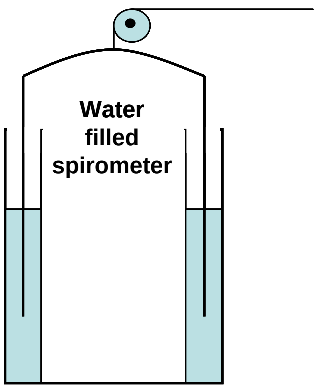
Cooling decreases total gas volume –

Does not affect gas concentration because all components are affected equally.

Drying of the sample has 2 effects-

1. **Decreases total gas volume but does not affect gas concentration (above)**
2. **Removes one of the components (water vapour) and concentrates all remaining components.**

4. How to calculate a volume correction factor: ATPS to BTPS



Actual VC = 4.00 L BTPS

Measured VC = 3.63 L ATPS

Two effects to correct –

1) Cooling
2) Drying

Step 1: Correct for Cooling Effect

The Secret: The number of molecules of the gas volume does not change when warmed.
Using the ideal gas equation –

At ambient temp: $n1 = \dfrac{P1 \times V1}{R \times T1}$

At body temp: $n2 = \dfrac{P2 \times V2}{R \times T2}$

Since n1 = n2, $\dfrac{P1 \times V1}{R \times T1} = \dfrac{P2 \times V2}{R \times T2}$

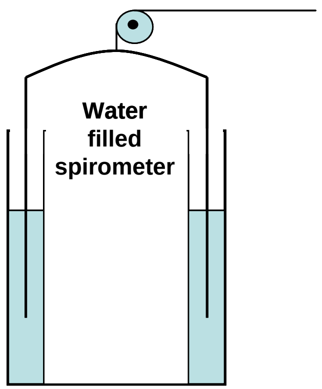
Re-arranging gives: $V2 = V1 \times \dfrac{R \times P1 \times T2}{R \times P2 \times T1}$

R's & P's cancel (P1=P2=Pb), thus $V2 = V1 \times \dfrac{T1}{T2}$

$$V\ (BTPS) = V(ATPS) \times \frac{273 + 37}{273 + 20}$$

V (BTPS) = 1.058 x V (ATPS)

4. How to calculate a volume correction factor: ATPS to BTPS ……



Actual VC = 4.00 L BTPS

Measured VC = 3.63 L ATPS

Two effects to correct –
1) Cooling
2) Drying

Step 2: Correct for Drying Effect

Adding water vapour increases the volume of the gas.

But, water vapour doesn't behave like an ideal gas.

Fortunately, we can calculate its effect by applying Boyle's law to the dry gas fraction of the total gas pressure

$$P1 \times V1 = P2 \times V2$$

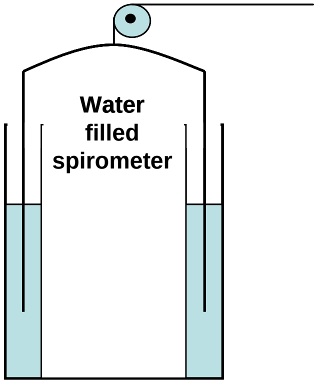
$$V2 = V1 \times \frac{P2}{P1}$$

$$V2 = V1 \times \frac{Pb - PH20(AT)}{Pb - PH20(BT)}$$

$$V(BTPS) = V(ATPS) \times \frac{760 - 18}{760 - 47}$$

V (BTPS) = 1.041 x V (ATPS)

4. How to calculate a volume correction factor: ATPS to BTPS ……



Actual VC = 4.00 L BTPS

Measured VC = 3.63 L ATPS

Two effects to correct –
1) Cooling
2) Drying

In practice - combined approach

Temperature and water vapour corrections combined into a single equation ……

$$\frac{V1 \times T1}{P1} = \frac{V2 \times T2}{P2}$$

$$V2 = V1 \times \frac{T1 \times P2}{T2 \times P1}$$

$$V2 = V1 \times \frac{273 + 37}{273 + 20} \times \frac{Pb - PH20(AT)}{Pb - PH20(BT)}$$

$$V2 = V1 \times \frac{273 + 37}{273 + 20} \times \frac{760 - 18}{760 - 47}$$

V (BTPS) = 1.101 x V (ATPS)

A challenge!
"Why is it so?"

1. Which of the gas laws are in operation here?
2. How do they work to get the boiled egg into the bottle?
3. How do you get the egg out of the bottle?