



## Scuba Learning Module 19

### Understanding gases

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### States of matter

- All matter is made up of particles (atoms or molecules) & Pascal's Principle
- Particles are in constant motion (have energy)
- There are three states of matter determined by particle energy (temperature):
  - Solids
  - Liquids
  - Gases

| Property                               | Solid | Liquid | Gas |
|----------------------------------------|-------|--------|-----|
| Compressible                           | No    | No     | Yes |
| Definite volume                        | Yes   | Yes    | No  |
| Shape                                  | Yes   | No     | No  |
| Transmit pressure (Pascal's principal) | Yes   | Yes    | No  |
| Need a container                       | No    | Yes    | Yes |

### Pascal's Principle

Pascal's Principle states that pressure exerted anywhere in a confined fluid is transmitted equally and undiminished in all directions throughout the fluid. As a consequence in diving:

- A diver's body (mostly fluid—incompressible) underwater assumes the same pressure as the water, except the diver's gas spaces
- The body's air spaces become subject to pressure changes and hence pressure injuries (barotrauma)

#### Solid



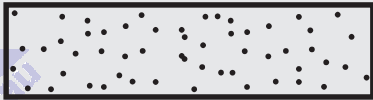
Particles close together in fixed positions

#### Liquid



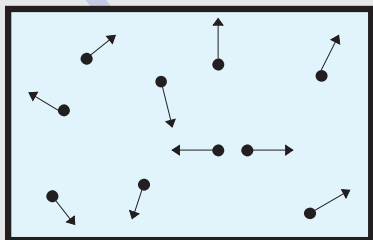
Particles close together but free to move

#### Gas



Particles far apart and free to move

Compressibility is a unique property of gases



## Gas behaviour

- Particles move in constant random motion
- Heavier particles move slower than lighter ones
- Gas particles continuously collide with container walls creating '**pressure**'
- Pressure is determined by the number of gas particles and their energy (which is temperature dependent):
  - 10 molecules of nitrogen in a container at the same temperature as 10 molecules of oxygen in an identical container will create the same pressure
- The relationship between the pressure, temperature and volume of a gas is expressed by the Combined Gas Law:
  - $PV = kT$ , where  $k$  is constant for a fixed mass of gas

## Effect of temperature

- Temperature determines the energy of gas particles:
  - Increased temperature increases energy of particles
  - Decreased temperature decreases energy of particles

## Gay-Lussac's Law (temperature & pressure)

- In a rigid container (eg. scuba cylinder) an increase in temperature leads to an increase in pressure and vice versa:
  - $P = kT$

## Charles' Law (temperature & volume)

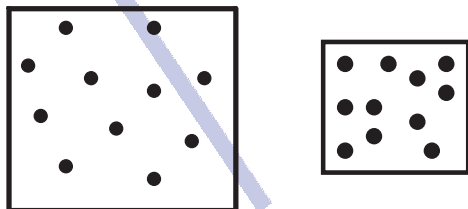
- In a flexible container (eg. balloon) an increase in temperature leads to an increase in volume and vice versa:
  - $V = kT$

In diving, Gay-Lussac's Law applies to the cylinder's temperature, such as when filling or

## Rigid container

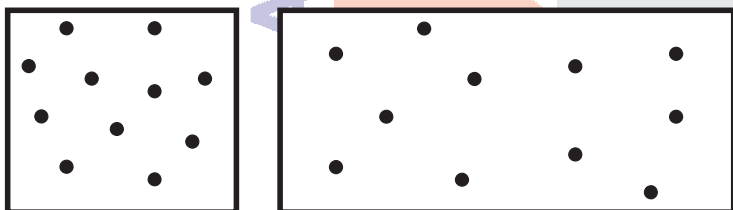
### Reducing volume

- If volume is reduced gas particles will collide with container walls more often resulting in higher pressure
- Gas density also increases



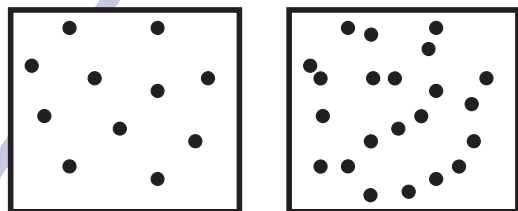
### Increasing volume

- If volume is increased gas particles will collide with container walls less often resulting in lower pressure
- Gas density also decreases



### In a fixed volume

- If gas particles are added, pressure will increase due to more collisions, gas density also increases
- If gas particles are released, pressure will decrease due to less collisions gas density also decreases

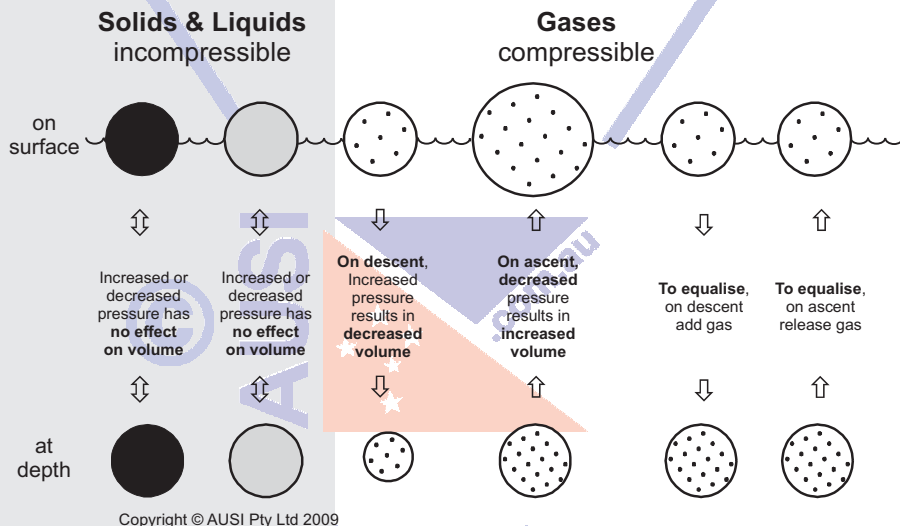


When compressing gases, such as filling cylinders, more particles result in higher pressure

## Flexible container

### Effects on volume with constant external pressure

- Introducing more particles into a flexible container will lead to an increase in volume as the container stretches
- The opposite occurs when particles are released



Boyle's Law applies to the body's gas spaces during descent and ascent (ie. pressure injuries), air consumption and air density

### Effects on volume with changing external pressure

- Increasing external pressure (eg. descending) will decrease the volume of the container
- Decreasing external pressure (eg. ascending) will increase the volume of the container
- Volume can be maintained during external pressure changes by adding or releasing particles from the container—this process is called **equalisation**

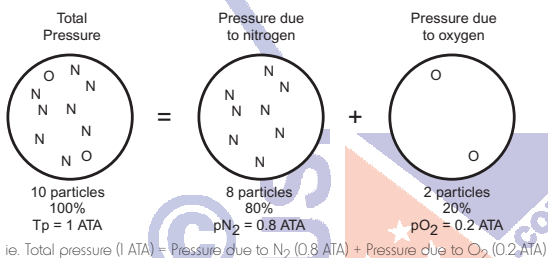
### Boyle's Law (pressure & volume)

- An increase in pressure will result in a decrease in volume, and vice versa:
  - $PV = k$

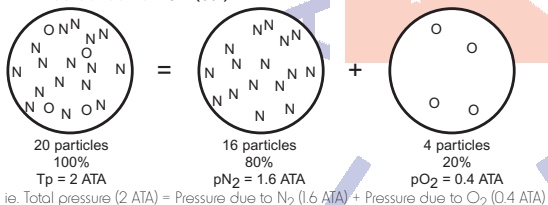
## Air

- Air is a gas mixture containing two major gases (oxygen and nitrogen) which act independently
- Oxygen is approximately 20% of air (actual—21%) and nitrogen 80% (actual—78%) plus other gases (1%)
- The partial pressure of a component gas in air is determined by its proportion (%) of the total pressure of the air

### Air filled balloon at surface



### Air filled balloon at 10m (33')



### Air at 5 ATA (40m/133'):

**Nitrogen** (80% or 4/5)  
therefore  $P_p N_2 = 4.0 \text{ ATA}$

**Oxygen** (20% or 1/5)  
therefore  $P_p O_2 = 1.0 \text{ ATA}$

- Breathing air at 40m (133') is the equivalent of breathing 100% oxygen on the surface

### Dalton's Law of Partial Pressures

- The total pressure of a gas mixture is the sum of the partial pressures of each component gas:
- $P_{\text{Total}} = P_1 + P_2 + P_3 + \dots + P_n$

Each component gas in a gas mixture contributes its own pressure, its **partial pressure** ( $P_p$ )

In diving, partial pressures apply to gas toxicity such as Nitrogen Narcosis and oxygen toxicity and using gases other than air (enriched air, Trimix, etc.), which require extreme caution and further education

The toxicity of a gas is a direct result of its partial pressure not its percentage

## Diffusion of gases

- Gas particles dissolve into a liquid via diffusion
- Diffusion is the natural movement of particles from an area of high concentration to an area of low concentration
- Over a period of time diffusion will lead to an even concentration of particles:
  - For example, when an open perfume bottle is placed in a room, the odour (perfume molecules) will spread from the bottle to all parts of the room

## Rate of diffusion

- The rate at which diffusion occurs is dependent on the pressure difference (a greater pressure differential results in more rapid diffusion):
  - ★ At deeper depths nitrogen is absorbed more rapidly into the tissues due to the greater pressure differential between nitrogen in inspired air and nitrogen already in the tissues
  - ★ When a person with nitrogen bubbles in their blood is given 100% oxygen to breathe, the nitrogen will diffuse out of the bubble rapidly due to the large pressure differential between the low partial pressure of nitrogen in the blood and the high partial pressure of nitrogen in the bubble

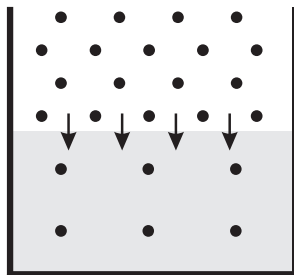
Diffusion applies to DCI and the benefits of oxygen for diving first aid

## Saturation & supersaturation

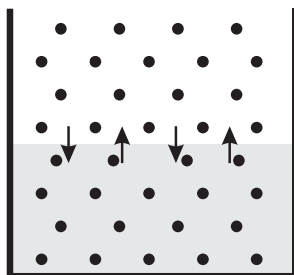
- If the partial pressure of a gas above a liquid is greater than that in the liquid (i.e. when a diver descends) then gas will diffuse into the liquid
- While the partial pressure of a gas above a liquid is greater than the partial pressure of the same gas within the liquid, gas will continue to diffuse into the liquid until eventually saturation (equilibrium) is reached
- At saturation the amount of gas going into liquid equals the amount of gas coming out
- If the partial pressure of a gas above a liquid is less than that in the liquid (i.e. on ascent) then gas will diffuse from the liquid
- Supersaturation occurs when the amount of gas dissolved in the liquid exceeds the partial pressure of the same gas above the liquid (i.e. when a diver ascends)

## Henry's Law

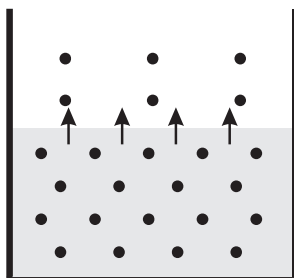
- The amount of gas which dissolves into a liquid is directly proportional to its partial pressure:
  - Different gases will absorb at different rates in a particular liquid
  - Different liquids will absorb specific gases at different rates
  - Rate of absorption is temperature dependant
- In diving, Henry's Law applies to the absorption of nitrogen into the body's tissues which can cause Nitrogen Narcosis and/or the formation of bubbles which can result in DCI



Gas diffuses into the liquid due to the high partial pressure of the gas above the liquid



Equilibrium or saturation is when the number of gas molecules diffusing in equals the number of gas molecules diffusing out of the liquid



The liquid is said to be supersaturated when the partial pressure of the gas in the liquid is greater than the partial pressure of the gas above the liquid, thus releasing gas

## Nitrogen absorption

The rate and amount of nitrogen absorbed into a tissue depends on a number of factors:

- Nitrogen is absorbed faster at depth due to the greater pressure differential (consequently shorter no-decompression times as the diver descends)
- The blood supply to the tissue (**perfusion**)—areas of high blood flow have more opportunity to take on and release nitrogen
- Fat content of the tissue—fatty tissue (e.g. adipose tissue, bone marrow and spinal cord) can absorb up to five times more nitrogen than other tissues

Diffusion between adjacent tissues:

- ★ Tissues can be described as **fast** or **slow**
- ★ **Fast** tissues have good blood supply and absorb and release nitrogen quickly e.g. blood (saturates instantaneously), brain, spinal cord, heart, kidneys and muscle tissue
- **Slow** tissues have poor blood supply and absorb and release nitrogen slowly e.g. bone, cartilage and tendon

## On-gassing during a dive

### At sea level

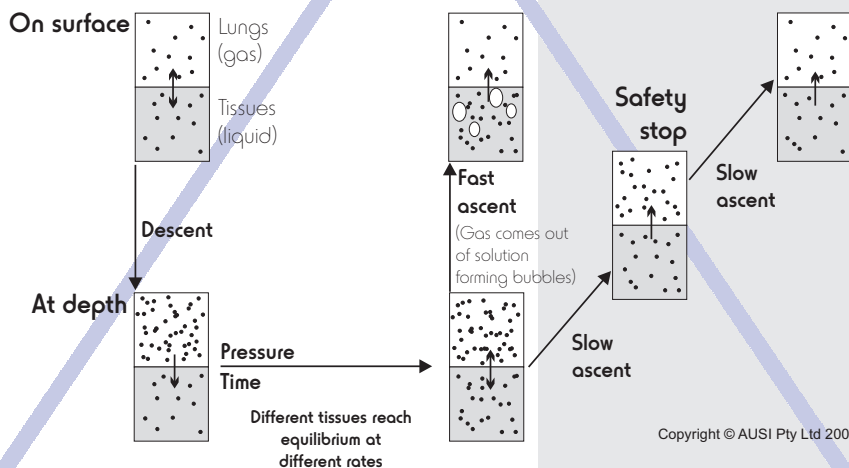
- Body tissues are saturated with nitrogen (for atmospheric pressure)
- The average person has approximately one litre of nitrogen dissolved in their tissues when saturated at sea level
- It takes up to 48 hours since last diving or flying to return to normal

### Increased nitrogen pressure

- When a diver descends the partial pressure of nitrogen in the inspired air increases
- More nitrogen will dissolve in the blood and hence more will be distributed to and dissolved in the tissues of the body

### Saturation at depth

- Whilst a diver is very close to saturation after 24 hours, complete saturation at a depth can take three to four days, only applicable to commercial diving
- The average person has approximately two litres of nitrogen dissolved in their tissues when saturated at 10 metres (33')



## Off-gassing on ascent

- During ascent, tissues have a higher level of nitrogen than in the blood and lungs
- Nitrogen will diffuse from the tissues back into the blood, which carries it back to the lungs where it will be expired
- During ascent nitrogen levels in the tissues exceed the level in inspired air (ie supersaturation occurs) and bubbles often form
- On most dives the bubbles that form are asymptomatic (ie cause no symptoms) and are trapped in the capillaries of the lungs where the nitrogen diffuses out
- Rapid ascents, normal is 9m (33') per minute, will increase the chance of forming symptomatic bubbles
- Bubbles can cause tissue damage and can slow the rate of nitrogen elimination

## Rate of elimination

- **"Slow"** tissues release nitrogen at a slower rate than **"fast"** tissues
- Fatty tissues will have more nitrogen to off-gas
- Most models used for nitrogen on-gassing and off-gassing assume on-gassing and off-gassing are at same rate but experimental work has shown off-gassing is slower

During ascent, whilst off-gassing is occurring, on-gassing by diffusion is still occurring in adjacent tissues

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## Bubble physics

- Two opposing forces are associated with the existence of a bubble:
  - Total gas pressure inside the bubble
  - Crushing force acting on the outside of the bubble
- To exist, the total gas pressure within a bubble must equal or exceed the crushing force on the bubble
- The crushing force on the bubble is due to surface tension of bubble walls, ambient pressure within the tissue and pressure exerted by the tissue

## Why bubbles form

- Traditional theory was supersaturation by a certain amount would cause bubbles but experimental data suggests they occur anytime supersaturation is achieved
- When and where bubbles form is still uncertain
- Detecting Bubbles:
  - Doppler ultrasonic bubble detector is used
  - This method only detects moving bubbles and cannot prove the absence of bubbles

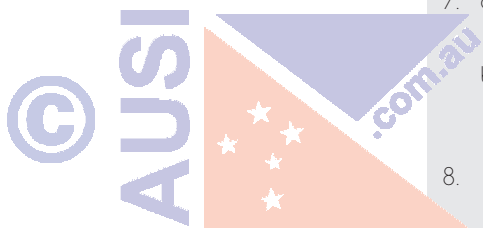
## Effects of bubbles in the tissues

- DCI is result of bubbles formed in tissues of the body
- Bubbles appear to slow the elimination of nitrogen
- Bubbles lodging in tissues of the body may block blood supply or nerve impulses
- Bubbles may cause permanent damage to tissues



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1. a) What is the unique property of a gas?  
  
b) Simply state Pascal's Principle.
2. What three physical elements does the combined gas law tie together?
3. If a scuba cylinder is filled "hot" what will happen to air pressure as it cools?
4. a) What would the volume of a six litre balloon at the surface become at?  
(i) 10m (33')  
(ii) 30m (100')
- b) What would the volume of a six litre balloon at 40 metres (133') become at?  
(i) 20m (67')  
(ii) 10m (33')
- c) How do you keep the volume of a flexible container constant?  
(i) on descent  
(ii) on ascent
- d) What happens to the density of air as we dive deeper?



5. a) What is the partial pressure of oxygen in air at?
  - (i) 0m (0')
  - (ii) 40m (133')
  - (iii) 90m (300')
- b) What is the partial pressure of pure oxygen at?
  - (i) 0m (0')
  - (ii) 10m (33')
6. What is the rate of diffusion dependent on?
7. a) What does saturation mean?
- b) What does supersaturation mean?
8. List two major factors that influence the rate and amount of nitrogen that will dissolve in a tissue.
9. What is an asymptomatic bubble?
10. List three effects of bubbles in the tissues.