Surface to Volume Ratio

Learning objectives

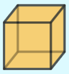
- ☐ Explain how the size of an organism and its structure relates to its surface area ratio
- ☐ Describe how larger organisms increase their surface area to volume ratio
- ☐ Know that exchange surfaces are adapted for exchange
- ☐ Understand that rate of diffusion is dependent on these adaptions
- ☐ Know that the rate of diffusion can be calculated using Flick's Law of Diffusion

Surface to volume ratio

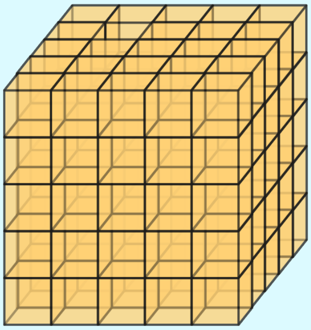
All organisms need to **exchange materials** with their **environments**. A cell needs oxygen and nutrients to grow and function. Cells also need to get rid of **waste products** like carbon dioxide and urea. The transfer of materials takes place across **cell membranes**. The **ease of exchange of materials** for an organism depends on **their surface area to volume ratio**. **Larger organisms** have a **smaller surface to volume ratios** than smaller organisms. This makes it hard for them to exchange with their environment. However, larger organism have specially adapted organs to increase their surface area.

Example

Consider a hamster and a giraffe; although a hamster has **much less surface area** than a giraffe, it has a much **bigger surface area to volume ratio**. This is because it is a ratio, it is easier to understand if we simplify the hamster to a cube, and the giraffe a larger sized cube:



This cube represents a hamster
It is has a width, length and high of 1 unit
Surface area: (1x1) x 6 = 6 units²
Volume: 1x1x1 = 1 units³
Surface area to volume ratio: **6.0:1**

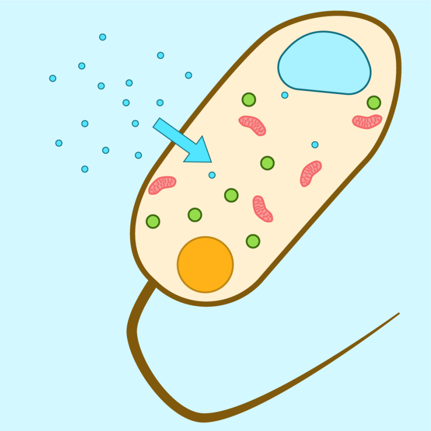


This cube represents a giraffe
It is has a width, length and high of 5 units
Surface area: (5x5) x 6 = 150 units²
Volume: 5x5x5 = 125 units³
Surface area to volume ratio: 150:125 = **1.2:1**

Even though the hamster-sized cube has **less surface area**, it has a much **higher surface area to volume ratio**. Organisms find all sorts of different ways to **maximise** surface area to volume ratio. It is why **leaves are flat** and it is why lungs branch into many **very tiny air sacs**. Each exchange organ increases the organism's surface area to volume ratio to achieve a **maximum** amount of **diffusion surfaces.**

Exchange surfaces

Exchange surfaces



Every cell in an organism must be **supplied** with the substances it needs to **function** and have the **waste products removed**. In single-celled organism substances **diffuse straight in and out of their membranes**, but multicellular organisms have many cells that are **deep within the body** and do not have contact with the outside environment. Multicellular organisms also have **smaller surface area to volume ratios, than single-celled organisms**. This means they do not have enough surface area in contact with their environment to absorption and excretion substances by **simple diffusion alone**. Multicellular organisms have evolved to have **specialised exchange organs**, like the lungs, small intestines and gills, that have **specialised exchange surfaces.**

Flick's law of diffusion

Diffusion is the **movement of molecules** from an area of **high concentration** to an area of **low concentration**. Diffusion is a **passive process** – it does **not** require energy. Multicellular organisms can use this to their advantage for **substance exchange**, so they do not have to waste energy to get substances they require. **Flick's law of diffusion states** that the **rate of diffusion** is **proportional** to serval factors:

$$rate\ of\ diffusion \propto \frac{surface\ area\ x\ difference\ in\ concentration}{width\ of\ gas\ exchange\ surface}$$

Flick's law of diffusion tells us what **affects the rate of diffusion**. Exchange surfaces need to be **adapted for fast rates of diffusion.** They do this by:

- Increasing surface area
- Increase the concentrations of the diffused substance
- Decreases the width of the exchange surface

Common adaptations of exchange surfaces:

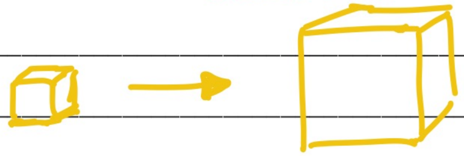
- A **large** surface area to volume ratio
- Only a **few cells** separate the internal and external environments so the diffusion distance is small
- **Selectively permeable membranes**
- **Movement** of the environmental medium (e.g. the movement of air into and out of the lungs), to **maintain a diffusion gradient**
- A **transport system** to **maintain a diffusion gradient**

Exchange surfaces

Exam Questions

1. (a) Describe the relationship between size and surface area to volume ratio of organisms.

As size increases surface area to volume ratio decreases



(1)

(b) A scientist calculated the surface area of a large number of frog eggs. He found that the mean surface area was 9.73 mm^2. Frog eggs are spherical.

The surface area of a sphere is calculated using this equation

$$\text{Surface area} = 4\pi r^2$$

where r is the radius of a sphere

$$\pi = 3.14$$

Use this equation to calculate the mean diameter of a frog egg.

Show your working.

1. Find radius

$SA = 4\pi r^2$

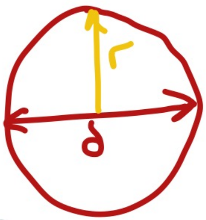
$\frac{SA}{4\pi} = r^2$

$\sqrt{\frac{SA}{4\pi}} = r$

$\sqrt{\frac{9.73}{4\pi}} = r = 0.88$

diameter = $2 \times r$

$d = 0.88 \times 2 = 1.76$



Diameter = 1.76 mm

(2)

The scientist calculated the ratio of surface area to mass for eggs, tadpoles and frogs. He also determined the mean rate of oxygen uptake by tadpoles and frogs.

His results are shown in the table.

Stage of frog development	Ratio of surface area to mass	Mean rate of oxygen uptake / μmol g^{-1} h^{-1}
Egg	2904 : 1	no information
Tadpole	336 : 1	5.7
Adult	166 : 1	1.3

(c) The scientist used units of μmol g^{-1} h^{-1} for the rate of oxygen uptake.

Suggest why he used μmol in these units.

Only a very small amount of Oxygen up take, μ avoids using too many decimal places.

$\mu = 10^{x-6}$

(1)

(d) The scientist decided to use the ratio of surface area to mass, rather than the ratio of surface area to volume. He made this decision for practical reasons.

Suggest **one** practical advantage of measuring the masses of frog eggs, tadpoles and adults, compared with measuring their volumes.

1. Measuring mass is more acurrate than measuring SA
2. Measuring mass is quicker
3. Measuring SA could destress/harm the animals

(1)

(e) Explain why oxygen uptake is a measure of metabolic rate in organisms.

Oxygen is used in respiration, which is a metabolic process, that provides energy

(1)

(f) A student who looked at these results said that they could not make a conclusion about the relationship between stage of development and metabolic rate.

Use information in the table to explain reasons why they were unable to make a conclusion.

There is no data for the egg - student can not compare all stages.

A statistical test has not been performed (T-test).

(3)

(Total 9 marks)

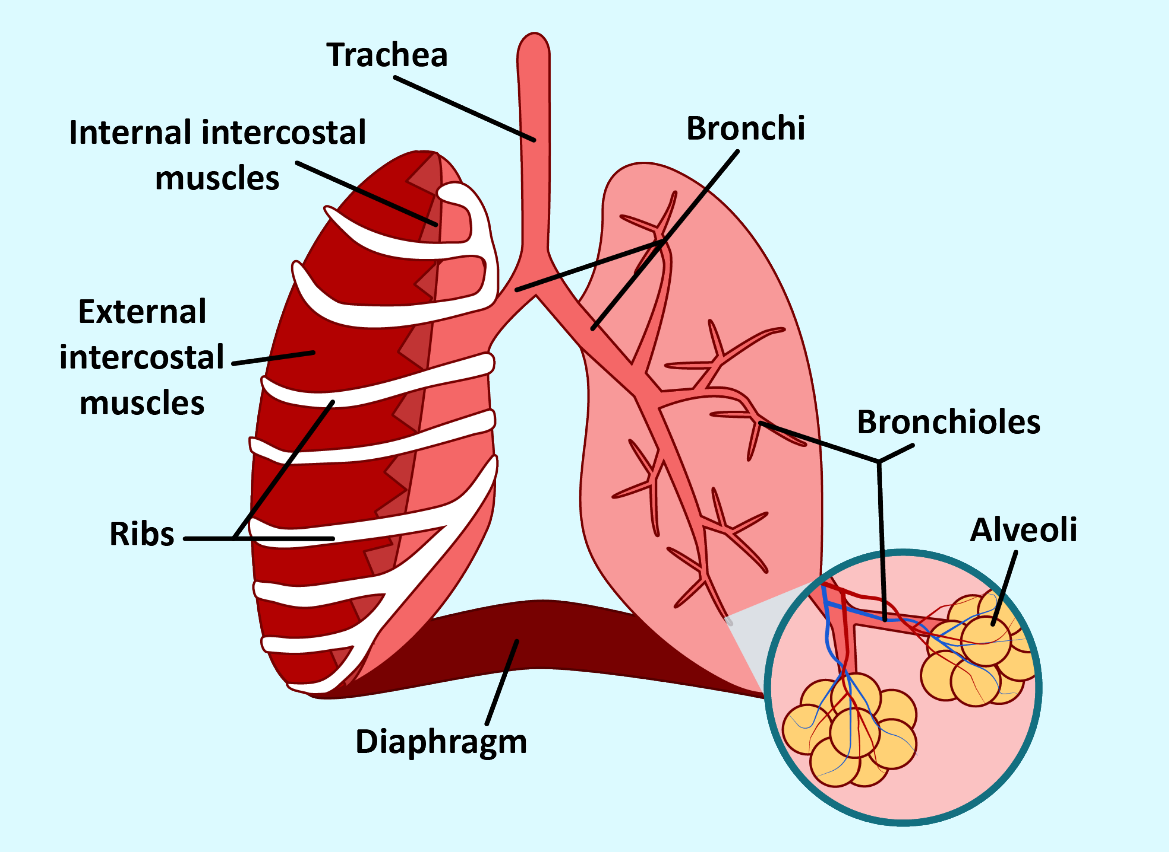
The Lungs

Learning objectives

- ☐ Know the gross structure of the human gas exchange system
- ☐ Understand the function of Goblet cells; Cilia; Cartilage; Smooth muscle; Elastic fibres
- ☐ Know the specialised feature of the alveoli and their capillaries for rapid gas exchange
- ☐ Understand mechanisms of breathing; including the role of the diaphragm and the intercostal muscles in causing pressure changes
- ☐ Understand what a spirometer measures
- ☐ Know how to read a spirometer trace for: tidal volume, vital capacity, breathing rate and oxygen consumption.

The structure of the lungs

Lungs are the **gaseous exchange organs** in **mammals**. They help **provide oxygen** and **remove carbon dioxide** from the blood. The lungs are inside the body, in the rib cage, because they are **delicate structures** that need **protection** and **support**. They also require **wet surfaces**. If they were on the outside of the body would lose a lot of water. The ribs have **muscles in-between** them called **intercostal muscles**. These muscles and the **diaphragm** work together to **ventilate the lungs**, by exhaling air with low oxygen and high carbon dioxide and refreshing it with air with high oxygen and low carbon dioxide. Ventilation maintains a **diffusion concentration gradient**.



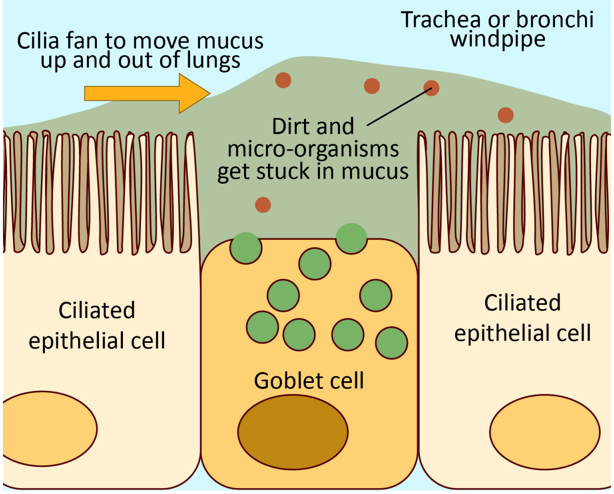
The Lungs

Key features of the lungs

Goblet cells – specialised cells that secrete **mucus** to **trap dirt** and **microorganisms** to stop them from reaching the alveoli and prevents lung infections.

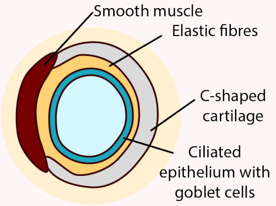
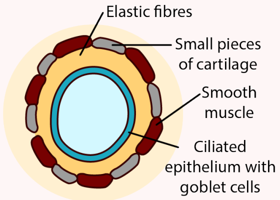
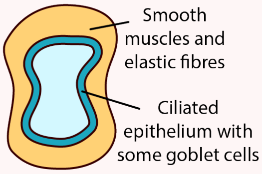
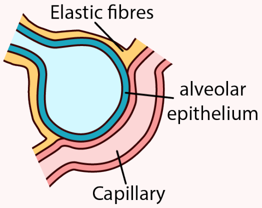
Cilia – **hair-like** structures on the epithelial cells. They move **mucus up and out** of the lungs to the throat.

Elastic fibres – aid in **breathing out.** When breathing in the fibres are stretched, then the fibres recoil helping to push air out.



Smooth muscle – controls the **diameter of the airways**. When you exercise, the smooth muscle relaxes making the airways wider, allowing for greater airflow.

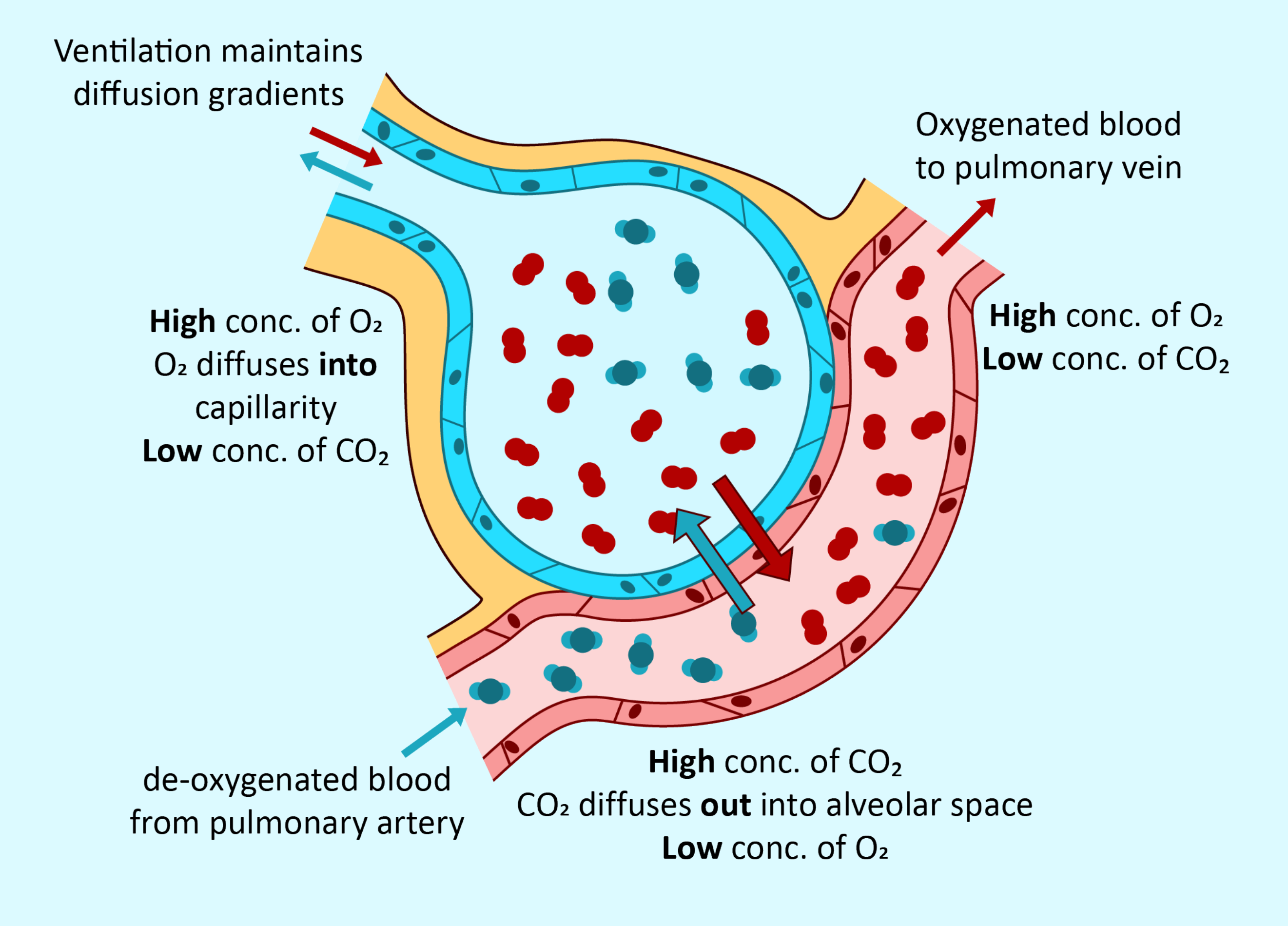
Cartilage – provides **support** and **prevents the trachea and bronchi** from **collapsing** when pressure drops from breathing in.

Part of the lung	Goblet cells	Cilia	Elastic fibres	Smooth muscle	Cartilage	Cross-section
Trachea	✓	✓	✓	✓	✓	
Bronchi	✓	✓	✓	✓	✓	
Large Bronchiole	✓	✓	✓	✓	✗	
Medium bronchiole	✗	✓	✓	✓	✗	
Small bronchiole	✗	✗	✓	✗	✗	
Alveoli	✗	✗	✓	✗	✗	

The Lungs

Gas exchange in the alveoli

Alveoli have **networks of capillaries** running over them. The **epitheliums** of the alveoli and capillaries are one cell thick and semi-permeable, gases can diffuse into and out of the blood from the alveolar space, and vice versa. Air contains **O_2, CO_2 and nitrogen**. At first, the **capillary** has a **low concentration of O_2** compared to air, and a **high concentration of CO_2**, but an equal amount of nitrogen. This creates **two diffusion gradients. O_2 will diffuse into** the capillary, and **CO_2 will diffuse out**. As this happens the amount of **O_2 in the alveolar space decreases** and the amount of **CO_2 increases**. This reduces the concentration gradients and so, the air is exhaled. Exhaled air also contains more water vapour, as the lungs are very moist.



Specific adaptations of the alveoli:

- **Large surface area** – due to **many** alveoli, this **increases** the organism's surface area to volume ratio
- **Moist walls** – diffusion of **gases is quicker** when they are **dissolved**
- **Permeable walls** – lets the gases diffuse from the alveola space into the blood
- **One cell thick walls** – **short diffusion distance** increases the rate of diffusion
- **Extensive blood supply** – maintains the **concentration gradients** by removing oxygenated blood and supplying de-oxygenated blood

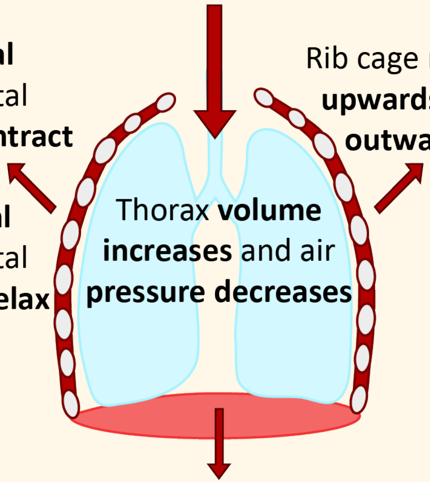
The Lungs

Ventilation (breathing)

Ventilation is the process of breathing in and out, or **inspiration** and **expiration**. The **movements** of the **diaphragm, intercostal muscles, and ribcage** control breathing. There are **two types** of intercostal muscles; internal and external. You need to know what happens during both inspiration and expiration.

Inspiration (breathing in)

Inspiration requires energy – it is an **active process**



Air flows **in**

External intercostal muscles **contract**

Internal intercostal muscles **relax**

Rib cage moves **upwards** and **outwards**

Thorax **volume increases** and air **pressure decreases**

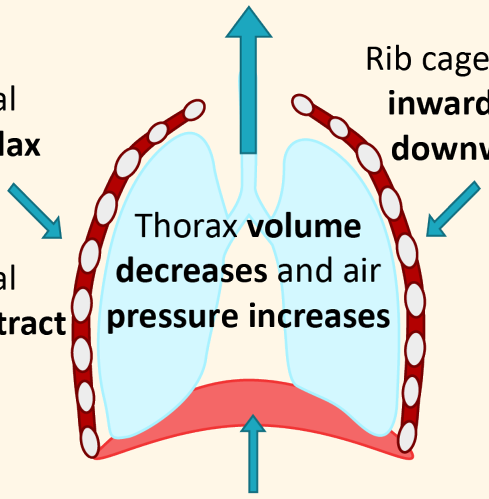
Diaphragm **contracts, flattens** and **moves down**

1. The **diaphragm** and **external** intercostal muscles **contract**; the **internal** intercostal muscles **relax**.
2. The rib cage moves **upwards and outwards.**
3. The diaphragm is **flat**; causing an **increase** in the **volume** of the lungs space or **thorax**.
4. An **increase** in the thorax volume causes a **decrease in lung pressure** to below atmospheric pressure.
5. Air **flows into lungs.**

Expiration (breathing out)

Expiration does not require energy – it is a **passive process.**

1. The **diaphragm** and **external** intercostal muscles **relax**, while the **internal** intercostal muscles **contract**.
2. The rib cage moves **downwards and inwards.**
3. The diaphragm is **curved**; this **decreases** the volume of the thorax.
4. A **decrease** in the thorax causes an **increase in air pressure** to above atmospheric pressure.
5. Air **flows out of lungs.**



Air flows **out**

External intercostal muscles **relax**

Internal intercostal muscles **contract**

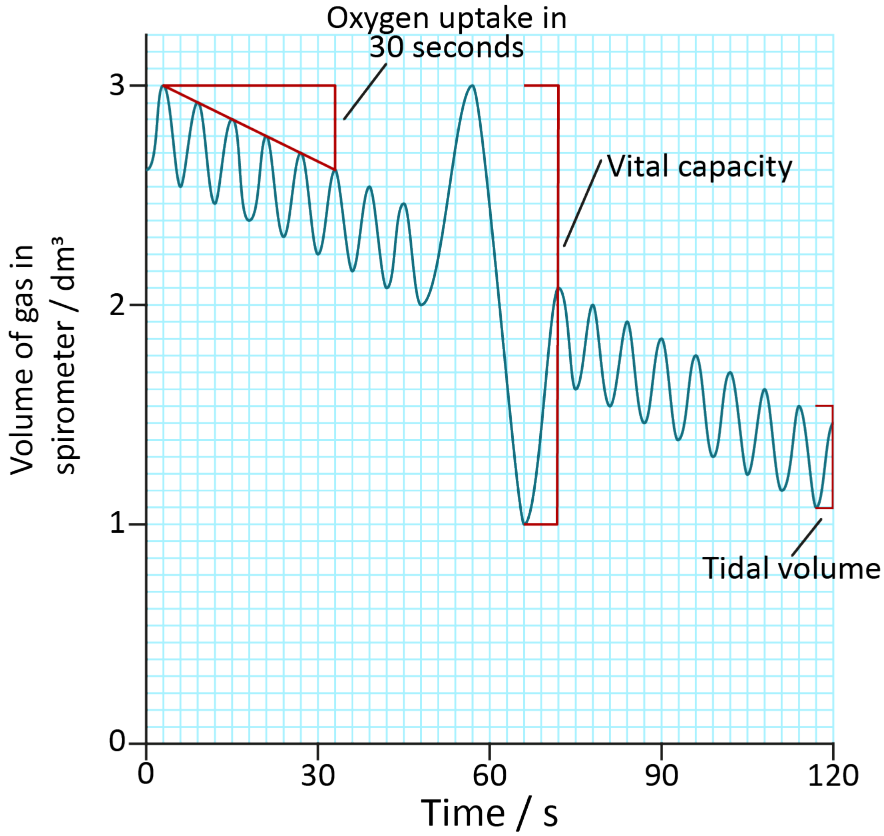
Rib cage moves **inwards** and **downwards**

Thorax **volume decreases** and air **pressure increases**

Diaphragm **relaxes, curves** and **moves up**

Spirometers

When doctors **investigate a patient's breathing**, they use a **spirometer**. It is a machine that measures data about someone's; **tidal volume, vital capacity, breathing rate** and **oxygen uptake.** It works by breathing into and out of a tube connected to an air chamber. The machine monitors the volume of air. As you **breath in** the **volume decreases,** creating **troughs** and as you breath **out** it **increases**, creating **peaks**. Over a period of time the **volume drops** as you use up the oxygen. A spirometer produces a **spirometer trace**, which you need to know how to read.



Tidal volume – the **amount** of air in each breath (~0.4dm^3)
Vital capacity – the volume of the **maximum amount of air** that can be breathed in or out
Breathing rate – the number of **breaths per minute**
Oxygen uptake – the **rate a person uses up oxygen**.

Medical uses

Spirometers are used in **medicine to diagnose asthma**, **chronic obstructive pulmonary disease** and other breathing conditions. They are also used to check whether **treatment is helping the patient to breathe better**, by taking a spirogram at the start of treatment and comparing it to one during treatment.

The Lungs

Disease of the lungs

COPD

Chronic obstructive pulmonary disease (COPD) is a lung disease characterised by long-term breathing problems and poor airflow. It is a chronic disease that gets worse with age. There is **no cure**. In COPD the **irritants damage both: t**he **alveoli** reducing the surface area for gas exchange; and the **lining of the bronchi and bronchioles** by destroying the **cilia.** As the cilia can not remove the mucus, people with COPD will cough it up, however this does not prevent lung infections from happening.

Symptoms:

- Shortness of breath
- Cough with sputum production
- Wheezing
- Tightness in chest

Causes:

- Long term expose to irritants, e.g. smoking
- And very rarely a genetic condition

Treatment includes:

- Lifestyle changes
  - Stopping smoking
  - Avoid second hand smoke
  - Changing diet
- Inhalers – makes breathing easier
- Oxygen therapy – in server COPD to increase oxygen levels in the blood
- Surgery – last resort, to remove damaged parts of lungs

Asthma

Asthma is a lung disease characterised by **recurring short-term**, breathing problems. These breathing problems are caused by the **swelling** of the windpipes in the lungs. They become **narrow** and this makes it hard to breath. The swelling can be **triggered** by many things, such as, the cold, exercise, pollution. When his happens it is known as an **asthma attack**. It is **unknown** what causes asthma but there is a higher rate of it in cities compared to the countryside.

Symptoms:

- Shortness of breath
- Wheezing
- Tightness in chest
- Asthma attacks
- Trouble breathing

Treatment includes:

- Relaxant inhalers
  - These relax the windpipes
  - Used during an asthma attack, or the when the patient can feel one coming on
  - Used only when needed
- Prevention inhalers
  - Prevent asthma attacks
  - Used regularly as part of a treatment plan

Exchange surfaces

Specific adaptations of the lungs:

- **Large surface area** for diffusion to happen across - from having **many alveoli**
- **Short diffusion distance** –the alveolar and capillary epithelium are **one cell thick**
- Are **moist** – moist surface increase the **speed of diffusion**
- Maintain a **diffusion gradient**
  - **Blood** continuously takes away oxygen and brings CO_2
  - The **diaphragm** and **intercostal muscle ventilate** the air in the alveolar space, providing oxygen and removing CO_2

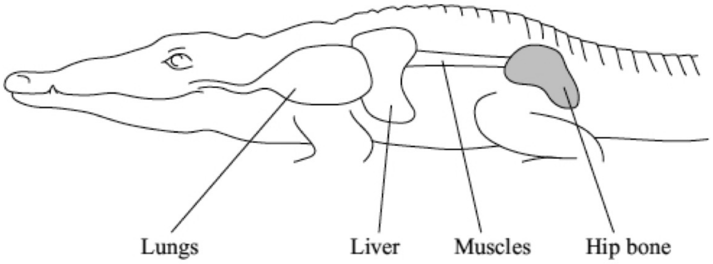
Exam Questions

3. Read the following passage.

When a person breathes in, the diaphragm muscle contracts and the diaphragm flattens. This, together with movement of the ribs, leads to air being drawn into the lungs. Breathing out is generally passive and results from the relaxation of the diaphragm muscle and the elastic recoil of the lung tissue.

Two sets of intercostal muscles also play an important part in breathing in humans. Contraction of the external intercostal muscles is associated with breathing in. During strenuous exercise, contraction of the internal intercostal muscles helps force air out of the lungs. In this case, breathing out is active.

Crocodiles also have lungs and breathe air. They have well developed intercostal muscles but do not appear to use these during breathing. They also lack a diaphragm. Breathing in, in crocodiles, is brought about by contraction of muscles attaching the liver to the hip bones (see diagram). This pulls the liver back and causes air to enter the lungs. Breathing out results from the contraction of abdominal muscles which move the liver forwards.



Use information in the passage and your own knowledge to answer the questions.

(a) Describe the movement of the ribs when a person breathes in (line 2).

Upwards and outwards

(1)

(b) (i) Explain what is meant by passive (line 3).

Does not require energy expenditure

(1)

(ii) Is breathing out in crocodiles active or passive? Explain your answer.

Active, as muscles contract

(1)

(c) Explain how movement of the liver causes air to enter a crocodile's lungs.

1. liver moves back
2. Volume of lungs increases
3. pressure in lungs lower than air
4. Air moves to low pressure

(3)

(d) Describe the difference in the composition of gases in inhaled and exhaled air. Explain how these differences are caused.

Inhaled air contains more O_2 and less CO_2 that exhaled air. Inhaled air also contains more water vapour. The relative amount of nitrogen changes. This happens because respiration uses O_2 and produces CO_2. When blood arrives at lungs it has a lower conc. of O_2 and a higher conc. of CO_2 than the inhaled air. This causes diffussion gradients. O_2 from air enters the blood and CO_2 leaves the blood and enters the air. The air is exhaled.

(6)

(Total 12 marks)

Fig. 3.1 shows a trace recorded from this apparatus.

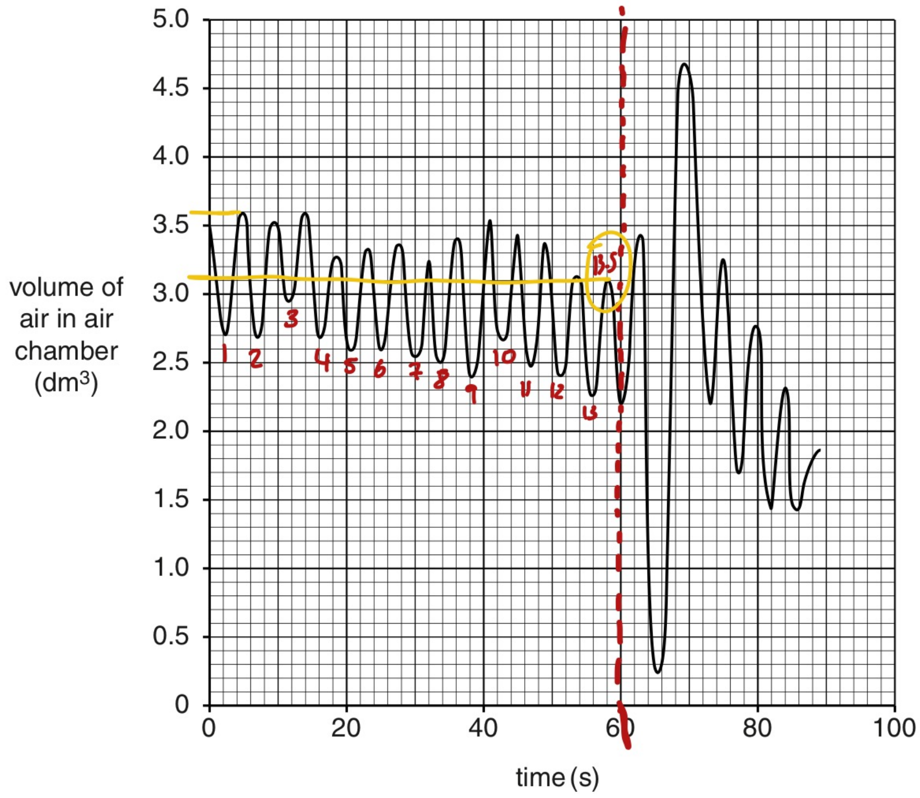


Fig. 3.1

(ii) Calculate the rate of breathing over the first minute from the trace.

answer = ...13.5.................... breaths per minute **[1]**

(iii) Using the trace, calculate the rate of oxygen consumption over the first minute.

Show your working.

First peak = 3.6

last peak = 3.1

3.6 − 3.1 = 0.5

answer = ...0.5................................ dm^3 min^{-1} **[2]**

[Total: 11]

(d) Fig. 4.1 shows the trace from a spirometer recorded from a 16-year-old student.

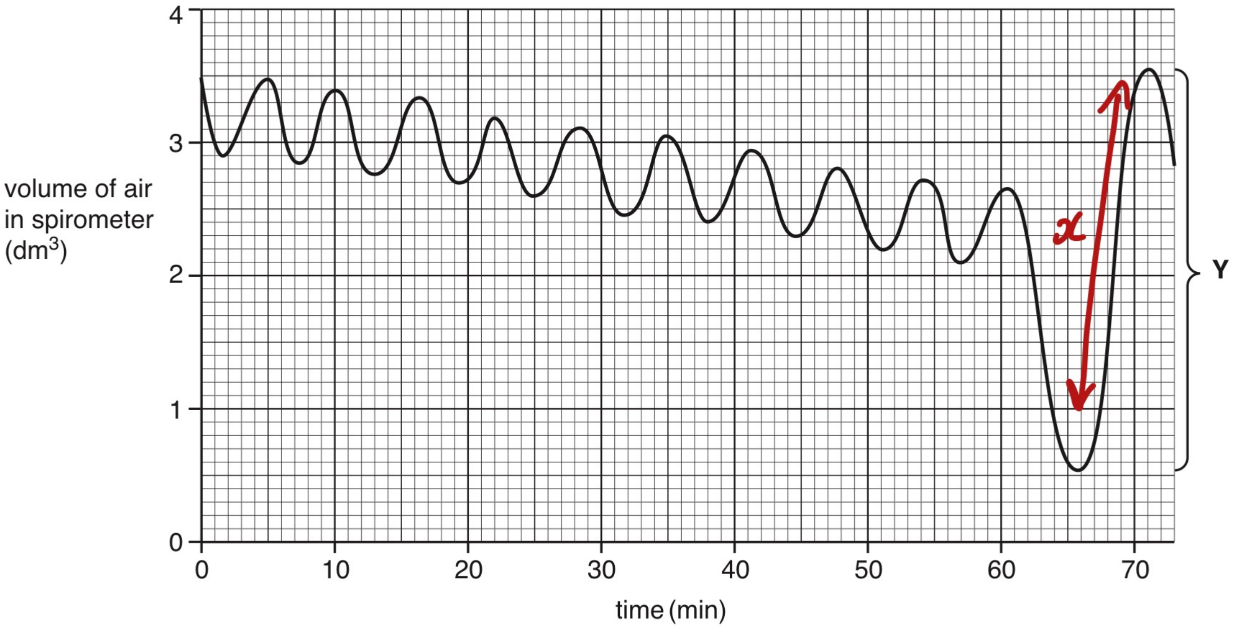


Fig. 4.1

(i) **Label on the trace**, using the letter **X**, a point that indicates when the student was inhaling. **[1]**

(ii) At the end of the trace the student measured his vital capacity. This is indicated by the letter **Y**.

State the vital capacity of the student.

3dm³ .... **[1]**

Tracheae and Gills

Learning objectives

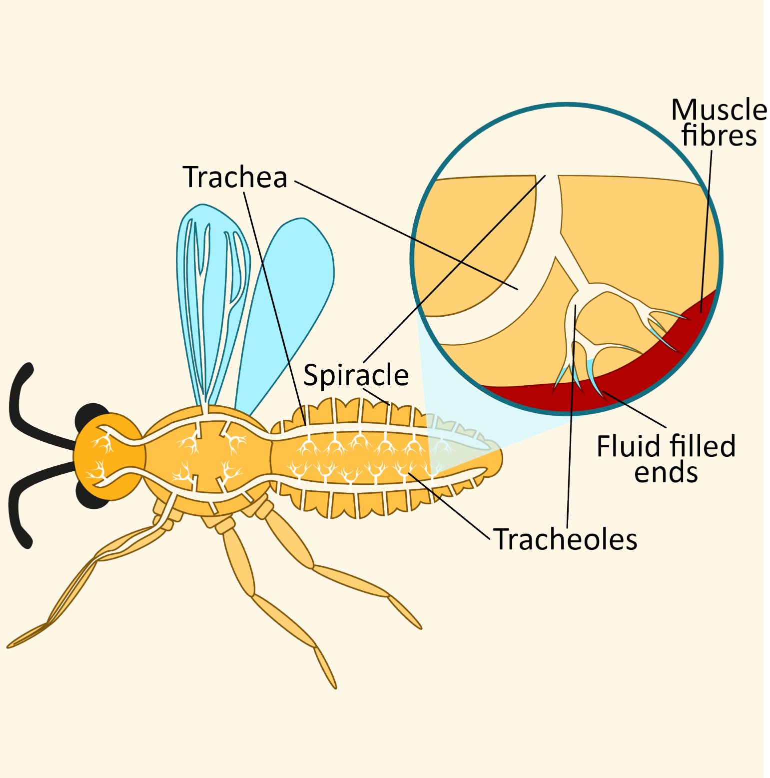
- ☐ Know the gaseous exchange system of an insect, including:
  - ☐ Function of spiracles, trachea, thoracic and abdominal movement
  - ☐ Gaseous exchange with tracheal fluid
- ☐ Know the gaseous exchange system of fish including:
  - ☐ Function of the operculum, gill filaments and gill lamellae
  - ☐ How countercurrent flow maintains a diffusion gradient

Gaseous exchange in insects

Insects do **not** have lungs; instead, they have a **series of internal tubes** called **tracheae.** The **larger tubes** are **called trachea.** The trachea branch into **tracheoles**. The tracheoles **extend throughout the body tissues** of the insect. Atmospheric air is **brought close to every single cell** in the insect's body, allowing for **diffusion** of oxygen and CO_2. Air **enters and leaves** the tracheae through tiny holes in the surface of the insect, called **spiracles.** The spiracles can **open and close**. When they are closed, it **prevents water loss**. The spiracles are closed most of the time.

When the insect is **less active** the end of the tracheoles is **filled with fluid**. The fluid is the boundary between where **gaseous exchange happens**. When the insect is **active** there is **less fluid**, making the diffusion boundary **closer to muscles** allowing for **quicker** diffusion. In **extreme cases** there is **no fluid** and diffusion occurs straight across the muscle cells.

However, **diffusion alone** does not meet the respiratory demands of **larger insects**. Insects **force air** in and out of their tracheae by **moving their body segments** (the thoracic and the abdominal).



Insects are **small** because the **tracheae cannot** meet the **respiratory demand of larger** animals. It is **not efficient enough**. However, about 300 million years ago, when oxygen levels were higher in the atmosphere there were giant insects. Dragon flies with wingspans of 70cm and millepedes bigger than 2.5 meters!

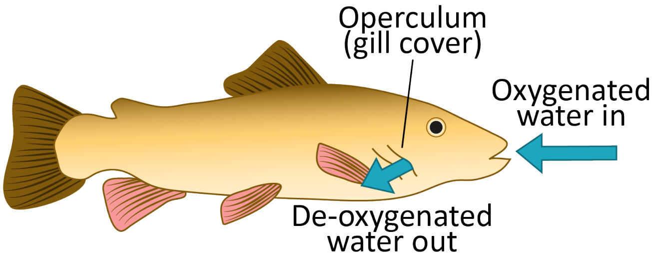
Tracheae and Gills

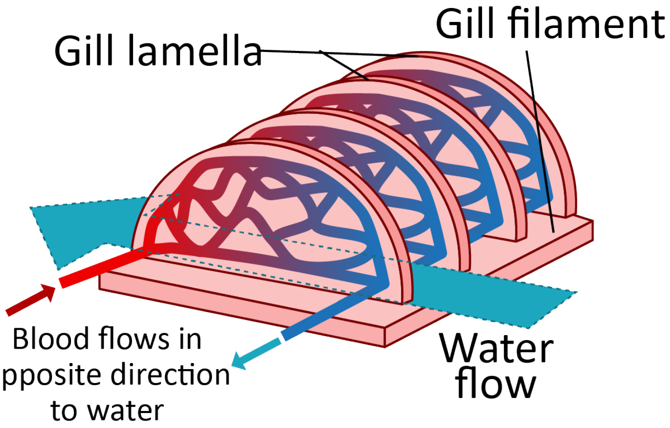
Specific adaptations of the tracheae:

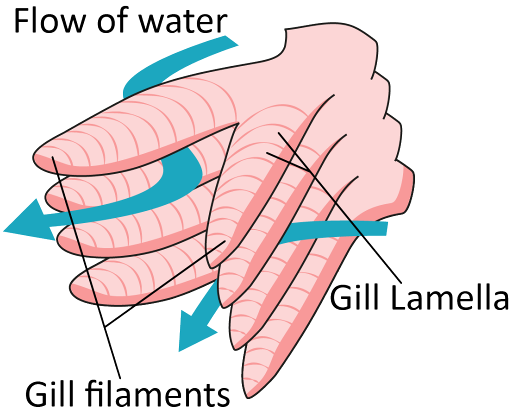
- **Large surface area** – the **extensive network of trachea** provides a large surface for diffusion to happen across
- **Short diffusion distance**
    - The **tracheoles end near every cell**, so there is a short diffusion distance for gas exchange
    - There is **fluid** in the ends of the tracheoles, during periods of anaerobic respiration lactate cause water to move into the muscles, in turn, this draws air further into the tracheoles
- **Maintaining a diffusion gradient** –
    - Insects can **contract muscles** around the **trachea** cause the **mass movement of air** into and out of the network

Gaseous exchange in bony fish

Oxygen is dissolved in water, to get oxygen and excrete carbon dioxide, fish have **gills**. Gills are specifically **adapted gaseous exchange surfaces**. They are located just **behind the head** and are made up of **stacks of gill filaments**. Coming out at **90°** to the gill filaments are **gill lamella.** There are **many lamella** this **increases** the surface area of the gills. The fish takes water in through its mouth, **forcing oxygenated water over the gills**, using bony structures called **operculum**. **Operculum** also **protect** the gills. Then deoxygenated water is **forced out** the through openings in the side of the fish.



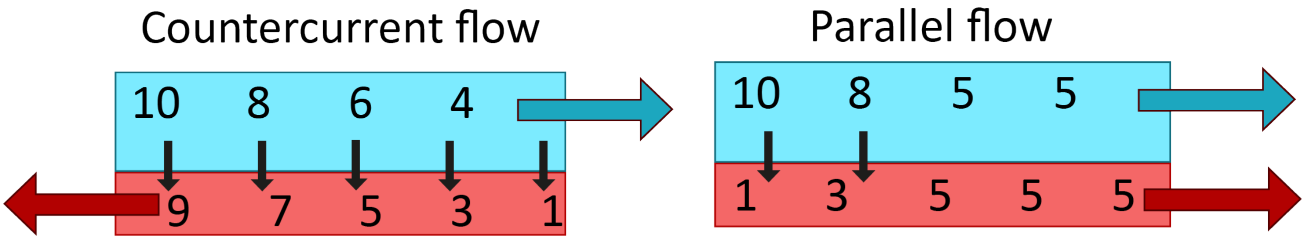




Tracheae and Gills

Countercurrent flow

The **flow of water over the gills** is in the **opposite** direction to the **flow of the blood.** This is an **essential** feature of the gills, as it allows for **maximum gas exchange**.



The numbers above represent the **relative oxygen concentration** of the blood and water. In the **countercurrent** flow the **blood with little oxygen** meets the water that has had **most of the oxygen removed**. The **blood** with the **most oxygen meets** water that has the **most oxygen in it**. Countercurrent flow **maintains** the **diffusion gradient** and about 80% of the available oxygen is absorbed into the blood. (Without countercurrent flow this would be about 50%).

Specific adaptation of the gills:

- **Large surface area** – the extensive network of **gill filaments and lamella** provides a **large surface** for diffusion to happen across
- **Short diffusion distance** – the blood vessel and water are **very close together**
- **Maintaining a diffusion gradient** – **Countercurrent flow system** and **ventilation** using the **operculum**

Exam Questions

5 Bony fish and insects have different gas exchange systems. Both can be observed by dissection.

(a) Describe how you would carry out the dissection to display maximum detail of either gas exchange system.

1. Remove Operculum
2. Observe under water placing in buccal cavity to display lamella

[2]

(b) Insects, such as beetles, obtain oxygen by drawing air in through holes in their exoskeleton, called spiracles. Pairs of spiracles on each abdominal segment connect to air tubes that take the air deep into the tissues of the insect for gas exchange.

Diving beetles live in ponds. They carry an air bubble under their wing when they swim underwater. The bubble supplies air to the spiracles. When the bubble has been used up, the beetle comes to the surface to collect a new bubble.

A student carried out an investigation into the effect of temperature on three diving beetles.

- Three beetles (A, B and C) from the same species were used in the investigation.
- They were placed in thermostatically controlled water baths at 10 °C, 20 °C and 30 °C respectively.
- They were observed for one hour.
- The number of times the beetle surfaced to renew its air bubble was recorded.
- Mean values for each temperature were calculated and recorded to the nearest whole number.
- The results are shown in Table 3.

Temperature (°C)	**Number of times beetle resurfaced in one hour**			
	Beetle A	**Beetle B**	**Beetle C**	**Mean**
10	10	12	8	10
20	18	22	18	20
30	44	48	38	43

19

Table 3

The student made an error in their working.

(i) Put a ring around the error in **Table 3** and write the correct answer next to it. Use the space below to show your working.

18
+18
+22
58

$\frac{58}{3} = 19.33 = 19$

[2]

(ii) Fig. 3 shows a diagram of part of the gas exchange system of an insect.

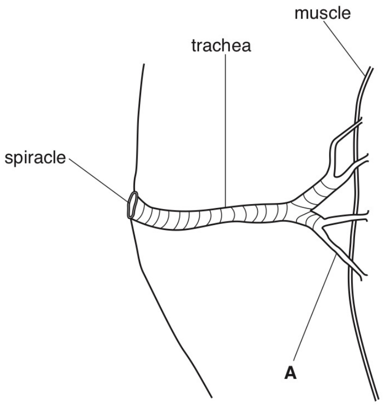


Fig. 3

Name the structure labelled **A**.

Trachede **[1]**

(iii) Describe how the trachea of a mammal is different from the trachea shown in Fig. 3.

Mammals have onl one trachea, insects have many, Mammals have Cartilage and insects don't. Mammals is longer and wider than insects. Mammal have **[2]** goblet cells and insects don't.

6. (a) (i) Name the structure through which gases enter and leave the body of an insect.

Spiracles

(1)

(ii) Name the small tubes that carry gases directly to and from the cells of an insect.

Tracheole and Trachea

(1)

(b) Explain the movement of oxygen into the gas exchange system of an insect when it is at rest.

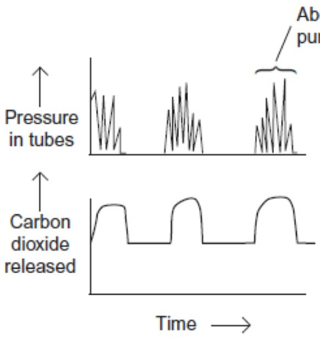
Oxygen is used in aerobic respiration So oxygen diffusion gradient forms, between air in tracheae and insect cells. Oxygen diffuses into Cells.

(3)

(c) Abdominal pumping takes place during vigorous activity in insects. This causes regular squeezing of the tubes of the gas exchange system.

A scientist investigated the effect of abdominal pumping on the pressure in the tubes and the volume of carbon dioxide released by the insect.

Her results are shown below.



Describe and explain these results.

The results show that abdominal pumping is LINKED to CO_2 release.

Abdominal pumping causes a pressure increase in the insects body. Air moves from high pressure to low pressure. Air exits the tracheae.

(3)
(Total 8 marks)