Questions

This Question is about the size limitations imposed upon organisms.

There exists a law, postulated by Einstein, about the rate of diffusion. It states that the time taken t for an object to diffuse a certain distance is proportional to the square of that distance x: $t \propto x^2$

a) Explain why the time taken for diffusion to occur isn't directly proportional to the distance.

b) What impact does this have on large, multicellular organisms?

Certain problems arise from the bulk flow of fluids within plants. Laplace's law states that the stress placed on a vessel wall is proportional to its radius. In plants, many narrow vessels with thin walls run in parallel to transport fluid around the plant.

c) Describe why you think this is necessary.

Giraffes have evolved to have very long necks in order to reach leaves in tall trees. The brain of any organism requires large amounts of blood to flow through per second, however the giraffe must pump this blood against gravity. When proposing hypotheses as to how the giraffe overcame this constraint, there were multiple suggestions. One involved large positive pressure, with giraffes having a systolic of 200mmHg, in order to provide sufficient pressure for the blood to reach the head.

d) Explain, in terms of processes occurring within the tissue, why the brain requires large amounts of blood.

Having a high systolic pressure may help blood to reach the brain, but it also comes with the danger of oedema, where blood pools in the lower limbs.

e) How could the giraffe be further adapted to prevent pooling of blood?

f) Suggest another possible mechanism that could allow the giraffe to send blood to its brain at sufficient rates without having an abnormally high systolic pressure.

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Hints

Question 1

a) Think about the how diffusion works. Do the molecules travel in a straight line from A to B?

b) Think about the implications this imposes on the distance between source and sink.

c) Start by considering why thin walled vessels are necessary. Now, think about the consequences this has on the effects of wall stress.

d) 1: What is provided by the blood that is crucial to all tissues, especially the brain and muscles?
2: What processes within the brain require energy in the form of ATP?

e) Blood in the lower limbs is under high pressure due to gravity and the weight of the blood higher up in the organism. How can this high pressure be counteracted?

f) The mechanism described involves positive pressure that forces the blood towards the brain. How could an opposite mechanism be used?

Suggested Answers

Question 1

a)

- Diffusion occurs via the random movement of particles.
    - Diffusion results in a net movement of particles from one area to another.
        - Collisions between particles, which result in a change in a particle's direction are more likely to occur where the concentration of these molecules is higher.
    - This results in molecules travelling into larger available space.

- Despite the kinetic energy and therefore velocity of the molecules remaining the same regardless of the distance travelled, the time taken is not inversely proportional to velocity unlike the situation for straight-line motion.

- Instead, a longer distance means the time taken is much larger because it requires random collisions to occur in such a way that molecules move in the desired direction a certain percentage of the time.

b)

- Large, multicellular organisms cannot rely on diffusion alone because it becomes exponentially slower as distance increases.
    - This explains the need for bulk flow mechanisms to deliver essential nutrients to tissues.
    - The larger the organism, the more efficient and complex the system must be. For example:
        - Insects can deliver oxygen to their tissues simply via a system of hollow tubes known as tracheoles.
        - In comparison, mammals have evolved lungs that require energy to allow tidal flow to occur to transport the absorbed oxygen around the animal's circulatory system.

c)

- The primary requirement of vessels is that they possess sufficiently thin walls to permit diffusion to occur across them at a rate that is sustainable for the metabolic requirements of life.
    - Since Einstein's equation illustrates that time taken for diffusion increases with the square of the distance travelled, it is imperative that walls are as thin as possible.
        - This minimises the diffusion distance.

- However, thin-walled vessels are less able to cope with wall stress than vessels with more robust walls.
    - Since the stress increases linearly with vessel radius, vessels must be kept below a certain size to prevent the walls rupturing.

- However, narrow vessels have a high resistance to flow.
    - Consequently, many vessels are arranged in parallel to allow sufficient volumes of fluid to be carried through the plant.

- This means that the flow rate in each vessel is decreased compared to a singular thin vessel.
    - The flow rate in one part of the plant cannot exceed another and so the overall flow rate will match the influx of fluid.

d)

- Blood provides glucose and oxygen, both of which are required for aerobic respiration to produce large amounts of ATP within neurons.
    - Neurons need higher concentrations of ATP than the average cell to power the active transport that occurs along the axon to maintain the sodium/potassium gradient across the membrane.
    - ATP is also required for the synthesis and secretion of neurotransmitters, and other basic cellular processes.

e)

- To prevent the pooling of blood in the lower tissues, the tissues need to be at a high enough pressure that blood is forced back towards the heart.
    - This can be achieved using tight, inelastic skin and connective tissue.

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- This provides a high tissue pressure making it unfavourable for the blood to pool in vessels in the lower limbs.

f)

- Instead of using positive pressure to force the blood upwards towards the head, negative pressure could be used to draw the blood up through the arteries.
    - This negative pressure can be established by the weight of blood in the veins causing that blood to flow downwards, leaving a deficit of blood near the brain.

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