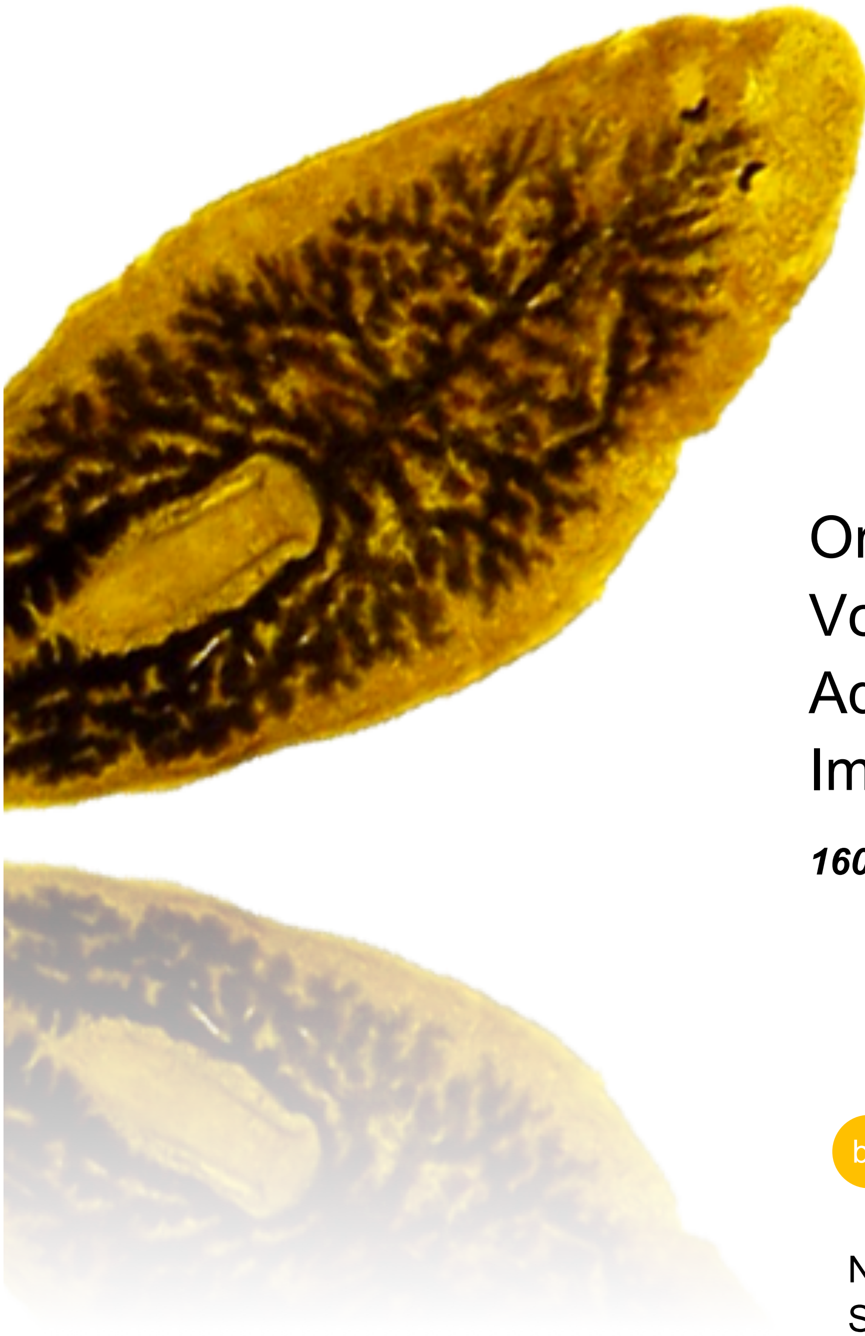

Organisms' Surface Area, Volume, Shape, Size and Adaptations and Implications for Diffusion

1601 ENV: Biological Systems

by

Name: Jessica Strickland
Student Number: S2793629
Laboratory Date: 17 May 2012
Submission Date: 31 May 2012

ABSTRACT

Writing

1.0 INTROCUDTION

Diffusion is important for gas exchange, nutrient distribution and waste removal in all living organisms and can be defined as the net movement of molecules down a concentration gradient (Campbell at al. 2006). Every cell in every type of organism undergoes diffusion to exchange gasses, food and waste with the organism's environment (Campbell at al. 2006). These substances diffuse across the cell membrane at a rate determined by Fick's law, which states that:

$$Rate\ of\ diffusion = \frac{surface\ area \times concentration\ difference}{distance}$$

(Wheatley 1998).

The rapid diffusion of these substances is vital for many functions within an organism, such as respiration, excretion and even photosynthesis in plants, however, there are limits to diffusion that have significant consequences for organisms of various shapes and sizes (Kraus 1984). It can be seen from Fick's Law that diffusion is slow at longer distances; hence it is important for organisms to have a large surface area to volume ratio, in order for all cells to be able to rapidly diffuse important molecules (Kraus 1984). It is important to note, though, that the relationship between surface area, a two-dimensional measurement, and volume, a three dimensional measurement is non-linear (Roberts et al. 2000). For example, as the size of a cell or organism increases, the surface area, which acts as the site of diffusion, increases however the volume of the cell, which requires the diffused substances, increases at a much greater rate (Roberts et al. 2000). This relationship is the reason that the cells of organisms, as well as unicellular organisms, can only reach a certain size (Roberts et al. 2000). This relationship also has implications for the rate of diffusion in larger animals, which has led to various evolutionary adaptations (Roberts et al. 2000).

The relationship between surface area and volume and the implications for diffusion mean that organisms must either be small and narrow or have evolved adaptations such as circulatory and respiratory systems (Roberts et al. 2000). These evolutionary adaptations often include large surface areas at sites of diffusion and are designed in a way that allows the effective transport of diffused substances around the organism (Roberts et al. 2000). Another requirement of these sites of diffusion is that they remain moist, in order to allow dissolved gasses or nutrients to be absorbed across the membrane. Examples of broad, moist surface areas where diffusion occurs in organisms include the lungs of mammals, the gills of fish and the skin of planarians

(Roberts et al. 2000). These are examples of evolutionary adaptations that allow for rapid diffusion of molecules between the organism and its environment (Roberts et al. 2000).

Two experiments were conducted using shapes of agar to test: (1) the effect of organism size on the rate of diffusion and (2) the effect of organism shape on the rate of diffusion and to relate these results to the way organisms carry out gas exchange and transport materials around their bodies.

2.0 METHODS

In order to test the effect of body shape and size on the rate of diffusion, comparisons were made between the rates at which acid diffused into blocks of agar of different dimensions and, therefore, different surface area to volume ratios. The agar was impregnated with an indicator (phenolphthalein and sodium hydroxide), which turns from red to clear in the presence of an acid. Care was taken to ensure the agar did not come into contact with acid as shapes of different dimensions were measured and cut out. The different shapes were then submerged in acid and a stopwatch was used to record the time it took for the shapes to become clear and completely infused with the acid. After ten minutes, any shapes that still had a red centre and that weren't completely infused with the acid were removed and rinsed with distilled water. The clear part of the shape, soaked with acid, was cut away carefully and the remaining agar shape was measured and recorded.

In order to determine the effect of body size on the rate of diffusion, impregnated agar was cut into three cubes of differing sizes, which were then submerged in the acid. The dimensions of the three cubes used are shown in table 2.1 and it can be seen that Cube 1 had the largest surface area to volume ratio and Cube 3 the smallest. Therefore, it was predicted that Cube 1 would have the fastest rate of diffusion and Cube 3 the slowest.

Table 2.1: Physical properties of three agar cubes of different dimensions.

Shape name	Cube dimensions (mm)	Surface area (mm^2)	Volume (mm^3)	SA:Vol ratio
Cube 1	5 x 5 x 5	150	125	1.2
Cube 2	10 x 10 x 10	600	1000	0.6
Cube 3	20 x 20 x 20	2400	8000	0.3

In order to determine the effect of body shape on the rate of diffusion, agar impregnated with the indicator was cut into prisms of varying dimensions, which were submerged in the acid. The dimensions of the three shapes are shown in table 2.2 and it can be seen that, despite the differences in volume and surface area, the surface area to volume ratios of the shapes are very similar. For this reason, there was not expected to be much difference in the rate of discolouration of the cubes. However, Prism 2 had the greatest surface area to volume ratio and Cube 4 had the smallest. Therefore, Prism 2 was predicted to have the fastest rate of diffusion and Cube 4 the slowest.

Table 2.2: Physical properties of three agar prisms of different dimensions and the predicted rate of discolouration of each.

Shape name	Prism dimensions (mm)	Surface area (mm^2)	Volume (mm^3)	SA:Vol ratio	Predicted rate of discolouration
Cube 4	20 x 20 x 20	2400	8000	0.300	3rd
Prism 1	13 x 20 x 30	2500	7800	0.321	2nd
Prism 2	15 x 15 x 35	2550	7875	0.324	1st

3.0 RESULTS

As was predicted, the smallest cube, with the highest surface area to volume ratio, had the fastest rate of diffusion, as the indicator showed that the acid had saturated Cube 1 completely after 120 seconds (table 3.1). As was also predicted, Cube 3, with the lowest surface area to volume ratio, had the slowest rate of diffusion as only 87.5 % of the shape was saturated with the acid after ten minutes of observation. Additionally, Cube 2 became completely discoloured and saturated after 540 seconds (table 3.1). The rate of diffusion, that is the average proportion of the shape discoloured per minute, appeared to increase exponentially as the surface area to volume ratio of each cube increased (figure 3.1).

Table 3.1: Comparison of the relative time taken for the agar cubes to discolour, or the percentage of the cube discoloured after ten minutes.

Shape Name	Cube dimensions (mm)	Cube volume (mm^3)	Time taken for cube to discolour (sec)	Volume of coloured portion (mm^3)	Volume of discoloured portion (mm^3)	Percentage of cube discoloured (%)
Cube 1	5 x 5 x 5	125	120	0	125	100
Cube 2	10 x 10 x 10	1000	540	0	1000	100
Cube 3	20 x 20 x 20	8000	600	100	7000	87.5

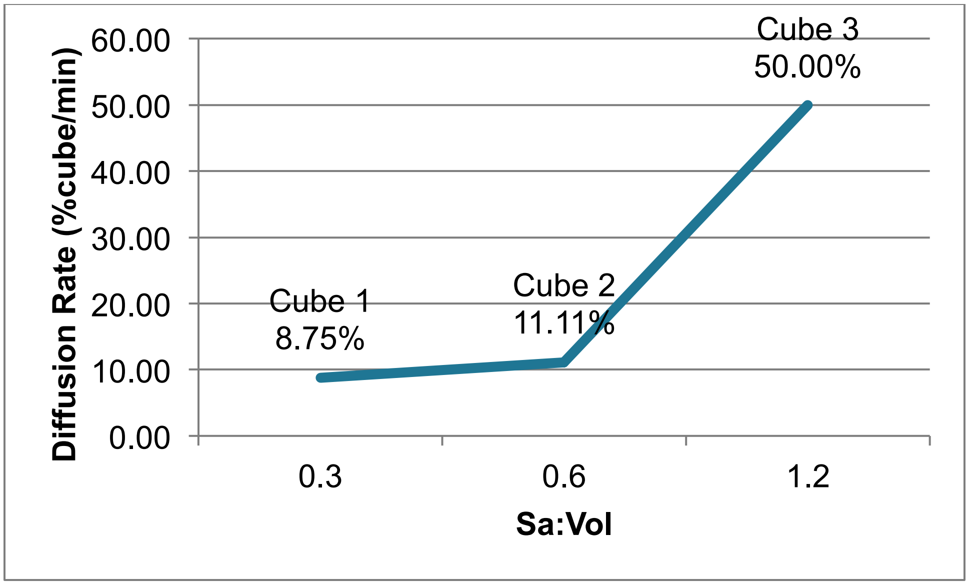

Figure 3.1: The non-linear relationship between the surface area to volume ratio and the diffusion rate of the first group of three agar shapes.

As was predicted, the rates of discolouration of the second group of three shapes observed were very similar. However, unexpectedly, the rate of diffusion of Cube 4, with the lowest surface area to volume ration, was the fastest as 89.9% of the shape was discoloured at the end of the ten minute observation period (table 3.2). On the other hand, Prism 2, with the highest surface area to volume ratio, had the slowest rate of diffusion as only 85.1% of the shape was discoloured after ten minutes (table 3.2). Prism 2 had the second highest surface area to volume ratio and, as was expected, the second highest rate of diffusion, wish 88.5% of the shape becoming discoloured after ten minutes. A comparison between the predicted order of diffusion and the observed order of diffusion are shown in table 3.3. The differences between the predictions and observed results was likely due to the very similar surface area to volume ratios as well as due to human error while cutting and measuring the agar. It can be seen that the average proportion of the shape discoloured per minute for each shape was very similar, ranging from 8.5% – 9.0% per minute (Table 3.3).

Table 3.2: Comparison of the relative time taken for the agar shapes to discolour, or the percentage of the shape discoloured after ten minutes.

Shape name	Prism dimensions (mm)	Prism volume (mm^3)	Time taken for prism to discolour (sec)	Volume of coloured portion (mm^3)	Volume of discoloured portion (mm^3)	Percentage of prism discoloured (%)
Cube 4	20 x 20 x 20	8000	600	810	7190	89.9
Prism 1	13 x 20 x 30	7800	600	900	6900	88.5
Prism 2	15 x 15 x 35	7875	600	1170	6705	85.1

Table 3.3: The surface area to volume ratios and the rates of diffusion for the second group of three agar shapes.

Shape name	SA:Vol ratio	Rate of diffusion (%shape/min)	Predicted rate of discolouration	Observed rate of discolouration
Cube 4	0.300	9.0	3rd	1st
Prism 1	0.321	8.9	2nd	2nd
Prism 2	0.324	8.5	1st	3rd

Table 3.4: Physical properties of different animals with varying body shapes.

Animal	Approximate shape	Approximate dimensions (mm)	Approximate surface area (mm^2)	Approximate volume (mm^3)	SA:Vol
Planarian	Flat Rectangle	0.1x5.5x0.8	10.1	0.4	22.9
Earthworm	Cylinder	length=32, diameter=2	207.3	100.5	2.1
Cricket	Rectangular Prism	19x5x5	430.0	475.0	0.9
Mouse	Barrel	length=95, diameter=38	13,609.4	107,740.9	0.1

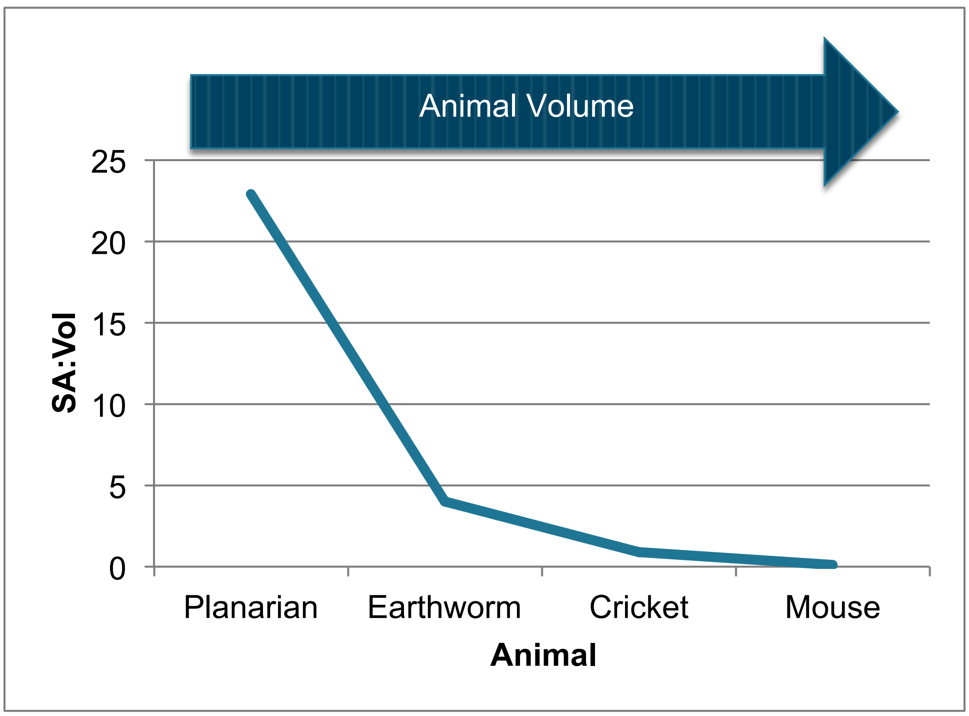

Figure 3.2: The surface area to volume ratios of four animals with different body shapes and sizes.

4.0 DISCUSSION

Diffusion is effective for transporting molecules over small distances, such as in and out of cells, as they have a high surface area to volume ratio (Roberts et al. 2000). Over greater distances however, such as in larger organisms where the surface area to volume ratio is low; diffusion is not as effective (Roberts et al. 2000). This was observed experimentally by noting the diffusion rates of three agar cubes of different dimensions, and therefore different surface area to volume ratios, soaking in acid. It was noted that the diffusion rate of the smallest cube, with the highest ratio, was the fastest (8.75% per minute) and the largest cube, with the smallest ratio, was the slowest (50.00% per minute). Furthermore, the surface area to volume ratio of a cell or organism can be linked directly to the rate of diffusion by Fick's Law (Wheatley 1998). This was observed experimentally in three prisms of agar soaking in acid, each of which had different dimensions, volumes and surface areas, but all of which had similar surface area to volume ratios. It was noted that the rates of diffusion for all three shapes were very similar, ranging from 8.5% - 9.0% of the shape being discoloured per minute.

These observed relationships are important as every cell in every organism relies on diffusion for the transfer of gasses, wastes and nutrients but the rate of diffusion is limited by the surface area to volume ratio (Roberts et al. 2000). So animals of various shapes and sizes have different adaptations in their respiratory and circulatory systems to allow diffusion to be effective in supplying and distributing important molecules to all of the cells in an organism's body (Campbell et al. 2006). Within the laboratory, the shapes, sizes, respiratory systems and circulatory systems of four different types of animals were observed and compared. The four animals that were: a planarian (Phylum Platyhelminthes), an earthworm (Phylum Annelida), a cricket (Phylum Arthropoda) and a mouse (Phylum Chordata).

PLANARIAN RESP & CIRC - A planarian is an example of a very small organism that does not require a respiratory system or a true circulatory system (Campbell et al. 2006). It is very small in size (volume is approximately $0.4mm^3$) and has a flat, rectangular structure (only 0.1mm think). This gives it a very large surface area to volume ratio (22.9) and means that it does not require a specialised respiratory system, as the exchange of gasses can occur directly across the animal's surface (Campbell et al. 2006). It also does not require a true circulatory system as all cells in the body are either adjacent to the external environment or a small, branched gastrovascular cavity, nutrients and wastes are absorbed and expelled simply by diffusion across the organism's surface (Campbell et al. 2006).

However, "for animals with many cell layers, gastrovascular cavities are insufficient for internal transport because diffusion distances are too great for adequate exchange of nutrients and wastes” (Campbell et al. 2006, p. 868). In such animals, circulatory systems exist to aid the transport of important molecules around the organism’s body (Campbell et al. 2006). WORM CIRC & RESP - For example, the earthworm has a simple, closed circulatory system, which involves blood being pumped through a network of vessels that transport materials to and from cells via diffusion into the interstitial fluid (Campbell et a. 2006). There are three main vessels that run the length of the earthworm and circulate blood (Campbell et al. 2006). Via waves of muscular contractions, the dorsal vessel moves blood anteriorly where it then then enters five vessels that act as hearts, pumping the blood posteriorly through two ventral vessels that run the length of the animal (Campbell et al. 2006). Smaller capillaries that connect these vessels and that are sit very close to the organism’s surface are important in the transport of dissolved gasses involved in respiration (Campbell et al. 2006). The long thin shape of the earthworm (approximately 32mm long and 2mm in diameter), as well as its small size, mean that it has a relatively high surface area to volume ratio (2.1) and hence it can rely on the diffusion of gasses across its skin for respiration (Campbell et al. 2006). These gasses are diffused directly into the dense network of capillaries where they are transported around the organism’s body (Campbell et al. 2006).

CONNECTION - Planarians and earthworms are two examples where the surface area to volume ratio is sufficient enough to allow gas exchange to occur through the organism’s skin. “For most other animals, the general body surface lacks sufficient area to exchange gasses for the whole body” (Campbell et al. 2006, p. 884). Therefore, respiratory organs with large surface areas such as lungs, tracheae and gills have evolved (Campbell et al. 2006). CRICKET RESP - Insects, such as crickets, which are rectangular prism shaped and had a relatively small surface area to volume ratio (0.9), use the tracheal system for respiration (Campbell et al. 2006). This involves a network of branched tubes dispersed throughout the organism’s body; the largest of which are called tracheae and are connected to openings on the organism’s body called spiracles (Campbell et al. 2006). Nearly every cell is adjacent to this network of tubules and is able to exchange gasses with the environment via diffusion (Campbell et al. 2006). CRICKET CIRC - The cricket is an example of an organism with an open circulatory system (Campbell et al. 2006). Unlike the closed circulatory system found in earthworms and vertebrates, the circulatory fluid (hemolymph) is not separated from the interstitial fluid by a closed network of vessels. ________

Mammals can get very large in volume and often have very small surface area to volume ratios, such as the mouse observed in the laboratory (0.1) (Roberts et al. 2000). Such organisms have evolved advanced respiratory and circulatory systems (Campbell et al. 2006). RESP HERE. However, unlike the branched network of respiratory tubules found in the cricket, lungs are restricted to the chest cavity, hence a circulatory system is required to transport dissolved gasses involved in respiration to all of the cells of the organism’s body (Campbell et al. 2006). Mice, like all mammals, have a closed circulatory system with a four-chambered heart that pumps blood around a network of vessels, transporting materials around the body (Campbell et al. 2006). In order to maintain sufficient blood pressure, mammals’ blood undergoes double circulation where it enters the heart twice in one circuit, once as oxygen-rich blood through the left side of the heart and again as oxygen-poor blood through the right side (Campbell et al. 2006). This separation increases the efficiency of the circulatory system as the oxygen rich-blood does not mix with, and become diluted by, the oxygen-poor blood (Campbell et al. 2006).

- Diffusion is effective for transporting nutrients into cells and wastes out of cells as cells are small (reference). This relationship was demonstrated experimentally ……
- Part B is basis for discussion – but must be linked to relationship between surface area and volume and diffusion
- Don’t rattle on without any real point to the details you are giving very low marks for this

5.0 REFERENCE LIST

Campbell, N. A., Reece, J. B. & Meyers, N. 2006, *Biology Australian Version*, 7th ed. Pearson Education Australia, Frenchs Forrest.

Wheatley, D.N. 1998, 'Diffusion theory, the cell and the synape', *Biosystems*, vol. 45, no. 2, pp. 151-63.

Kraus, D. 1984, *Concepts in Modern Biology*, 5th ed. Globe Book Co., Englewood Cliffs, New Jersey.

Roberts, M., Reiss, M. & Monger, G., 2000, *Advanced Biology*, Nelson Thornes, Cheltenham.

CHECK REF AGAINST 1ST REPORT