With Respect to Surface Area to Volume Ratios Affecting Rates of Diffusion, Is One Cell Shape More Efficient Than Others?

HL Biology Internal Assessment

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Background Information:

In this experiment, the effect of cell shape on efficiency of surface area to volume ratio – and thus osmosis and diffusion – was investigated.

Various types of cells come in various shapes and sizes. Many types of cells are small cubic or spherical shapes however some cells, such as muscle cells, are long narrow structures. A similar concept can be applied to plant leaves as well: plant leaves are thin and flat to allow the most sun to penetrate, thus allowing maximum photosynthesis to occur while requiring the plant to expend the least amount of energy growing larger (more volume).

Research Question

With respect to surface area to volume ratios affecting rates of diffusion, is one cell-shape more efficient than others?

Variables

For this experiment the manipulated variable was the dimensions of the piece of potato being submersed in the water and indicator solution. I changed the dimensions of the pieces of potato to investigate different shapes and sizes on the time taken for the indicator to diffuse to the centre of the piece of potato. The dimensions of potato used are cubes with side length of 0.5 mm, 3.0 mm and 7.0 mm, elongated slivers with dimensions of 0.5 x 1.0 x 100 mm, 3.0 x 3.0 x 100 mm and 5.0 x 5.0 x 100 mm, thin slices with dimensions of 0.75 x 18 x 51 mm, 1.5 x 25 x 54 mm and 3.0 x 36 x 84 mm.

The responding variable was the time it took for the triiodide ion (I_3^-) to diffuse to the centre of the piece of potato. When the triiodide molecule slips inside the amylose in starch, it forms a dark black colour[1] – thus providing a visual aid to gauge the diffusion of the liquid from the beaker. For the two smallest cubes, the two smallest slivers and all of the thin slices of potato, it was fairly easy to judge when the indicator had turned the potato black all the way through since the pieces were so thin. For the largest of the cubes and elongated slivers however, several trials had to be dedicated to gauging an approximate time taken for the indicator to diffuse to the middle of the potato. This was done by removing a piece of potato and slicing it in half to see whether the middle was black or not. These trials are not counted in the results used for analysis since if placed back in the beaker, indicator would diffuse through the incision and thus reach the middle faster than the other untouched pieces.

The controlled variables used in this experiment are included in the table on the next page (Figure 1).

[1] Starch and Iodine. (2013, October 1). Retrieved October 16, 2015, from http://chemwiki.ucdavis.edu/Biological_Chemistry/Carbohydrates/Case_Studies/Starch_and_Iodine

Figure 1: Controlled variables

Controlled variable	**Reason for controlling this variable**	**How this variable was controlled**
Type of potato	Since different types of potatoes may have slightly different densities, diffusion rates, etc. it is necessary to maintain consistency as any of the factors listed could cause discrepancies with the results obtained, even if all other variables were identical. Further, using a darker coloured potato for some trials and a lighter potato for others would introduce a great deal of error since the darker potato may appear to have undergone more diffusion when in reality it has not.	The same type of potato from the same bag of potatoes was used for all trials. Plain russet potatoes (*Solanum tuberosum*) were used for all trials.
Temperature of potato, triiodide solution	Increasing the temperature would increase the amount of kinetic energy the particles have. This would cause them to move faster and since diffusion is the movement of particles through membranes, the higher kinetic energy would cause this to happen more quickly even if all other variables were identical.	The potato used in this experiment was stored in the same refrigerator each day prior to use and the indicator and deionized water were kept at room temperature.
Concentration of triiodide solution	If the amount of I_2KI indicator per volume of deionised water was changed per each trial, this would introduce a range of possible errors such as all the indicator becoming used up for some of the trials and not others (thus making it seem that it took longer to diffuse to the centre) or that by having much more indicator in some trials this would cause diffusion to proceed at a faster rate due to a concept known as the collision theory.	Approximately one drop of indicator was used for every 1.5 cm^3 of deionised water in the beaker. This was kept consistent for all trials. To make certain that each trial was starting from the same concentration of indicator, fresh batches were prepared for each trial.

Hypothesis

Since the majority of cells in living organisms are of a small cubic or spherical shape, I expect this to be the most efficient shape of potato since in nature through evolution and natural selection, only the best and healthiest organisms with the most efficient cell-shape would have survived this far. If the shape of a cell is incredibly inefficient, the organism would presumably be unhealthy or at the very least, require more energy to accomplish the same functions as its more efficient counterpart and thus be less favourable for natural selection. This would cause organisms with the inefficient cell-shape to slowly become extinct.

Materials

- 50 cm^3 beaker
- 200 cm^3 beaker
- 1000 cm^3 beaker
- Glass stirring rod
- Tongs
- I_2KI indicator
- Russet potatoes (*Solanum tuberosum*)
- Sharp knife
- Gloves
- Safety glasses
- Lab coat
- 1.0 cm^3 dropping pipette

Explanation of Indicator Used

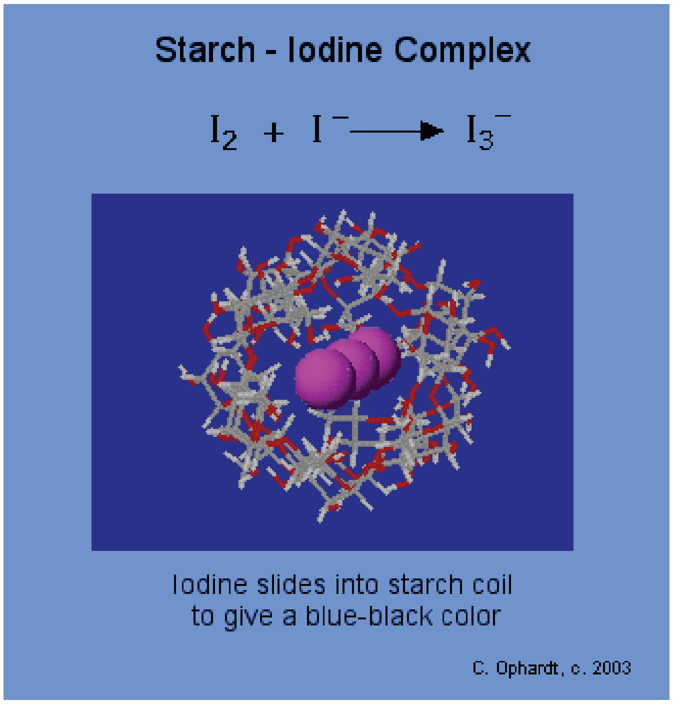
The iodine-potassium-iodide indicator used is also known as Lugol's Iodine Solution and can be made by dissolving 10 g of KI in 20-30 cm^3 of distilled water and then adding 5 g of iodine and heating gently until iodine is dissolved. The solution is then diluted to 100 cm^3 with more distilled water[2]. Note that the indicator used in this experiment was already pre-made in the lab so the procedure that was just described is not part of the experiment.

This indicator can be used to detect starch as the linear triiodide ion complex that is formed by dissolving iodine in the presence of potassium iodide can slip into the coil of the starch, causing an "intense blue-black colour"[3]. This can be shown in Figure 2 on the next page.

[2] U.S. Food and Drug Administration. (n.d.). Retrieved October 19, 2015, from http://www.fda.gov/Food/FoodScienceResearch/LaboratoryMethods/ucm062245.htm

[3] Starch and Iodine. (2013, October 1). Retrieved October 19, 2015, from http://chemwiki.ucdavis.edu/Biological_Chemistry/Carbohydrates/Case_Studies/Starch_and_Iodine

Figure 2[4]: I_3^- slides into starch molecule to produce black colour



Procedure

1. Using a sharp knife, cut pieces of potato that measure the following dimensions. Five pieces of each shape are needed to have five trials of data for each size. For larger pieces, cut two or three extra pieces to use for obtaining a benchmark of how long the entire process will take.

0.5 x 0.5 x 0.5 mm	5.0 x 5.0 x 100 mm
3.0 x 3.0 x 3.0 mm	0.75 x 18 x 51 mm
7.0 x 7.0 x 7.0 mm	1.5 x 25 x 54 mm
0.5 x 1.0 x 100 mm	3.0 x 36 x 84 mm
3.0 x 3.0 x 100 mm	

2. Prepare a solution to submerge the potato in by measuring an adequate amount of deionised water to fully submerge the potato. Using the dropping pipette, add one drop of iodine-potassium-iodide indicator for every 1.5 cm^3 of deionised water.
3. Place all pieces of a certain dimension of potato (eg. All the 3.0 x 3.0 x 3.0 mm pieces) in the beaker and start the timer.
4. Gently stir the contents of the beaker to ensure even distribution of indicator. Using the stirring rod, occasionally turn over any pieces of potato that have sunken to the bottom of the beaker. This is to allow all sides to have even contact with the solution. For larger pieces, if necessary, use additional stirring rods to prevent the pieces of potato from sticking to one another which would prevent contact with the solution.

[4] Starch and Iodine. (n.d.). Retrieved November 2, 2015, from http://chemwiki.ucdavis.edu/@api/deki/files/500/547starchiodine.gif

5. Record time at which the indicator has diffused to the centre of each piece of potato. For larger trials, the "benchmark" pieces should be used first to determine roughly how far the indicator has diffused since this would otherwise not be visible in the same way it is for the thinner pieces.

Safety

- Wear safety goggles throughout the experiment to prevent iodine from getting in your eyes.
- Wear rubber gloves while near iodine to prevent it from staining your skin by accident.
- For your safety, always wear a lab coat when operating in the lab.
- This experiment involves the use of sharp knives to cut very thin slices of potato, use caution not to cut yourself.

Results

Data Collection

Included in Figure 3 is all the raw numerical data that was gathered while conducting the experiments. This table includes the measurements of the potato as well as times for each of the five trials.

Figure 3: Raw data from experiment

Dimensions (mm)	**Trial No. 1 (hh:mm:ss)**	**Trial No. 2 (hh:mm:ss)**	**Trial No. 3 (hh:mm:ss)**	**Trial No. 4 (hh:mm:ss)**	**Trial No. 5 (hh:mm:ss)**
0.5 x 0.5 x 0.5	173	189	266	178	183
3.0 x 3.0 x 3.0	1026	1037	1344	1130	1105
7.0 x 7.0 x 7.0	77096	83866	74923	81170	79452
0.5 x 1.0 x 100	00:34:58	00:22:37	00:29:14	00:25:41	00:26:12
3.0 x 3.0 x 100	01:12:38	01:04:29	00:53:47	01:02:45	00:57:39
5.0 x 5.0 x 100	01:38:57	02:26:32	02:13:37	02:13:43	02:04:56
0.75 x 18 x 51	00:53:30	00:48:27	01:03:49	01:07:24	00:57:18
1.5 x 25 x 54	01:34:19	01:22:46	01:29:19	01:23:54	01:39:26
3.0 x 36 x 84	02:48:35	03:31:54	03:36:20	03:12:52	02:59:32

On the next page, in Figure 4 through Figure 8 there is photographic data that was also gathered when conducting the experiment.

Note that the potato pictured in Figure 4 is not an actual trial but rather a piece of potato being used to demonstrate how the indicator alters the colour of the potato as it diffuses towards the centre. This piece was submerged for a little while and then cut for demonstration purposes.

Figure 4: Demonstration of indicator diffusion in potato

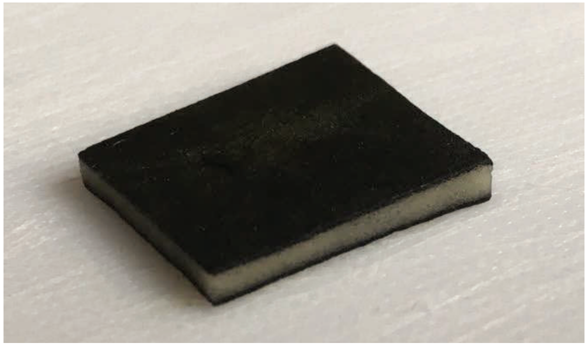


Figure 5: 3.0* x *3.0* x *3.0 mm cubes after submersion

Figures 5-8 are photos of real trials. Some of the photos are of trials that were used as "benchmark" pieces to establish a baseline for how long a given shape of potato would take and others are trials being used for analysis. This is specified in each figure's caption.

Above, Figure 5 shows three official trials of 3.0 x 3.0 x 3.0 mm cubes after submersion. The cube on the left was squished a bit by metal tongs used to remove it from the beaker however it did in fact measure 3.0 x 3.0 x 3.0 mm. Figure 6, shows eleven of the 7.0 x 7.0 x 7.0 mm cubes during submersion. Six of these cubes were designed to be used as dry-runs to determine approximately how long it would take since only five official trials are required. Figure 7 and Figure 8 (p. 7) show a 7.0 x 7.0 x 7.0 mm cube and a 3.0 x 36 x 84 mm thin after they have been submerged and removed from the solution. Each piece has been cut to show the centre of the potato. Notice how in both pictures, the entire piece of potato is black – even the centre.

Figure 6: 7.0* x *7.0* x *7.0 mm cubes during submersion

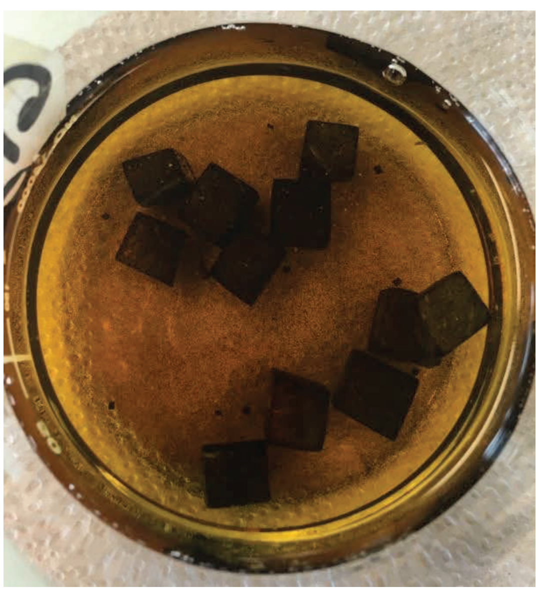
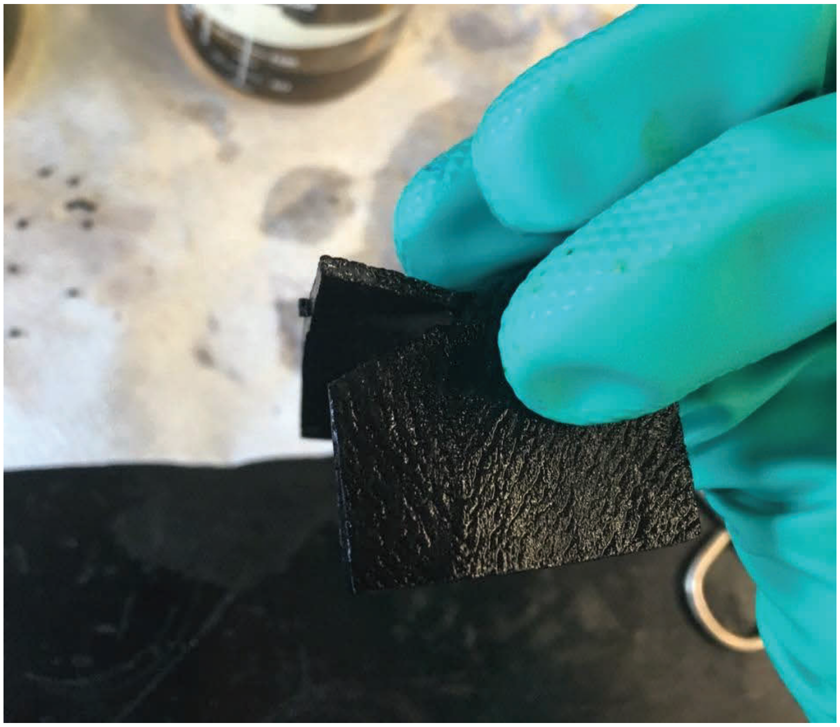


Figure 7: 7.0* x *7.0* x *7.0 mm cube after diffusion is complete

Figure 8: 3.0 x 36 x 84 mm thin flat rectangular prism after diffusion is complete



Data Processing

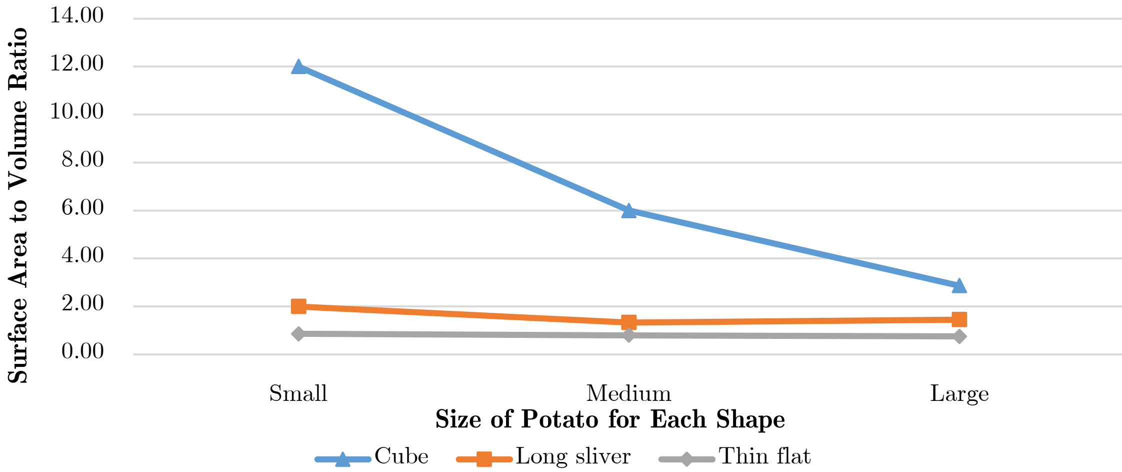
Figure 9: Surface area, volume and approximate surface area to volume ratio

Dimensions (mm)	Surface Area (mm^2)	Volume (mm^3)	Approx. Surface Area to Volume Ratio	Shape
0.5 x 0.5 x 0.5	1.5	0.125	12:1	Sm. cube
3.0 x 3.0 x 3.0	54	27	2:1	Med. cube
7.0 x 7.0 x 7.0	294	343	0.86:1	Lg. cube
0.5 x 1.0 x 100	301	50	6:1	Sm. elongated
3.0 x 3.0 x 100	1218	900	$1\frac{1}{3}:1$	Med. elongated
5.0 x 5.0 x 100	2050	2500	0.8:1	Lg. elongated
0.75 x 18 x 51	1939.5	688.5	2.866:1	Sm. thin, flat
1.5 x 25 x 54	2937	2025	1.45:1	Med. thin, flat
3.0 x 36 x 84	6768	9072	0.75:1	Lg. thin, flat

Shown above in Figure 9 is the surface area, volume and surface area to volume ratio. Surface area was calculated by finding the sum of the area of each side of the piece of potato, volume was found by multiplying each dimension of the potato and surface area to volume ratio is found by dividing surface area by volume and putting the quotient in lowest terms. To maximize the simplicity of the ratios in Figure 9, some of the quotients were rounded to whole numbers or multiplied to form whole numbers. For example, 4:3 was originally 1.333333:1.

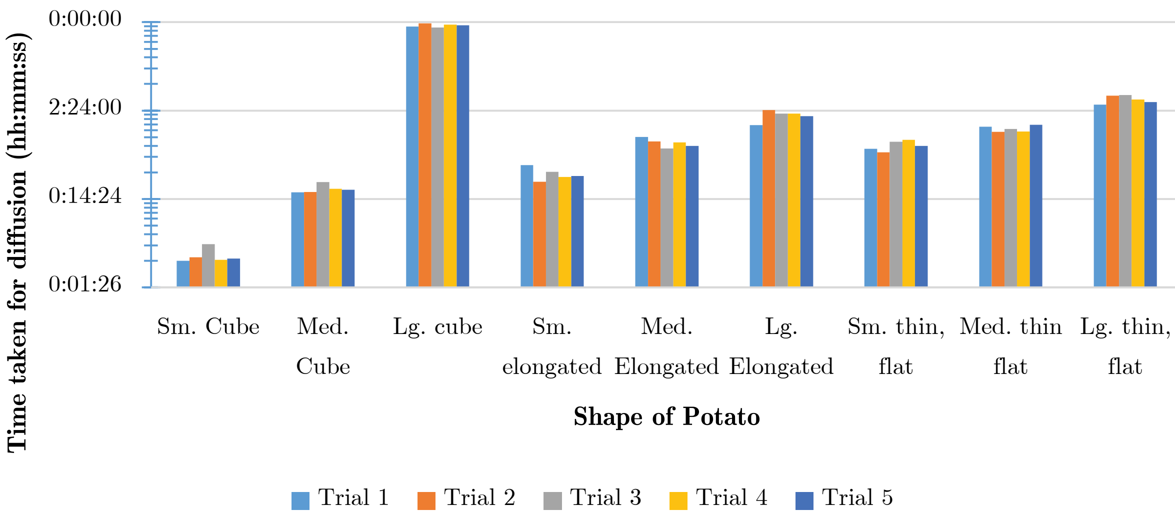
To visualize how effective altering the size of the potato was for each shape in an effort to change surface area to volume ratio, Figure 10 shows the surface area to volume ratio of each size of each shape.

Figure 10: Comparing Surface Are to Volume Ratio for Each Potato Shape



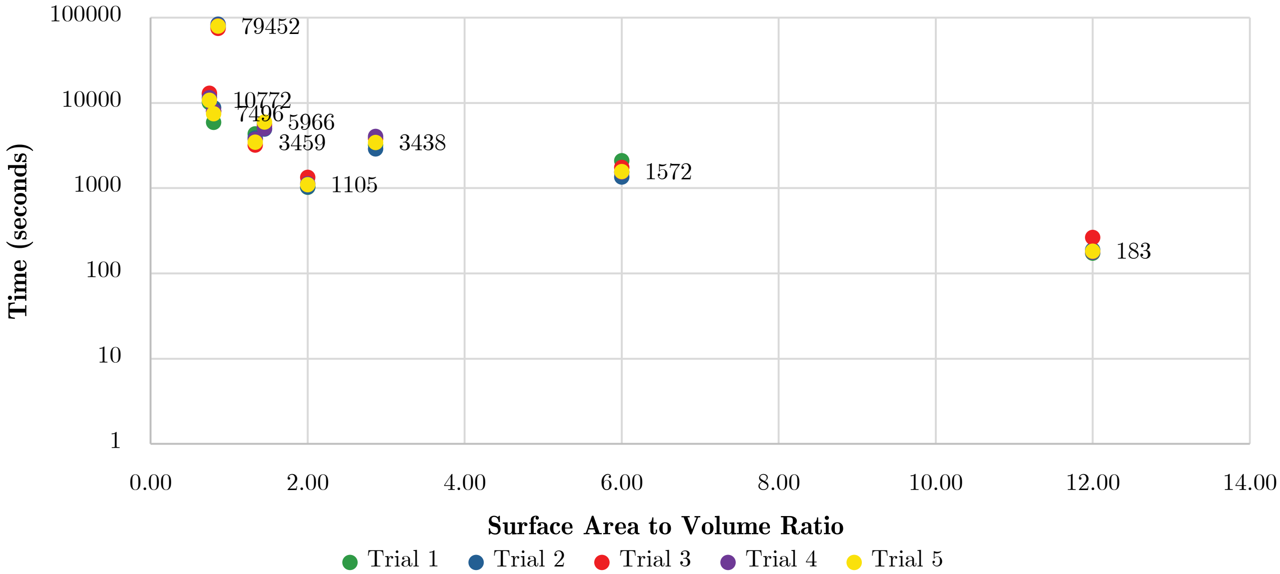
Next, Figure 11 demonstrates the amount of time taken for each trial of each shape. The different trials are shown in different colours.

Figure 11: Shape and size of potato vs. time of diffusion



Similar to Figure 11, Figure 12 examines the amount of time taken except Figure 12 relates it to surface area to volume ratio rather than volume. Once again a logarithmic scale is used on the y-axis to allow a better representation of the data set.

Figure 12: Surface area to volume ratio of potato vs. time of diffusion



Next, by finding the mean of the surface area to volume ratios graphed above and using this to create the least squares regression line of this data, it is possible to find the equation which best represents the data. This line is shown in Figure 13 and its equation and correlation coefficient is repeated in Figure 14.

Figure 13: Least squares regression line for data from Figure 12

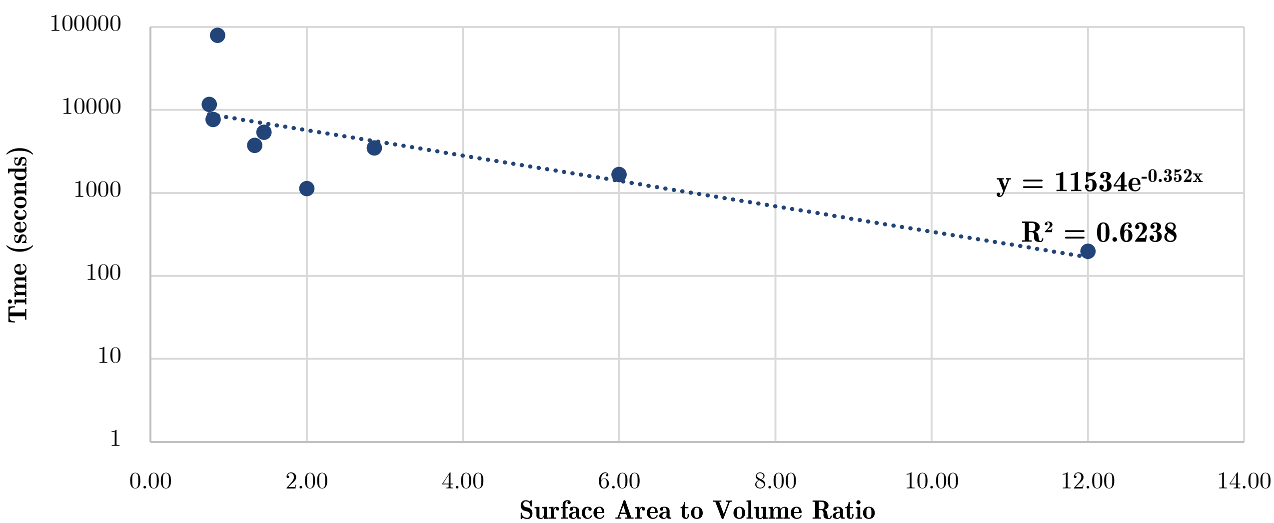


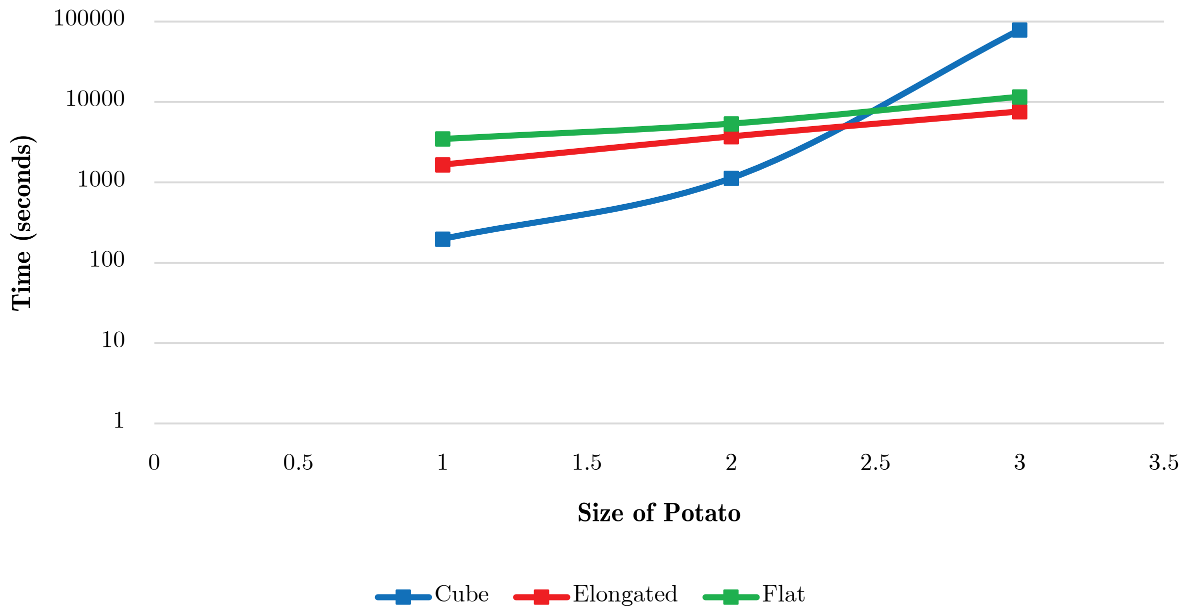
Figure 14: Equation of least squares regression line[5] from Figure 13

$$y = 11534\mathrm{e}^{-0.352x}$$
$$r^2 = 0.6238$$

Figures 12 and 13 prove that the data gathered fits an exponential regression line fairly well. Quantitatively, this is proved by the correlation coefficient (r^2) of 0.6238 which means that the data falls relatively close to the line $y = 11534\mathrm{e}^{-0.352x}$. Since the data has a good correlation to this function (i.e., points are not randomly scattered around the graph), this proves a relationship between the surface area to volume ratio and the time it takes for a solution to diffuse to the centre of the potato.

The results from Figure 13 can be further summarized using the average times for each shape and comparing them on a shape-to-shape basis. This helps to distinguish which shape (i.e., cube, sliver or flat) was, in general, the most efficient.

Figure 15: Effect of altering size on diffusion time on a shape-by-shape basis



Notice how in Figure 15 the red and green lines that represent the elongated and flat shapes take a much smoother ascent as the size of the potato is increased while the blue line that represents the cubic shape rises more steeply between Small and Medium and even steeper from Medium to Large. This shows that altering the size (and thus the SA:V) of the potato had the most drastic effect on the cubic shape.

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[5] Formula used by Microsoft Excel for correlation coefficient can be found at Clemson U. Physics Tutorial: Linear Regression. (n.d.). Retrieved February 24, 2016, from https://www.clemson.edu/ces/phoenix/tutorials/regression/index.html

Reflection

Based on the results shown in the data collection and processing sections it can be concluded that the small cube was the most efficient shape for facilitating a quick diffusion of the iodine solution in the beaker. This was to be expected however since it was by far the smallest and thus had the greatest surface area to volume ratio.

The trend that is being focused on, however, is the effect of altering the size of the different shapes on the efficacy of the shape for diffusion. The results from Figure 15 prove that changing the size of a cube has a much more dramatic effect on its speed of diffusion than changing the size of a long narrow shape or a thin flat rectangular shape.

Conclusion

Overall the experiment was a success since the results were fairly conclusive and, with the exception of the 7.0 x 7.0 x 7.0 mm cube, they all fit well on the exponential regression line in Figure 13 which means that the line's correlation coefficient is fairly high at 0.6238 (Figure 14). This proves consistency throughout the trials which increases the value and reliability of the results in the investigation.

Due to the fact that Figure 15 showed such a difference in the cube's level of response to size change, it can also be concluded that the cube is the most efficient shape at lower sizes however at the highest size the cube took much longer than the elongated piece and the thin piece. This largest cube size is shown on Figure 13 as being the dot (cluster of dots from Figure 12) that is much higher than all the rest and thus doesn't lie remotely near the regression line in Figure 13. Although upon first glance this appears to be an outlier, this is not the case since all five trials agreed with one another. Instead, what this shows is that regardless of the fact that the cube is the most effective shape tested, when SA:V ratios become too small, there is a point at which shape has minimal impact and efficiency is dramatically reduced despite other factors.

Since all of the pieces of potato were designed to mimic a cell, it is safe to say that very small, cubic (or spherical) cells are by far the most efficient shape. This finding aligns with the logic used for my hypothesis that, in nature, evolution and natural selection would force the most common cell shape to be the most efficient.

Limitations and Improvement

Even though overall the experiment was a success, there are many ways that the experiment can be improved. Firstly, since there is no quantifiable way to determine when the indicator has reached the middle of the potato and is dark enough, this allows for human error due to discrepancies between trials for what level of blackness counts as fully diffused. One way to ensure that the same "endpoint" is being recognized each time would be to place indicator directly on a piece of potato and wait for it to become as dark as possible. This piece could then be used as a tool to compare each trial to determine if it is finished.

Another way that the experiment would be able to be improved on is by conducting retrials with even smaller dimensions of each shape to see if the trends continue. With only three sizes of potato for each shape, it's difficult to determine if the findings are conclusive or if they just *appear* to be consistent. To do this, more precise cutting tools would be required for safety reasons. To cut the potato for this experiment a kitchen knife was used in the absence of a scalpel – which for pieces smaller than 0.5 x 0.5 x 0.5 mm, might even be too big.

Another limitation would be rather than placing a set concentration of indicator in the beaker with the potato and then leaving it, adding more indicator as the water began to fade to a paler shade of orange (i.e., the indicator is getting used up). In the trials that involved the large cubes, it is possible that the cubes took so long to completely turn black solely because the concentration of indicator was so low towards the end of the trial. The only way to combat this would be to add indicator to a beaker filled with water but is otherwise empty and use this beaker to visually compare the concentration of indicator in the water, adding more to the beaker with the potato when the water appears to be too light. Once again, this is subject to human error however it would certainly improve on the original design of the experiment.