Gas exchange

B3.1 · SL and HL

Why can fast breathing coexist with poor gas transfer?

Follow air, the barrier and blood separately

Common content: exchange surfaces and gradients; mammalian lungs, ventilation and volumes; leaf tissues, transpiration and stomatal density.

AHL: cooperative oxygen binding, foetal/adult haemoglobin and the Bohr shift.

All numerical traces, counts and curves here are invented teaching models. They are not clinical measurements.

Geometry creates a demand for specialized exchange surfaces

Area, distance, moisture and permeability serve different functions

Increasing size in similar shapes reduces surface area per volume and increases internal distances. Transport systems help supply internal cells.

Large area allows simultaneous transfer; thin tissue shortens diffusion distance; moisture permits gases to dissolve; permeability permits crossing.

Plants respire as well as photosynthesize. Net gas exchange depends on the balance, rather than a permanent plant/animal direction rule.

Compare area and distance under controlled conditions

1. **Model.** Transfer rate is proportional to area $\times$ concentration difference / distance for the same gas and barrier.
2. **Change.** Three times the area and 1.5 times the distance give $3/1.5 = 2$ times the transfer rate at the same gradient.
3. **Limit.** A real lung also depends on ventilation, blood flow, barrier properties and functioning area.

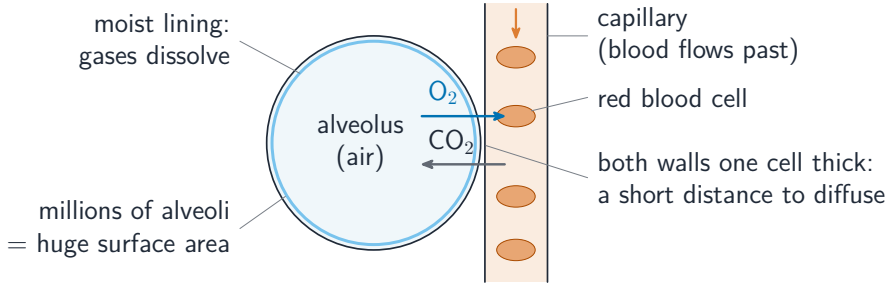
Distinguish movement from the metabolic process

Process	Mechanism
Ventilation	Bulk movement of air or water over an exchange surface
Perfusion	Blood flow through an exchange surface or tissue
Diffusion	Net molecular movement down the relevant gradient
Cellular respiration	Metabolic reactions releasing usable energy; aerobic respiration consumes oxygen

A thin barrier cannot maintain its own gradient

1. **Sealed model.** Equal, fixed-volume compartments; same solvent and temperature. Oxygen concentrations: outside 100, inside 40 (arbitrary units). Initial net diffusion is inward.
2. **Later.** Both sides at 70: no net transfer, although molecules still move in both directions.
3. **Renewal.** Ventilation renews the external medium; flow brings and removes blood. Compare the same gas across the barrier, not oxygen on one side with carbon dioxide on the other.

Gas exchange at an alveolus



Ventilation and blood flow keep both gradients steep

Connect each lung feature to its contribution

Feature	Contribution
Bronchi and bronchioles	Branching distributes air to alveolar regions
Many alveoli	Large total area for diffusion
Thin walls and capillaries	Short air-to-blood diffusion distance
Surfactant	Lowers surface tension and helps alveolar stability
Capillary blood flow	Renews the blood and maintains gradients

Separate four possible limits on transfer

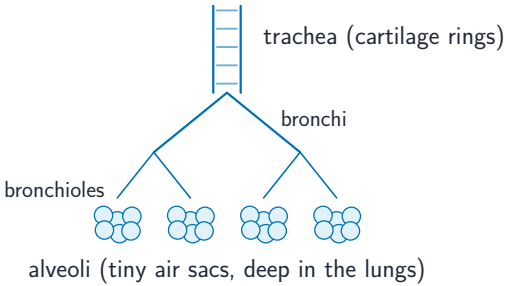
Fast air movement cannot compensate for every defect

Reduced functioning area, a thicker barrier, inadequate ventilation and inadequate perfusion are different limitations.

Surfactant stabilizes the interface; it neither pumps oxygen nor creates the oxygen gradient.

Breathing rate alone does not identify the limiting step or quantify oxygen uptake.

The airways branch



Branching gives an enormous surface

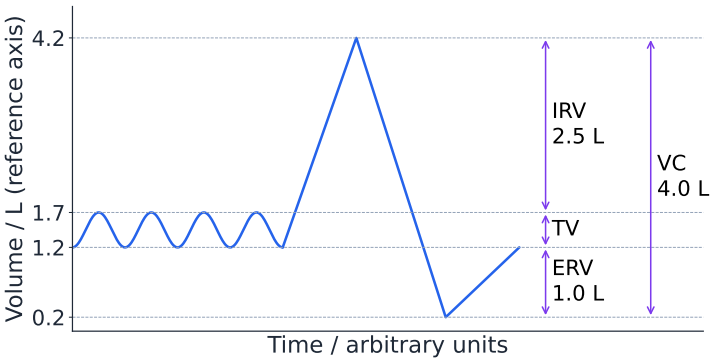
Explain inspiration in causal order

1. **Muscles.** The diaphragm contracts and flattens; external intercostal activity raises ribs up and out.
2. **Volume and pressure.** Thoracic and lung volumes increase; alveolar pressure falls slightly below atmospheric during inflow.
3. **Flow.** Air enters down the pressure difference until pressures equalize. Lungs follow thoracic movement; individual alveoli are not muscular pumps.

Quiet and forced expiration differ

Condition	Causal account
Quiet expiration	Inspiratory muscles relax; diaphragm returns toward its dome; elastic recoil reduces volume
Air outflow	Alveolar pressure exceeds atmospheric while air leaves
Forced expiration	Abdominal and expiratory intercostal activity reduces thoracic volume more forcefully
End of flow	No pressure difference driving flow does not mean lungs contain no air

Read differences from the reference axis



The lowest point is not zero air remaining: this axis measures relative volume.

Extract four volumes from the invented trace

1. **Normal breath.** $1.7 - 1.2 = 0.5$ L tidal volume.
2. **Reserves.** Inspiratory reserve: $4.2 - 1.7 = 2.5$ L. Expiratory reserve: $1.2 - 0.2 = 1.0$ L.
3. **Vital capacity.** $4.2 - 0.2 = 4.0$ L, also $2.5 + 0.5 + 1.0$. Residual volume is not directly measured by this trace.

The same minute ventilation can hide different alveolar values

1. **Patterns.** 0.50 L $\times$ 12/min and 0.30 L $\times$ 20/min both give 6.0 L/min.
2. **Assumed dead space.** At 0.15 L/breath: $(0.50 - 0.15) \times 12 = 4.2$ L/min; $(0.30 - 0.15) \times 20 = 3.0$ L/min.
3. **Interpret.** These are air volumes, not oxygen uptake. Transfer also depends on gas composition, gradients and **perfusion**.

Measure under an approved protocol and explain what repeats mean

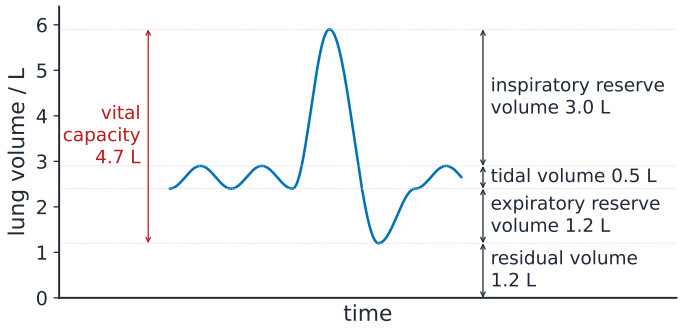
Use a calibrated trace and several regular resting breaths

Read tidal differences and time intervals; supplied or appropriately supervised spirometry data can identify reserves and vital capacity.

Human demonstrations use voluntary resting measurements. Do not induce breathlessness, hyperventilation or unapproved forceful manoeuvres.

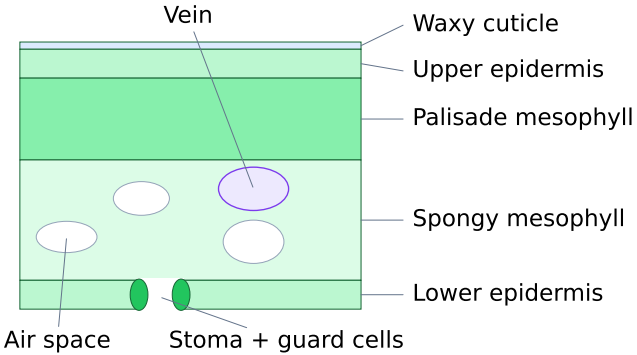
Repeated breaths estimate within-person variability. They are not independent people or population reference ranges.

Reading a spirometer trace



The residual 1.2 L always stays in the lungs

Trace gases through a representative dicot leaf



A tissue plan shows regions and relative positions; gas moves through connected spaces to moist cell surfaces.

Follow carbon dioxide and identify the tissue functions

1. **Path.** Stoma → intercellular air spaces → moist mesophyll wall → cell membrane.
2. **Regulation and trade-off.** Guard cells regulate pore width. The cuticle limits uncontrolled water loss but also restricts direct exchange.
3. **Support.** Spongy mesophyll air spaces distribute gases; xylem supplies water and phloem transports assimilates. Tissue arrangement varies among leaves.

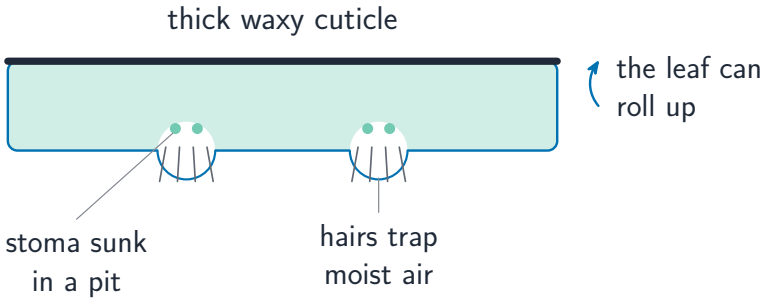
Predict a driver and check the response

Factor	Reasoning with other conditions controlled
Higher humidity	Usually lowers the internal-to-external vapour gradient
Wind	Removes humid boundary-layer air
Temperature	Can increase evaporative demand, but water stress can close stomata
Light	Often promotes opening; response depends on species and water supply

Water uptake approximates transpiration under suitable conditions

1. **Invented data.** 0.20 and 0.35 mL uptake over equal ten-minute intervals.
2. **Rates and change.** 0.020 and 0.035 mL/min; increase $0.015/0.020 \times 100 = 75\%$.
3. **Evaluate.** Check leaks, equilibration, leaf area and temperature; repeat. Uptake does not directly count every molecule leaving or prove a change in pore width.

A leaf that saves water



Each feature reduces transpiration

Count pores and divide by sampled area

1. **Equal fields.** Counts 32, 36, 28, 40, each over 0.20 mm^2: total 136 over 0.80 $\text{mm}^2 = 170$ stomata/mm^2.
2. **Circular field.** Radius 0.25 mm gives area $\pi(0.25)^2 = 0.196$ mm^2. Count 35 gives approximately 178 stomata/mm^2.
3. **Reliability.** Calibrate; use a boundary rule; avoid selecting crowded patches; sample leaves and independent plants. Two guard cells form one stoma.

Density is not the current rate of photosynthesis

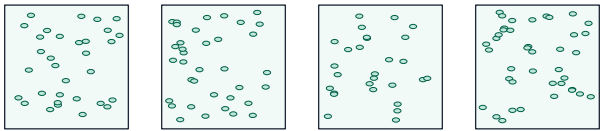
Capacity and actual performance require different evidence

Pore size, degree of opening, gas gradients, light and other metabolic limitations also affect exchange.

Record leaf side, position and age. Several fields from one leaf do not substitute for independent plants.

For unequal fields use total count / total sampled area, rather than an unweighted average of counts.

Estimating stomatal density



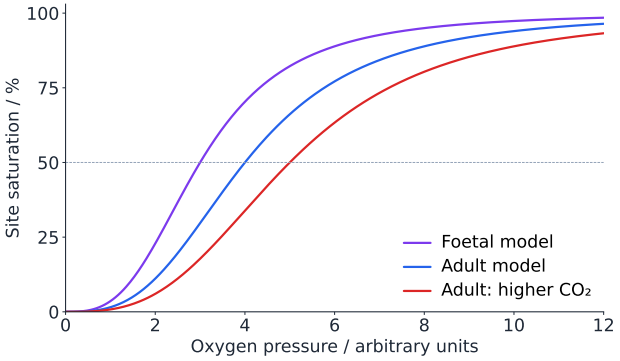
field 1: **32** field 2: **36** field 3: **28** field 4: **40**

each field 0.20 mm^2

$$\text{density} = \frac{\text{total count}}{\text{total area}} = \frac{32 + 36 + 28 + 40}{4 \times 0.20\ \text{mm}^2} = \frac{136}{0.80} = 170\ \text{per mm}^2$$

Density $= 170$ per mm^2

Read affinity at the same oxygen pressure



Left shift indicates higher affinity under compared conditions; the curves use arbitrary oxygen-pressure units.

Explain the sigmoid and interpret saturation

1. **Binding.** Four haem groups can bind four oxygen molecules. Binding alters conformation and increases subsequent binding affinity.
2. **Axes.** Oxygen partial pressure versus percentage of binding sites occupied. Saturation is a population average, not oxygen percentage in air.
3. **Shape.** Steep middle range permits marked loading/unloading; high oxygen availability approaches saturation. A lower half-saturation pressure indicates greater affinity.

Compare protein composition and physiological function

Comparison	Interpretation
Adult A	Two alpha and two beta chains
Foetal	Two alpha and two gamma chains
Affinity in red cells	Foetal haemoglobin has higher affinity under physiological conditions; different allosteric interactions contribute
Placental exchange	Oxygen crosses a barrier between normally separate maternal and foetal circulations

Hold binding capacity constant when comparing amounts

1. **Invented comparison.** Adult 50%, foetal 70% saturation at the same oxygen pressure; capacity 200 units each.
2. **Bound amounts.** $0.50 \times 200 = 100$ units; $0.70 \times 200 = 140$ units.
3. **Limit.** The 40-unit difference is not a universal amount transferred at a placenta. Gradient, flow and barrier properties also matter.

Connect tissue metabolism to oxygen release

1. **Conditions.** Actively respiring tissue produces carbon dioxide; increased carbon dioxide and hydrogen-ion conditions lower oxygen affinity.
2. **Curve.** Right shift: at the same tissue oxygen pressure, lower saturation means more oxygen is released.
3. **Mechanism.** Carbon dioxide binds distinct globin sites and affects acid–base conditions. It is not carbon monoxide competing at the oxygen-binding haem site; no ATP pump ejects oxygen.

Calculate unloading as a difference in saturation

1. **Start.** Blood enters at 96%; tissue values 72% at lower carbon dioxide and 54% at higher carbon dioxide.
2. **Unload.** $96 - 72 = 24$ versus $96 - 54 = 42$ percentage points.
3. **Compare.** 18 percentage points more; $42/24 = 1.75$ times as much at equal starting saturation and capacity.

Attempt before revealing the worked answers

Use the full handout practice set

Trace levels 0.9, 1.5, 3.9 and 0.3 L: find tidal volume, reserves and vital capacity; state what remains unknown.

Compare 0.60 L $\times$ 10/min with 0.40 L $\times$ 15/min at dead space 0.15 L/breath.

Counts 18, 24, 21 and 27 over four 0.15 mm^2 fields: calculate density and plan independent replication.

Check units, subtraction and denominators

1. **Volumes.** Tidal 0.6 L; inspiratory reserve 2.4 L; expiratory reserve 0.6 L; vital capacity 3.6 L. Residual volume is unknown.
2. **Ventilation.** Both minute values 6.0 L/min; alveolar estimates 4.50 and 3.75 L/min. Neither directly measures oxygen uptake.
3. **Stomata.** 90 over 0.60 mm^2 = 150/mm^2. Diameter 0.50 mm gives area 0.19635 mm^2; count 30 gives about 153/mm^2.

AHL practice: curve reading and unloading

1. **Question 12.** 80% and 60% of equal 150-unit capacities give 120 and 90 units; compare affinity at the same oxygen pressure.
2. **Question 13.** Foetal alpha-two/gamma-two differs from adult alpha-two/beta-two. Average saturation does not require identical occupancy of all molecules.
3. **Question 14.** From 98% to 74% or 50%: unload 24 or 48 points. Difference 24 points; ratio two. Explain lower affinity at higher carbon dioxide.

Check yourself

Connect a structure or condition to its mechanism

Separate ventilation, perfusion, diffusion and respiration. Link lung and leaf features to area, distance, moisture or gradients.

Subtract trace levels; calculate field area; count pores; distinguish fields from independent plants.

AHL: read curves at equal oxygen pressure, distinguish saturation from content, and explain loading as well as unloading.