Gas exchange

International Baccalaureate · IB Diploma · Biology · HL

Scope and prerequisites

This unit covers B3.1 SL understandings plus additional higher-level content (marked AHL): exchange surfaces and gradients, mammalian lungs and ventilation, lung volumes, leaf tissues, transpiration and stomatal density, and haemoglobin affinity. Sections marked **AHL** are for Higher Level only.

Prerequisites: diffusion, membranes, area/volume and proteins. Numerical data and curves are invented teaching models, not clinical references. Scope: IB Biology guide, first assessment 2025.

Exchange supplies gases across a permeable surface

A person can move air rapidly yet transfer little oxygen if blood flow or the exchange barrier is impaired. Conversely, blood cannot collect a continuing oxygen supply from an isolated, unventilated volume indefinitely. Follow both sides of the surface rather than explaining exchange with "the lungs breathe".

Gas exchange transfers gases between an organism and its surroundings. Aerobic respiration consumes oxygen and releases carbon dioxide; photosynthesis uses carbon dioxide and releases oxygen. Plants respire as well as photosynthesize. A photosynthesizing leaf can have net carbon dioxide uptake while individual cells are still producing carbon dioxide in respiration. Net exchange depends on the balance of processes and conditions, not simply whether the organism is an animal or a plant.

Small organisms can exchange directly over much of their body surface. In a geometrically similar larger organism, volume increases faster than surface area and internal cells lie farther from the exterior. A thin, folded internal exchange surface plus transport can meet these constraints. No universal size cutoff follows from geometry alone: shape, demand and transport also matter.

Effective surfaces combine a large area, a short diffusion path, permeability and moisture. Gases dissolve in the thin aqueous layer before crossing cell membranes. A thin layer helps; a thick layer of fluid adds a diffusion barrier. Area permits many molecules to cross simultaneously. Thin epithelial and capillary layers reduce distance. These features affect transfer without turning diffusion into an ATP-driven pump.

For comparisons with other factors held constant, a useful qualitative model is:

$$\text{transfer rate} \propto \frac{\text{area} \times \text{concentration difference}}{\text{diffusion distance}}.$$

Doubling area doubles the predicted rate; doubling distance halves it. Doubling both leaves the predicted rate unchanged. This simple relationship compares the same gas and barrier under controlled conditions; it is not a complete numerical model of a living lung.

Ventilation and blood flow maintain separate gradients

Ventilation moves air over lung surfaces or water over gill surfaces. **Perfusion** is blood flow through tissue, including an exchange surface. These are bulk movements; oxygen and carbon dioxide cross the exchange barrier by diffusion down their own gradients. They need not move in the same direction.

In a mammalian alveolus, fresh air helps maintain a higher oxygen partial pressure than in incoming blood. Oxygen dissolves and diffuses into blood. Incoming blood generally has a higher carbon dioxide partial pressure than alveolar air, so carbon dioxide diffuses the other way. Partial pressure describes the contribution of a gas to the total pressure and indicates its diffusion tendency; compare the same gas across the barrier. Do not compare the oxygen percentage on one side with the carbon dioxide percentage on the other.

Continuous blood flow brings blood requiring oxygen and removes oxygenated blood. It also supplies carbon dioxide for removal. A dense capillary network provides extensive contact with alveoli. Ventilation renews alveolar air, while blood flow prevents the blood immediately next to the surface simply reaching equilibrium with a sealed air space and staying there. Haemoglobin binding helps blood carry oxygen without requiring all of it to remain dissolved.

An original sealed-chamber model starts with 100 oxygen units outside and 40 inside a permeable sac. Oxygen initially moves net inward. If the outside falls to 70 and the inside rises to 70, net transfer ceases although molecules still move both ways. Replacing the outside solution and flowing fresh low-oxygen fluid through the sac can restore a gradient. This model isolates renewal; it omits living tissue, metabolism and haemoglobin.

Mammalian lungs combine branching with thin alveoli

Air passes through the trachea, bronchi and progressively smaller bronchioles to alveolar regions. Branching distributes air through the lung; many alveoli provide a large total surface area in a compact volume. Bronchioles conduct and regulate airflow, rather than serving as the main thin gas-exchange barrier themselves.

An alveolar wall includes very thin type I pneumocytes. Adjacent capillaries also have thin walls; short distances between air and blood support rapid diffusion. A moist lining enables gases to dissolve. Surfactant, secreted by type II pneumocytes, lowers surface tension at the air–liquid interface and helps alveoli remain stable during breathing. It does not provide the oxygen gradient or pump oxygen through the wall. Extensive capillary beds combine a large contact area with ongoing blood renewal.

Link each feature to a mechanism: many alveoli increase area; thin walls shorten distance. Loss of area, thickening, reduced ventilation and reduced perfusion can each

decrease exchange; breathing rate alone cannot distinguish them.

Ventilation follows muscle, volume and pressure changes

Muscles change the volume of the thorax; air moves because a pressure difference is created between alveoli and the atmosphere. Lungs follow chest movements through the pleural arrangement and elastic tissues. They do not contain muscles that actively expand each alveolus like a small pump.

Stage	Movement and consequence
Inspiration	Diaphragm contracts and flattens; external intercostal activity raises ribs up and out. Thoracic and lung volumes increase.
Air enters	Alveolar pressure becomes slightly lower than atmospheric pressure during inflow. Air moves inward until pressures equalize.
Quiet expiration	Inspiratory muscles relax; diaphragm returns toward its dome and elastic recoil reduces lung volume. Alveolar pressure rises slightly above atmospheric during outflow.
Forced expiration	Abdominal contraction raises abdominal pressure and pushes the diaphragm upward; expiratory intercostal activity can help draw ribs down. Volume falls more forcefully.

Quiet expiration is normally largely passive, whereas inspiration uses muscle contraction. Avoid saying that the diaphragm contracts upward during expiration. Its upward return during quiet expiration follows relaxation and recoil. See the NHLBI explanation of breathing muscles and recoil.

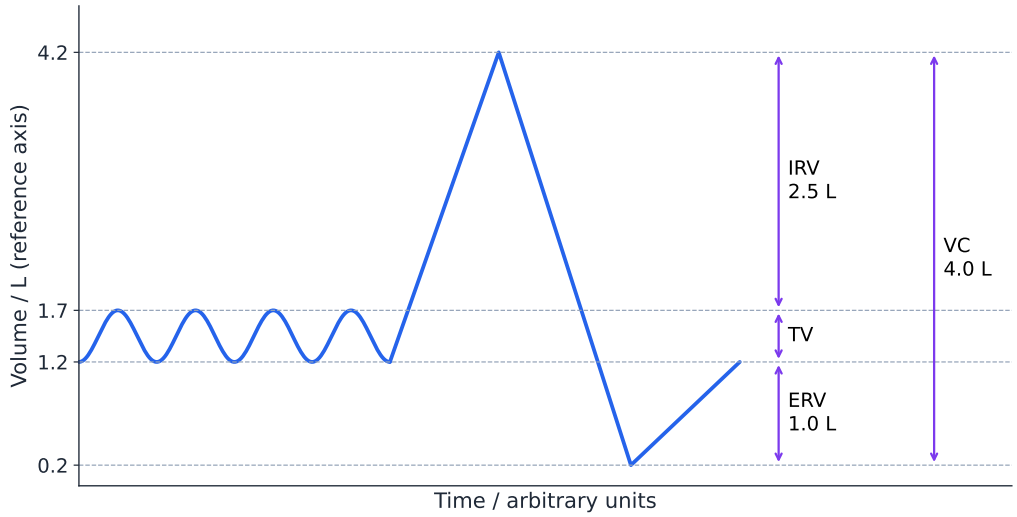
At the end of a breath, airflow can be zero even though lungs still contain air. A larger pressure difference tends to drive greater flow for the same airway resistance; a blocked or narrowed airway changes that resistance. Pressure difference, volume and airflow are related quantities, not interchangeable names for ventilation.

Measure lung volumes and distinguish ventilation from uptake

Tidal volume is the air moved in one ordinary breath. Inspiratory reserve volume is the additional volume that can be inhaled after a normal inspiration; expiratory reserve is the additional volume that can be exhaled after a normal expiration. Vital capacity spans the greatest inhalation to the greatest exhalation:

$$\text{vital capacity} = \text{inspiratory reserve} + \text{tidal volume} + \text{expiratory reserve}.$$

Residual volume remains after maximal expiration. A simple spirometer that measures air moving through the mouth does not measure this trapped remaining volume directly, so it does not directly provide total lung capacity. Do not put zero lung volume at the lowest point of such a trace unless an independent absolute-volume measurement supports it.



The vertical zero is an arbitrary reference. The trace shows changes in volume, not all the air remaining in the lungs.

In the invented trace, normal expiration is at 1.2 L and normal inspiration at 1.7 L on its reference axis. Tidal volume is $1.7 - 1.2 = 0.5$ L. Maximum inspiration is 4.2 L and maximum expiration 0.2 L. Inspiratory reserve is 2.5 L; expiratory reserve is 1.0 L; vital capacity is 4.0 L. These differences do not reveal residual volume.

Minute ventilation is tidal volume multiplied by breaths per minute. A model with 0.50 L per breath at 12 breaths per minute moves 6.0 L per minute. This is air moved, not 6.0 L of oxygen absorbed. Some air occupies conducting airways, called anatomical dead space, and does not reach alveolar exchange surfaces in that breath. With an assumed fixed dead space of 0.15 L per breath, estimated alveolar ventilation is $(0.50 - 0.15)(12) = 4.2$ L per minute. A different pattern, 0.30 L at 20 breaths per minute, has the same minute ventilation but only 3.0 L per minute alveolar ventilation in this model.

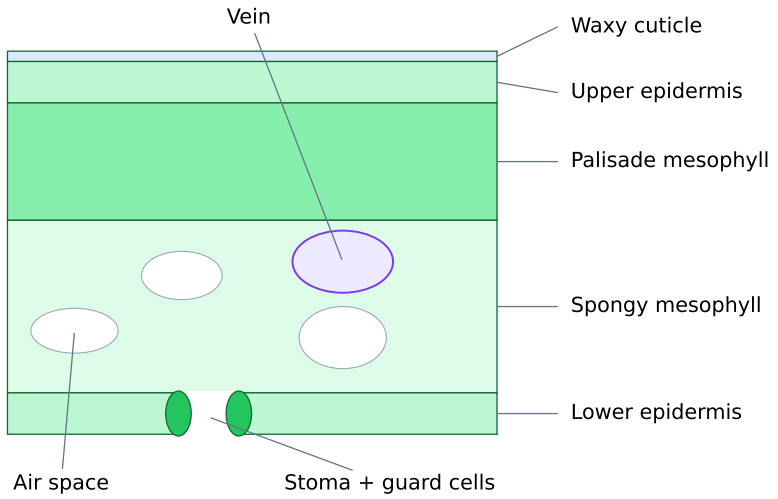
For measurement, calibrate the volume scale, read several regular resting breaths and measure intervals on the time axis. Use clean equipment and the institution's approved supervised protocol. An approved spirometry activity or supplied trace can support identification of reserves and vital capacity. For human demonstrations use voluntary resting measurements; do not induce breathlessness, hyperventilation or unapproved forceful manoeuvres. Explain the distinction using model data when appropriate. Repeated breaths improve an estimate of that person's pattern; they do not represent independent people or establish a population reference range.

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A dicot leaf has connected air spaces and distinct tissues

Leaves exchange gases through stomatal pores, intercellular air spaces and moist mesophyll surfaces. In many terrestrial dicot leaves, the broad thin blade provides area and short distances, while air spaces in spongy mesophyll connect internal surfaces to stomata. Carbon dioxide can diffuse through a pore and air spaces, dissolve on a moist cell wall and enter a photosynthesizing cell. Oxygen can take the reverse path when photosynthesis exceeds respiration.

A typical transverse section has an upper waxy cuticle, upper epidermis, palisade mesophyll, spongy mesophyll with air spaces, and lower epidermis with stomata and guard cells. Veins contain vascular tissues: xylem supplies water and phloem transports assimilates. The cuticle limits uncontrolled water loss but also restricts direct gas exchange over the epidermis. Guard cells regulate pore width, affecting both carbon dioxide entry and water-vapour loss. Stomata are not permanently open holes; the distribution and anatomy vary among species and environments.



This representative arrangement is not universal. A plan diagram shows tissue regions, rather than every individual cell.

When drawing a plan diagram, use clear continuous outlines for tissue boundaries, show relative thickness and position, and label tissues with ruled lines. Indicate a vascular bundle, upper and lower surfaces, mesophyll regions and stomatal position. Do not fill a low-power tissue plan with detailed organelles or invent separate cells where the task asks for tissue distribution. At higher magnification, a cellular diagram can instead show individual guard cells, mesophyll cells and their walls.

Gas exchange brings a water-loss trade-off

Water evaporates from moist mesophyll walls into leaf air spaces, then water vapour diffuses outward through open stomata when the internal-to-external water-vapour gradient favours loss. This transpiration accompanies access for carbon dioxide. It is not the same process as photosynthesis consuming water, nor is most lost water being converted into oxygen at the pore.

Higher external humidity usually reduces the vapour gradient at a given leaf temperature. Wind can remove the humid boundary layer, increasing loss while other factors remain suitable. Increased temperature can increase evaporative demand; light often promotes stomatal opening as photosynthesis becomes possible. However, water stress can close stomata, so a warmer or brighter treatment does not guarantee a measured increase. Explain both the physical driver and the possible plant response. Species, water supply, leaf temperature and air movement are important controls.

In an invented potometer comparison, corrected water uptake is 0.20 mL in 10 minutes in still air and 0.35 mL in 10 minutes under moving air. Uptake rates are 0.020 and 0.035 mL per minute, an increase of 75%. A potometer measures water uptake, which approximates transpiration under suitable conditions; it does not directly measure every water molecule leaving a leaf. Check leaks, allow equilibration, control leaf area and temperature, and include repeats. A change in uptake alone does not identify whether pore width changed.

Estimate stomatal density using area and replication

Stomatal density is the number of stomata per unit epidermal area. Count pores, not each of the two guard cells as a separate stoma. Use a calibrated micrograph or an approved leaf impression. Apply one boundary rule consistently, such as counting pores touching the top and left edges but not the bottom and right edges. Otherwise overlapping fields can bias counts.

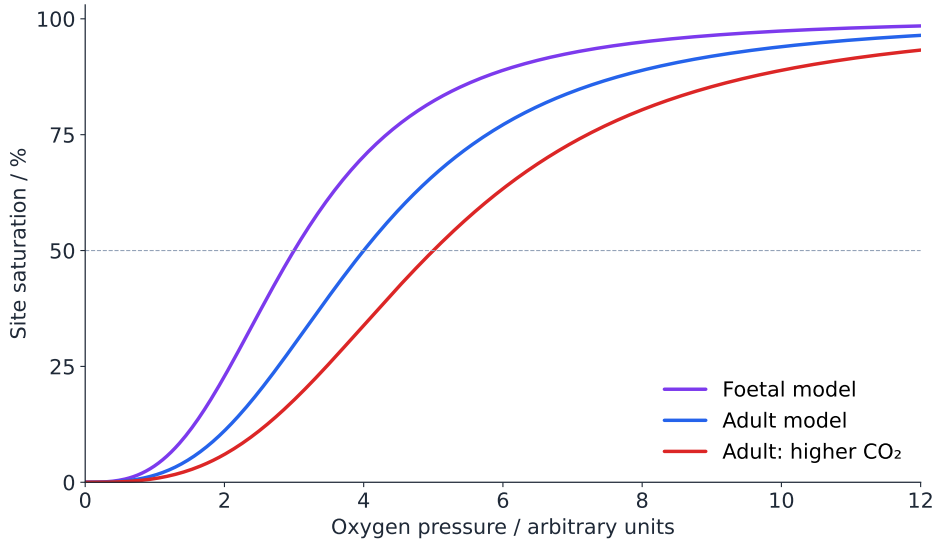
An invented set of four equal fields, each 0.20 square millimetres, contains 32, 36, 28 and 40 stomata. The total is 136 over 0.80 square millimetres; density is 170 per square millimetre. Equivalently, average count 34 divided by 0.20 gives 170. If field areas differ, divide total count by total sampled area rather than averaging unweighted counts. A circular field with radius 0.25 mm has area $\pi(0.25)^2 = 0.196$ square millimetres; 35 stomata correspond to about 178 per square millimetre. Diameter must first be halved.

Sample fields systematically or randomly rather than selecting crowded patches. Repeat across leaves and plants, record the leaf side, position and developmental stage, and distinguish within-leaf fields from independent plant replicates. Compare upper and lower surfaces under the same counting and calibration method. Higher density can permit a greater maximum conductance, but actual exchange also depends on pore size, opening and conditions; density alone does not prove a higher current photosynthetic rate.

AHL: Haemoglobin combines cooperative binding with oxygen release

A haemoglobin tetramer has four haem groups, each able to bind one oxygen molecule reversibly. A fully occupied molecule carries four oxygen molecules, not eight. Binding changes protein conformation so further oxygen binding becomes easier: this positive cooperativity gives a sigmoidal oxygen dissociation curve. At low oxygen availability, relatively little is bound; over the steep region, a small change can cause substantial loading or unloading; at high availability the curve approaches saturation.

The horizontal axis commonly shows oxygen partial pressure; the vertical axis shows percentage saturation of binding sites. Saturation is not the percentage of oxygen in air, the number of red cells or the rate of oxygen uptake. A value of 75% means three quarters of the available sites are occupied across the sample, not that every molecule must have exactly three oxygen molecules attached at that instant.



These illustrative curves use an arbitrary oxygen-pressure scale. They are not clinical measurements or reference ranges.

At a given oxygen partial pressure in the useful comparison region, a left-shifted curve has greater saturation and higher affinity. At half saturation, a lower required oxygen partial pressure likewise indicates higher affinity. “Higher affinity” describes stronger binding under the compared conditions, not automatically better delivery everywhere: blood must also unload oxygen to tissues.

AHL: Foetal haemoglobin supports transfer across the placenta

Foetal and maternal blood exchange gases across a placental barrier without normally mixing directly as one blood pool. Oxygen must diffuse from maternal blood through the exchange tissues into foetal blood. Under physiological red-cell conditions, foetal haemoglobin has higher oxygen affinity than adult haemoglobin, helping foetal blood load oxygen at the lower partial pressures encountered at this interface.

Adult haemoglobin A has two alpha and two beta chains; foetal haemoglobin has two alpha and two gamma chains. Different protein subunits change interactions with allosteric effectors, including weaker binding of 2,3-bisphosphoglycerate by foetal haemoglobin. This helps account for its higher affinity in red cells. Do not claim purified foetal protein must always have greater affinity under every artificial solution condition. The primary study of human foetal and adult haemoglobin interfaces examines how subunit interactions differ.

In an invented comparison at the same oxygen pressure, adult sites are 50% saturated and foetal sites 70% saturated. With equal capacities of 200 oxygen units, the bound amounts would be 100 and 140 units. This difference is not a universal 40-unit transfer at a real placenta; it isolates affinity while holding capacity fixed. Actual transfer also depends on partial-pressure gradients, perfusion and diffusion conditions.

AHL: Carbon dioxide promotes unloading through the Bohr shift

Actively respiring tissues produce carbon dioxide. Increased carbon dioxide and the accompanying increase in hydrogen-ion concentration lower haemoglobin’s oxygen affinity, shifting the oxygen dissociation curve to the right under otherwise comparable conditions. At the same oxygen partial pressure, saturation is lower and more oxygen can be released to tissues. In the lungs, removal of carbon dioxide favours the reverse conditions and oxygen loading.

Carbon dioxide can bind at sites on globin distinct from the oxygen-binding haem sites, contributing to allosteric regulation. It also changes hydrogen-ion conditions through the carbon dioxide–bicarbonate system. Do not describe it as carbon monoxide competing with oxygen for the same haem site, or say that haemoglobin pumps oxygen out using ATP. The Bohr shift changes binding equilibrium; oxygen then diffuses down its gradient.

An invented blood sample enters a tissue at 96% saturation. At the tissue oxygen pressure, a lower-carbon-dioxide condition gives 72% saturation while a higher-carbon-dioxide condition gives 54%. Unloading is 24 versus 42 percentage points of total capacity. The latter is 18 percentage points greater, or $42/24 = 1.75$ times as much under these assumptions. Keep the same starting saturation and capacity in this comparison; differing blood flow or haemoglobin concentration would require additional information.

Practice

All numerical values below are invented models or datasets. Explain mechanisms as well as giving numbers.

1. Explain why a larger multicellular organism faces exchange challenges. Link four properties of a gas-exchange surface to their functions.
2. Distinguish ventilation, perfusion, diffusion and cellular respiration. Explain how a lung can lose an oxygen gradient even while its wall remains thin.
3. In a controlled transfer model, surface area is multiplied by 3 and diffusion distance by 1.5 while the gradient remains constant. Predict the rate relative to the original and state a limitation.
4. Trace air from trachea to alveoli. Explain bronchiole branching, alveolar area, capillaries and surfactant. Compare inspiration, quiet expiration and forced expiration.
5. A reference trace has normal expiration at 0.9 L, normal inspiration at 1.5 L, maximal inspiration at 3.9 L and maximal expiration at 0.3 L. Calculate tidal volume, both reserves and vital capacity. Explain why residual volume is unknown.
6. Compare 0.60 L breaths at 10 per minute with 0.40 L breaths at 15 per minute. Assume dead space 0.15 L per breath. Calculate minute and estimated alveolar ventilation; explain why neither is oxygen uptake.
7. Label a typical terrestrial dicot leaf tissue plan. Trace carbon dioxide into mesophyll; explain stomata, air spaces, cuticle and veins.
8. Explain humidity, wind, temperature and light effects on transpiration, including possible stomatal closure. Uptake changes from 0.24 to 0.36 mL in equal 12-minute periods. Calculate rates and percentage increase; state a measurement limitation.
9. Four equal 0.15-square-millimetre fields have 18, 24, 21 and 27 stomata. Calculate density. Repeat for 30 stomata in a 0.50-mm-diameter circular field. Improve sampling reliability.
10. One field has 20 stomata over 0.10 square millimetres and another 80 over 0.40 square millimetres. Calculate pooled density and explain why doubling the field diameter changes area fourfold rather than twofold.
11. Critique three claims: plants only absorb carbon dioxide; stomatal density proves photosynthesis rate; breathing rate proves oxygen uptake.
12. **AHL:** Explain haemoglobin cooperativity and the axes of an oxygen dissociation curve. A left-shifted sample has 80% saturation and a right-shifted sample 60% at the same oxygen pressure. With equal 150-unit binding capacities, calculate bound amounts and explain affinity.
13. **AHL:** Compare foetal and adult haemoglobin, their subunits and placental oxygen transfer. Explain why a 70% saturated sample need not have every molecule carrying the same number of oxygen molecules.
14. **AHL:** Blood enters at 98% saturation. At a fixed tissue oxygen pressure, low-carbon-dioxide blood leaves at 74% and high-carbon-dioxide blood at 50%. Calculate unloading in percentage points, the difference and ratio. Explain the Bohr shift without confusing carbon dioxide with carbon monoxide.

Worked answers

1. Larger similar shapes have lower area/volume and longer internal distances. Exchange requires large area for parallel transfer, thin tissue for short distances, moisture for dissolution, and permeability for crossing. Demand and transport also matter.
2. Ventilation moves air/water; perfusion moves blood; diffusion transfers molecules down gradients; cellular respiration supplies usable energy. Without renewal on either side, oxygen conditions approach equilibrium and net transfer falls even through a thin wall.
3. Relative rate $= 3/1.5 = 2$: twice the original. This assumes the same gas, barrier permeability and maintained gradient. A living system may have changing blood flow, pressure gradients or functioning area.
4. Trachea $\rightarrow$ bronchi $\rightarrow$ bronchioles $\rightarrow$ alveoli. Branching distributes air; alveoli provide area; thin walls shorten distance; capillary flow renews blood; surfactant stabilizes surfaces. Inspiration: diaphragm flattens, ribs rise, volume increases, pressure falls. Quiet expiration: relaxation/recoil. Forced expiration: abdominal and expiratory intercostal contraction.
5. Tidal $1.5 - 0.9 = 0.6$ L; inspiratory reserve $3.9 - 1.5 = 2.4$ L; expiratory reserve $0.9 - 0.3 = 0.6$ L; vital capacity $3.9 - 0.3 = 3.6$ L, also $2.4 + 0.6 + 0.6$. Relative expired-air measurements cannot establish absolute air remaining after maximal expiration.
6. Both minute values are 6.0 L per minute. Estimated alveolar ventilation is $(0.60 - 0.15)(10) = 4.50$ and $(0.40 - 0.15)(15) = 3.75$ L per minute. Airflow includes gases other than oxygen, and uptake across the barrier depends on gradients, diffusion, perfusion and blood binding.
7. Label cuticle, epidermises, palisade and spongy mesophyll, air spaces, vein, guard cells and stoma. Path: pore $\rightarrow$ air spaces $\rightarrow$ moist wall $\rightarrow$ cell membrane. Cuticle restricts water loss; stomata regulate access; air spaces distribute gases; xylem supplies water and phloem transports assimilates. Plans show tissues, not organelles.
8. Humidity reduces the vapour gradient; wind removes humid air; heat increases evaporative demand; light can promote opening. Water stress can close pores. Rates $0.24/12 = 0.020$ and $0.36/12 = 0.030$ mL per minute: $0.010/0.020 \times 100 = 50\%$ increase. Uptake approximates loss; leaks/storage can affect it. Control area/conditions and repeat.

9. Total $90/0.60 = 150$ stomata per square millimetre. Radius 0.25 mm gives area 0.19635 square millimetres and density $30/0.19635 \approx 153$. Calibrate, use a boundary rule, sample unbiased fields, and repeat across leaves and independent plants.
10. Pooled density $100/0.50 = 200$ per square millimetre, matching both fields individually. Circular area scales with diameter squared: doubling diameter quadruples area.
11. Plants also respire. Net exchange depends on the balance. Photosynthesis also depends on pore size/opening and metabolic conditions. Breathing rate omits tidal volume, dead space, gas composition and transfer/perfusion evidence.
12. **AHL:** Oxygen binding changes conformation and increases subsequent binding affinity, producing a sigmoid rather than a straight line. Axes are oxygen partial pressure and percentage site saturation. Amounts $0.80(150) = 120$ and $0.60(150) = 90$ units. At the same pressure, the left-shifted sample has greater affinity under the specified conditions; this is not automatically greater tissue delivery.
13. **AHL:** Adult A is alpha-two/beta-two; foetal is alpha-two/gamma-two. Foetal haemoglobin's higher affinity under physiological red-cell conditions helps oxygen load across the placental barrier; blood normally remains in separate circulations. Different allosteric interactions contribute. Saturation is a population average over binding sites: 70% of sites occupied does not require identical occupancy of all four-site molecules.
14. **AHL:** Unloading is $98 - 74 = 24$ versus $98 - 50 = 48$ percentage points: 24 points more and twice as much. Higher carbon dioxide/hydrogen-ion conditions lower affinity, shifting the curve right. Carbon dioxide acts through distinct globin sites and acid–base conditions; it is not carbon monoxide competing at haem. Starting saturation and capacity are held constant.

Exam tips

Link structures to mechanisms; separate ventilation, diffusion and uptake. Subtract trace levels; calculate field area and count pores. Use independent plants.

- **AHL:** Compare at equal oxygen pressure. Separate saturation from content and percentage points from relative change. Explain both loading and unloading.

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