AB3D Organisms Exchange Substances with their Environment: Depth and Exam Drill

AQA 7402 · Calculator allowed · about 140 minutes

Total Marks

Name: ________________________________ Date: ____ / ____ / ______

Answer ALL questions. Show all your working.

1 This question tests core vocabulary used to describe digestion and absorption.

(a) State the enzyme, and its site of production, that hydrolyses starch to maltose in the human digestive system. **(1)**

(b) State the location and role of maltase in carbohydrate digestion. **(1)**

(c) Define co-transport. **(1)**

(d) State one structural adaptation of an epithelial cell lining the ileum that increases the rate of absorption. **(1)**

(Total for Question 1 is 4 marks)

2 This question tests key facts about mass transport and gas exchange systems. For each part, identify the correct option.

(a) In the countercurrent system of a fish gill, which statement correctly describes the relative direction of blood flow and water flow? **(1)**

- ☐ A) Blood and water flow in the same direction
- ☐ B) Blood and water flow in opposite directions
- ☐ C) Blood flows only within the gill filament while water is stationary
- ☐ D) Water flows only over alternate lamellae

(b) Which vessel carries oxygenated blood away from the heart to the body? **(1)**

- ☐ A) Pulmonary artery
- ☐ B) Pulmonary vein
- ☐ C) Vena cava
- ☐ D) Aorta

(c) Which structure prevents backflow of blood from the ventricles into the atria during ventricular systole? **(1)**

- ☐ A) Semilunar valves
- ☐ B) Atrioventricular valves
- ☐ C) The septum
- ☐ D) The sinoatrial node

(d) In the tracheal system of an insect, which structure allows gas exchange directly with individual cells without the involvement of a blood transport system? **(1)**

- ☐ A) Spiracles
- ☐ B) Tracheae
- ☐ C) Tracheoles
- ☐ D) Haemolymph

(Total for Question 2 is 4 marks)

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3 A student investigated the effect of exercise on the cardiac cycle. At rest, a subject had a heart rate of 68 beats per minute and a stroke volume of 72 cm3. During moderate exercise, the heart rate increased to 132 beats per minute and the stroke volume increased to 108 cm3.

(a) State the equation linking cardiac output, heart rate and stroke volume. **(1)**

(b) Calculate the resting cardiac output, in cm3/minute. **(2)**

(c) Calculate the cardiac output during exercise, in cm3/minute, and hence calculate the percentage increase in cardiac output caused by exercise. **(3)**

(d) Explain, in terms of control of the cardiac cycle, how heart rate increases during exercise. **(3)**

(Total for Question 3 is 9 marks)

4 A biologist compared the oxygen dissociation curve of adult human haemoglobin (Hb) with that of a diving mammal's myoglobin and with fetal haemoglobin (HbF). At a partial pressure of oxygen of 4.0 kPa, percentage saturation values were: adult Hb 25%, HbF 45%, myoglobin 85%.

(a) Explain what is meant by saying that myoglobin has a 'higher affinity for oxygen' than adult haemoglobin, using the data given. **(2)**

(b) Explain the functional significance of myoglobin's high oxygen affinity in a diving mammal's muscle tissue. **(2)**

(c) Explain why fetal haemoglobin (HbF) has a higher affinity for oxygen than adult haemoglobin, and why this is essential for the fetus. **(3)**

(d) During intense exercise, muscle tissue produces more CO2 and becomes more acidic (the Bohr effect). Explain how this shifts the oxygen dissociation curve of adult haemoglobin and why this is beneficial. **(1)**

(Total for Question 4 is 8 marks)

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5 A student used a potometer to measure the rate of water uptake by a leafy shoot under different conditions, as a proxy for transpiration rate. An air bubble was introduced into the capillary tube, and its movement was timed over a fixed distance. The internal diameter of the capillary tube was 1.0 mm. The bubble took 150 seconds to travel 60 mm along the tube in still air, and 50 seconds to travel 60 mm in front of a fan.

(a) Calculate the volume of water taken up while the bubble moved 60 mm (use volume = πr^2 x length, with r = 0.50 mm). Give your answer in mm3 to 3 significant figures. **(2)**

(b) Calculate the rate of water uptake, in mm3 per second, in still air. **(2)**

(c) Calculate the percentage increase in the rate of water uptake caused by the fan, compared with still air. **(3)**

(d) Explain, in terms of the water potential gradient at the leaf surface, why moving air increases the rate of water uptake. **(2)**

(Total for Question 5 is 9 marks)

6 A student prepared a leaf epidermal peel and viewed it under a light microscope using a x40 objective lens, giving a circular field of view of diameter 0.45 mm. Within this field of view the student counted 18 stomata.

(a) Calculate the area of the field of view, in mm2, to 3 significant figures (area of a circle = πr^2). **(2)**

(b) Calculate the stomatal density, in stomata per mm2, to 3 significant figures. **(2)**

(c) The same leaf has an estimated total surface area of 42 cm2. Using your answer to (b), estimate the total number of stomata on this leaf. **(2)**

(d) A xerophytic plant adapted to hot, dry conditions typically has a much lower stomatal density than this leaf, and its stomata are often sunken in pits. Explain how these adaptations reduce water loss by transpiration. **(2)**

(Total for Question 6 is 8 marks)

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7 Glucose is absorbed from the lumen of the ileum into epithelial cells against its concentration gradient by co-transport with sodium ions, then moves into the blood by facilitated diffusion.

(a) Describe the role of the sodium-potassium pump, located on the basal membrane of the epithelial cell, in maintaining the concentration gradient needed for glucose co-transport. **(3)**

(b) Explain how the co-transporter protein allows glucose to move into the epithelial cell against its own concentration gradient, using the energy of the sodium ion gradient. **(2)**

(c) Explain why a poison that inhibits ATP production (e.g. cyanide) would eventually stop glucose absorption by this route, even though the co-transporter protein itself does not directly use ATP. **(2)**

(Total for Question 7 is 7 marks)

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8 A potometer measures the rate of water uptake by a shoot, which is used as an estimate of transpiration rate, but it is not a direct measure of transpiration itself.

(Total for Question 8 is 6 marks)

9 Ringing experiments involve removing a ring of bark (including the phloem but not the xylem) from around the trunk of a tree, to investigate the function of phloem in translocation.

(a) State the type of cell in phloem tissue responsible for the mass flow of sugars, and the type of cell closely associated with it that provides the metabolic energy for loading sugars. **(2)**

(b) Predict and explain what would be observed in the region of the trunk directly above the ring (relative to the ground), over the following weeks, and explain your reasoning. **(3)**

(c) Predict and explain what would happen to the region of the trunk below the ring over an extended period. **(2)**

(Total for Question 9 is 7 marks)

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10 A gas exchange surface must have specific structural adaptations to maximise the rate of diffusion, as described by Fick's law.

(a) State Fick's law of diffusion in words, identifying the three factors that determine the rate of diffusion. **(1)**

(b) An alveolus has a surface area of 1.8×10^{-3} mm2 and its exchange surface (alveolar epithelium plus capillary endothelium) has a combined thickness of 0.50 micrometres. Under given conditions the rate of oxygen diffusion across this alveolus is 6.0×10^{-6} arbitrary units. A patient develops pulmonary fibrosis, which thickens the exchange surface to 2.0 micrometres, with surface area and concentration difference unchanged. Calculate the new rate of diffusion. **(3)**

(c) Explain how emphysema, which destroys the walls between adjacent alveoli, reduces the rate of gas exchange, using Fick's law. **(2)**

(d) Explain how a high concentration gradient of oxygen across the alveolar epithelium is maintained during normal breathing. **(2)**

(Total for Question 10 is 8 marks)

11 This final question draws together ideas about gas exchange, mass transport and exchange surfaces across different organisms.

(a) A fish has a countercurrent gas exchange system across its gills, achieving up to 80% extraction of the dissolved oxygen from water passing over the gill lamellae. Explain why a countercurrent system is more efficient than a parallel (concurrent) flow system would be. **(3)**

(b) Unlike a fish, an insect's tracheal system delivers oxygen directly to respiring tissues by diffusion (and, in some species, mass movements of air) through air-filled tracheae and tracheoles, without the involvement of a blood pigment such as haemoglobin. Suggest one advantage and one limitation of this system compared with a blood-based (circulatory) gas transport system, particularly in relation to insect body size. **(3)**

(c) A mammal's circulatory system is described as a double, closed circulation. Explain why a double circulatory system, in which blood passes through the heart twice on each complete circuit of the body, is necessary to maintain a high blood pressure (and hence a fast delivery rate of oxygen) to body tissues. **(3)**

(Total for Question 11 is 9 marks)

Mark scheme · AB3D Organisms Exchange Substances with their Environment: Depth and Exam Drill

Question 1

- (a) **B1** amylase, produced in the salivary glands and/or pancreas oe
- **(a) Answer: Amylase, produced in the salivary glands and the pancreas.**
- (b) **B1** found on the cell-surface membrane (microvilli) of epithelial cells lining the ileum; hydrolyses maltose to glucose oe
- **(b) Answer: Maltase is bound to the cell-surface membrane of epithelial cells in the ileum, and hydrolyses maltose into glucose.**
- (c) **B1** the movement of one molecule/ion across a membrane linked to (facilitated by) the movement of a different molecule/ion, using a shared membrane protein oe
- **(c) Answer: The movement of one molecule across a membrane linked to the movement of a different molecule, via a shared transport protein.**
- (d) **B1** e.g. microvilli, increasing surface area; many mitochondria, providing ATP for active transport; oe (any one valid feature)
- **(d) Answer: Microvilli on the cell surface, which increase the surface area for absorption.**

Question 2

- (a) **B1** B
- **(a) Answer: B**
- (b) **B1** D
- **(b) Answer: D**
- (c) **B1** B
- **(c) Answer: B**
- (d) **B1** C
- **(d) Answer: C**

Question 3

- (a) **B1** cardiac output = heart rate x stroke volume
- **(a) Answer: Cardiac output = heart rate x stroke volume.**
- (b) **M1** 68 x 72
- (b) **A1** 4896 cm3/minute, cao
- **(b) Answer: 4896 cm3/minute**
- (c) **M1** exercise cardiac output = 132 x 108 = 14256 cm3/minute
- (c) **M1** percentage increase = (14256 - 4896)/4896 x 100, ft
- (c) **A1** 191% (accept 190-192%), awrt
- **(c) Answer: Cardiac output during exercise = 14256 cm3/minute; a 191% increase.**
- (d) **B1** exercise increases CO_2 concentration in the blood (and decreases blood pH), detected by chemoreceptors in the aortic and carotid bodies (and the medulla) oe
- (d) **B1** chemoreceptors send impulses to the cardiovascular (cardiac) centre in the medulla oblongata oe
- (d) **B1** the cardiovascular centre increases the frequency of impulses along the sympathetic nerve to the sinoatrial node (SAN), increasing the rate at which it generates excitation waves, increasing heart rate oe
- **(d) Answer: Rising CO_2 (falling pH) is detected by chemoreceptors, which signal the cardiovascular centre in the medulla; this increases sympathetic stimulation of the SAN, raising heart rate.**

Question 4

- (a) **B1** at the same partial pressure of oxygen (4.0 kPa), myoglobin is more saturated with oxygen (85%) than adult haemoglobin (25%) oe
- (a) **B1** so myoglobin binds/holds on to oxygen more readily, and only releases it at very low partial pressures of oxygen, whereas adult Hb readily releases oxygen at this partial pressure oe
- **(a) Answer: At 4.0 kPa myoglobin is 85% saturated compared with 25% for adult Hb, showing myoglobin binds oxygen more strongly and only releases it at very low oxygen partial pressures.**
- (b) **B1** myoglobin acts as an oxygen store within the muscle, loading oxygen readily from the blood oe
- (b) **B1** it only releases this stored oxygen at the very low partial pressures found in actively respiring muscle during a prolonged dive, supplying the muscle with oxygen when the animal cannot breathe oe
- **(b) Answer: Myoglobin stores oxygen in muscle and releases it only at the very low oxygen partial pressures reached during a dive, supplying respiring muscle when the animal cannot breathe.**
- (c) **B1** HbF has a different structure (different polypeptide chains) from adult Hb, giving it a higher affinity for oxygen at any given partial pressure oe
- (c) **B1** in the placenta, fetal blood and maternal blood are close together but do not mix, so oxygen must diffuse from maternal Hb to fetal Hb oe
- (c) **B1** because HbF has a higher affinity, it can load oxygen from the maternal blood (where the adult Hb is releasing it), ensuring the fetus is not oxygen-deprived oe
- **(c) Answer: HbF's different structure gives it a higher oxygen affinity than adult Hb, which allows it to take up oxygen from maternal blood across the placenta at a partial pressure where maternal Hb is releasing oxygen, ensuring adequate oxygen transfer to the fetus.**
- (d) **B1** increased CO_2/lower pH shifts the dissociation curve to the right, decreasing haemoglobin's affinity for oxygen, so more oxygen is released/unloaded to respiring tissues at a given partial pressure oe
- **(d) Answer: Higher CO_2 and lower pH shift the curve right, reducing Hb's affinity for oxygen so more oxygen is released to the actively respiring muscle.**

Question 5

- (a) **M1** volume = $\pi \times (0.50)^2 \times 60$
- (a) **A1** 47.1 mm3, awrt
- **(a) Answer: 47.1 mm3**
- (b) **M1** rate = volume / time = 47.1 / 150, ft from (a)
- (b) **A1** 0.314 mm3/s, awrt
- **(b) Answer: 0.314 mm3/s**
- (c) **M1** rate with fan = 47.1 / 50 = 0.942 mm3/s, ft
- (c) **M1** percentage increase = (0.942 - 0.314)/0.314 x 100, ft
- (c) **A1** 200% (accept 199-201%), awrt
- **(c) Answer: Approximately 200%**
- (d) **B1** moving air removes water vapour molecules from the leaf surface (boundary layer) as soon as they diffuse out of the stomata, preventing a build-up of humid air oe
- (d) **B1** this maintains a steep water potential (concentration) gradient between the inside of the leaf and the air outside, increasing the rate of diffusion of water vapour out of the stomata (transpiration), and so the rate of water uptake by the shoot oe
- **(d) Answer: Moving air sweeps away water vapour at the leaf surface, maintaining a steep water potential gradient that increases the rate of diffusion of water out of the stomata and therefore the rate of water uptake.**

Question 6

- (a) **M1** radius = 0.45/2 = 0.225 mm; area = π x $(0.225)^2$
- (a) **A1** 0.159 mm2, awrt
- **(a) Answer: 0.159 mm2**
- (b) **M1** density = number of stomata / area = 18 / 0.159, ft from (a)
- (b) **A1** 113 stomata/mm2 (accept 112-114), awrt
- **(b) Answer: 113 stomata/mm2**
- (c) **M1** convert 42 cm2 to mm2: 42 x 100 = 4200 mm2, then multiply by density from (b), ft
- (c) **A1** approximately 4.75 x 10^5 stomata (474600, accept a range consistent with ft from (b)), cao
- **(c) Answer: Approximately 4.75 x 10^5 stomata.**
- (d) **B1** fewer stomata reduce the total surface area/number of pores available for water vapour to diffuse out of the leaf, reducing transpiration oe
- (d) **B1** sunken stomata (in pits) trap a pocket of still, humid air close to the pore, reducing the water potential (concentration) gradient between the leaf interior and the air immediately outside, slowing diffusion of water vapour out oe
- **(d) Answer: A lower stomatal density reduces the total pore area for water loss, and sunken stomata trap humid air close to the pore, reducing the diffusion gradient and further slowing transpiration.**

Question 7

- (a) **B1** the sodium-potassium pump actively transports (using ATP) sodium ions out of the epithelial cell, into the blood, against their concentration gradient oe
- (a) **B1** this maintains a low concentration of sodium ions inside the epithelial cell compared with the lumen of the ileum oe
- (a) **B1** this creates a concentration (electrochemical) gradient for sodium ions to diffuse from the lumen into the epithelial cell down their gradient, via a co-transporter protein oe
- **(a) Answer: The sodium-potassium pump actively removes sodium from the epithelial cell into the blood, keeping intracellular sodium low and so maintaining a steep gradient for sodium to re-enter from the lumen via the co-transporter.**
- (b) **B1** the co-transporter protein binds both a sodium ion and a glucose molecule at the same time oe
- (b) **B1** as sodium ions diffuse into the cell down their concentration gradient through the co-transporter, glucose is carried in with them, even though glucose itself is moving against its own concentration gradient oe
- **(b) Answer: The co-transporter binds sodium and glucose together; as sodium moves in down its gradient it drags glucose in with it, even against glucose's own concentration gradient.**
- (c) **B1** the sodium-potassium pump requires ATP to actively transport sodium ions out of the cell oe
- (c) **B1** without ATP, the pump stops working, so the sodium concentration gradient across the epithelial cell membrane cannot be maintained/collapses, removing the driving force for the co-transporter, so glucose absorption stops oe
- **(c) Answer: Without ATP the sodium-potassium pump stops, the sodium gradient collapses, and with no gradient to drive it the co-transporter can no longer bring glucose into the cell.**

Question 8

- **Level 3** (5-6): A detailed, well-structured evaluation that explains why water uptake is used as a proxy for transpiration, identifies at least two valid reasons the two measurements can differ (e.g. water used in photosynthesis/turgidity/metabolism, air bubbles affecting resistance, time lag), and discusses how the design of the potometer (e.g. cutting the shoot underwater, sealing joints) improves validity, reaching a supported overall judgement on the reliability of the potometer as a measure of transpiration.
- **Level 2** (3-4): A reasonably clear evaluation identifying at least one valid reason why water uptake differs from water lost by transpiration, and some reference to potometer design features that affect validity, but the discussion is not fully developed or balanced.
- **Level 1** (1-2): Limited evaluation; may simply state that the potometer measures water uptake rather than transpiration without explaining why this matters, or lists a feature of the apparatus with no evaluative comment.
- **Indicative content:**
  - A potometer measures the volume of water taken up by the cut shoot per unit time, not the volume of water vapour lost through the stomata.
  - Not all the water taken up is lost by transpiration: a small proportion is used in photosynthesis, retained to maintain cell turgidity, or used in other metabolic reactions, so water uptake slightly overestimates transpiration in this respect.
  - Conversely, some water uptake can lag behind water loss because of the shoot's own water storage capacity (used to refill cells that have lost water), so uptake and loss are not perfectly synchronised moment to moment, though they are similar over longer time periods.
  - The apparatus must be set up carefully to give valid readings: the shoot is cut underwater and under the surface of water in the apparatus to prevent air entering the xylem (which would block water columns and give false low readings).
  - All joints must be airtight/watertight (e.g. sealed with petroleum jelly) to prevent water loss or air entry that would introduce error unrelated to the plant's own water uptake.
  - Despite these limitations, because the overwhelming majority of water taken up by a shoot is indeed lost by transpiration, and because uptake is easy to measure precisely (via bubble movement) whereas water vapour loss is very difficult to measure directly, the potometer is widely regarded as a good, practical proxy for the pattern (though not the exact absolute value) of transpiration rate and how it responds to variables such as wind speed, humidity, light and temperature.

Question 9

- (a) **B1** sieve tube element(s)
- (a) **B1** companion cell(s)
- **(a) Answer: Sieve tube elements carry out mass flow; companion cells provide the metabolic support/energy.**
- (b) **B1** the region above the ring would show little change / continue to receive water and mineral ions normally, since xylem (which is unaffected by the ring) continues to supply these upward oe
- (b) **B1** however, since phloem has been removed, sugars produced by photosynthesis above the ring cannot be transported down past the ring oe
- (b) **B1** sugars would accumulate above the ring, potentially causing swelling of the bark just above the cut, as the region above continues to receive water/support growth oe
- **(b) Answer: Above the ring, water and mineral supply (via xylem) continue as normal, but sugars made by photosynthesis cannot move down past the missing phloem, so sugar accumulates and the bark may swell just above the ring.**
- (c) **B1** the region below the ring would eventually die back/show reduced growth, because it can no longer receive sugars (an energy/carbon source) transported from photosynthesising leaves above oe
- (c) **B1** the roots in particular would be starved of sugars needed for respiration and growth, since roots cannot photosynthesise oe
- **(c) Answer: The region below the ring, including the roots, would eventually be starved of sugar and die back, since roots cannot photosynthesise and can no longer receive sugars from the leaves via the phloem.**

Question 10

- (a) **B1** rate of diffusion is proportional to (surface area x concentration difference) / thickness of the exchange surface oe
- **(a) Answer: Rate of diffusion is proportional to (surface area x concentration difference) / diffusion distance (thickness).**
- (b) **M1** recognise rate is inversely proportional to thickness when surface area and concentration difference are constant
- (b) **M1** new rate = old rate x (old thickness / new thickness) = 6.0×10^{-6} x (0.50/2.0)
- (b) **A1** 1.5×10^{-6} arbitrary units, cao
- **(b) Answer: 1.5×10^{-6} arbitrary units**
- (c) **B1** destruction of alveolar walls merges many small alveoli into fewer, larger air spaces, greatly reducing the total surface area available for gas exchange oe
- (c) **B1** by Fick's law, a smaller surface area (with concentration difference and thickness roughly constant) directly reduces the rate of diffusion of oxygen into the blood oe
- **(c) Answer: Emphysema destroys alveolar walls, reducing total surface area; since rate of diffusion is proportional to surface area, this reduces the rate of gas exchange.**
- (d) **B1** ventilation (breathing in and out) continually replaces air in the alveoli with air of a higher oxygen concentration than the blood oe
- (d) **B1** a good blood supply (dense capillary network) continually removes oxygenated blood and brings in deoxygenated blood, maintaining a low oxygen concentration on the blood side oe
- **(d) Answer: Ventilation continually refreshes the air in the alveoli with oxygen-rich air, while a good blood supply constantly removes oxygenated blood and delivers deoxygenated blood, maintaining a steep concentration gradient.**

Question 11

- (a) **B1** in a countercurrent system, blood and water flow in opposite directions, so blood with a relatively low oxygen concentration always meets water that has already had some oxygen removed, but still has a higher concentration than the blood oe
- (a) **B1** this means a diffusion gradient favouring oxygen movement into the blood is maintained along the entire length of the lamella oe
- (a) **B1** in a parallel system, blood and water would reach equilibrium partway along the lamella, so no further net diffusion could occur over the remaining length, giving lower overall extraction oe
- **(a) Answer: Opposite flow of blood and water maintains a diffusion gradient along the whole gill lamella, unlike a parallel system where blood and water would equalise partway along and diffusion would stop, so countercurrent exchange extracts far more oxygen.**
- (b) **B1** advantage: diffusion of gases through air is much faster than diffusion through a liquid (blood plasma), so oxygen can reach tissues rapidly and directly without needing a circulatory pigment oe
- (b) **B1** limitation: diffusion alone is only efficient over short distances, so as insects increase in body size, tracheal air-filled tubes cannot supply oxygen to central tissues fast enough, limiting the maximum body size of insects oe
- (b) **B1** a further valid point, e.g. some larger/more active insects supplement diffusion with abdominal pumping movements to ventilate the tracheal system oe
- **(b) Answer: An advantage is that diffusion through air is much faster than through blood plasma, delivering oxygen quickly without a circulatory pigment; a limitation is that diffusion is only efficient over short distances, which is thought to limit the maximum body size insects can reach, though some species use abdominal pumping to help ventilate larger tracheal systems.**
- (c) **B1** blood pressure falls substantially as blood passes through the narrow capillaries of the lungs (pulmonary circulation), because of the resistance of the many small vessels oe
- (c) **B1** if blood then went straight to the body without returning to the heart, it would arrive at the body tissues at too low a pressure to be delivered efficiently/quickly oe
- (c) **B1** by returning to the heart after the lungs, blood pressure is boosted again by a second pumping chamber (left ventricle) before being sent to the body, maintaining a high pressure and rapid delivery of oxygenated blood to respiring tissues oe
- **(c) Answer: Pressure drops sharply across the narrow capillaries of the lungs; a double circulation returns blood to the heart to be re-pressurised by the left ventricle before travelling to the body, maintaining high pressure and a fast rate of oxygen delivery to tissues.**