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Article

Modeling the heart's reaction to narrow blood vessels

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SUMMARY

Cardiovascular diseases are the largest cause of death globally, making it a critical area of focus. The circulatory system is required to make the heart function. One component of this system is blood vessels, which is the focus of our study. Whether due to low temperatures or a medical condition, blood vessels can constrict, occasionally to a dangerous degree. Despite the serious consequences narrow blood vessels can have on one's body, due to their complexity and size, there is little information pertaining to how their constriction relates to the heart's ability to pump blood. Therefore, our work aims to demonstrate the numeric relationship between a blood vessel's diameter and the number of pumps needed to transport blood. We explored this concept using a water bottle model to represent the heart, and straws of varying diameters to represent the blood vessels. The experiment recorded the number of pumps necessary to transport 200 mL of red-dyed water to a second bottle using straws. We hypothesized that the number of pumps would increase as the diameter decreased, and that there would be a linear relationship between these variables. The data supported the numeric relationship we hypothesized, in which the largest diameter straw, 1 cm, required the least pumps and the smallest diameter, 0.4 cm, required the most. Our results depict how the heart must overcompensate to transport blood through narrow vessels, providing a better understanding of how the heart behaves when vessels constrict.

INTRODUCTION

The heart is an essential organ to the circulatory system. Blood vessels, such as pulmonary veins and arteries, transport blood throughout the body, carrying oxygen andnutrients to sustain growth (1). The transportation of blood, facilitated by a pumping heart, allows the body to function (2). Despite the importance of the circulatory system, blood vessels can narrow or clog, diminishing — or completely stopping — the heart's ability to circulate blood (3). From heart disease to colder temperatures, blood vessels can narrow. Because the blood vessels are unable to respond to such acute changes, constriction can occur (4). Due to the narrowing, the brain is deprived of oxygen and nutrients, causing individuals to experience chest pain, shortness of breath, and fatigue (5, 6).

The dangers of cardiovascular diseases are widely known. When cardiovascular diseases involve obstructed or narrow blood vessels, they are even more threatening, becoming the leading cause of death around the world (7). The number one cause of death out of the group is coronary heart disease, which involves the narrowing of coronary arteries (8). Constricted vessels having the highest cause of death highlights the dangers of narrow blood vessels and the necessity of treatments, such as bypass surgeries which are commonly used (9). However, due to vessel graft diseases and other complications, treatments are no longer as viable as they previously were (9). Narrow blood vessels are seen to be a deadly issue with risky treatments, displaying its medical relevance.

Generally, a narrowing of less than 60% does not significantly limit blood flow and is considered a mild form of vessel constriction. Any narrowing over 60% is critical and typically treated with surgery (10). However, due to the complexity and size of blood vessels, technology has not yet become advanced enough for individuals to see exactly how these percentages affect blood circulation (11). For example, there is no information pertaining to how many pumps it would take to circulate blood through unaffected vessels, as opposed to ones that are 50% narrower. Understanding the numeric relationship a blood vessel's diameter and the heart's ability to pump blood is a question of interest which we explore with our model.

Our study examines the concept of narrow vessels and how their constriction affects circulation. Narrow vessels limit blood flow; the same notion follows with straws, as it is more arduous to drink liquid through thinner straws, than ones with larger diameters. We modeled the circulatory system by connecting two flexible plastic bottles with straws of varying diameters such that pumping one bottle would force liquid through the straw into the other bottle. In our model, the straws mimicked the blood vessels, and the water bottle mimicked the heart. We hypothesized that our model would reveal a linear relationship in which the number of pumps increases as the diameter decreases. Our results supported our claim, displaying how more pumps were needed as the diameters became smaller. Relating this information to the circulatory system, our results display how the heart must pump more as blood vessels become narrower. Since the two variables had a linear relationship, we can estimate how other levels of constriction will affect the number of pumps the heart must make in accordance. With our model, we were able to see how the heart overcompensates when blood vessels become constricted.

RESULTS

Our study modeled how constriction affects liquid transport, and we related our data to blood vessel constriction

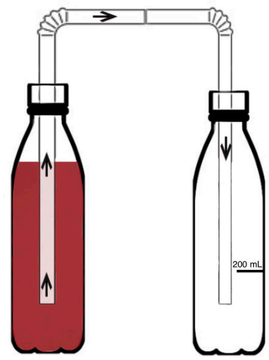

Figure 1: Diagram of model used to demonstrate circulation. One bottle is filled with water mixed with red food coloring. By squeezing this bottle in regular intervals, to model the heart's pump, the liquid transports through the straw, into the second bottle. The pumps stop once the water reaches the line marked at 200 mL.

on the heart's circulation (**Figure 1**). We tested four diameters: 1 cm, 0.8 cm, 0.6 cm, and 0.4 cm. The diameters were used to represent blood vessels at different levels of constriction, with 1 cm being 0% constriction and 4 cm being 60% constriction, where surgery is typically necessary.

The 1 cm, 0.8 cm, 0.6 cm, and 0.4 cm straws had an average number of pumps 5, 7.5, 9.25, and 13.5 respectively (**Figure 2**). The averages were calculated by completing 4 replicates for each diameter. On the graph, there are 16 points representing each of the replicates. A decrease in pumps as the diameter becomes larger can be seen with the 16 points. Also on the graph is the trendline, displaying a negative slope. The line intersects between or on most of the data points, exhibiting the relatively linear relationship between the number of pumps and the diameter. Using the graph, the inverse relationship can be seen, in which the number of pumps decreases as the diameter increases.

Along with finding the number of pumps for each diameter,

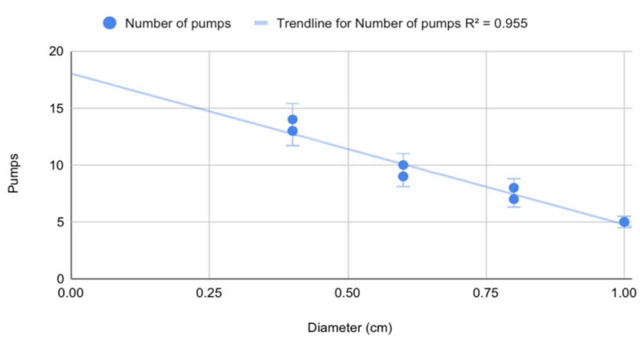

Figure 2: The Effect of Straw Diameter on Average Number of Pumps. The graph displays a negative slope, highlighting the inverse relationship between the straw diameter and the number of pumps. The points at 0.4 cm, 0.6 cm, 0.8 cm, and 1.0 cm show the corresponding 4 replicates per diameter. The line displays the trend of the points, with the coefficient of determination as well (0.955). The graph also contains standard deviation error bars for each of the diameters.

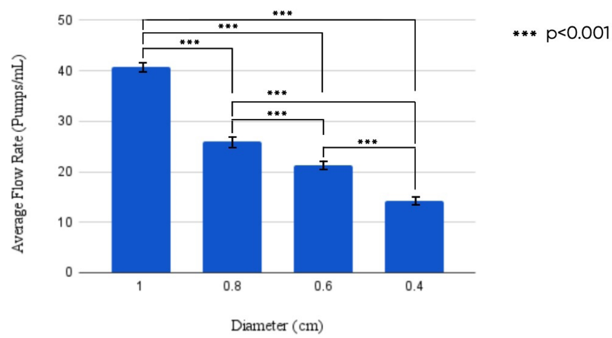

Figure 3: The Flow Rate of Straw Diameters 1 cm, 0.8 cm, 0.6 cm, 0.4 cm. On the graph, the flow rate for each of the diameters is displayed. The flow rate exhibits how much water is transferred with each pump. For each diameter, 5 replicates were completed, and then the average was calculated. The flow rate decreases as the diameter decreases. The graph contains error bars for the standard deviation from each diameter. A one-way ANOVA test with post-hoc testing was calculated. The ANOVA test revealed an f-ratio value of 1147.88 and the post-hoc testing revealed p-values that were less than our significance level (0.05).

we also calculated an average flow rate (**Figure 3**). The flow rate measures how much water is transferred in each pump. The 1 cm diameter straw had a flow rate of 40.8 ml/pump, while the 0.4 cm straw had a significantly smaller rate, which was 14.2 ml/pump. The 0.8 cm and 0.6 cm diameter straws had flow rates within those two values, being 26 ml/pump and 21.4 ml/pump respectively. With 60% constriction, from 1 cm to 0.4 cm, the amount of water transported decreased by about 65%. Having such a drastic difference between the diameters displays the extent to which blood flow can be restricted with narrow vessels. Additionally, we also conducted a one-way ANOVA test with post-hoc testing to determine whether our data was statistically significant. The tests yielded an f-ratio value of 1147.88 and p-values of less than 0.001, indicating that our data was statistically significant. Our results demonstrate that our experiment provided reasonable evidence to support our hypothesis.

DISCUSSION

Our data revealed the numeric relationship between the average number of pumps and the diameter of the straws. As the size of the straw became thinner, the volume decreased, permitting less water to travel through the object. The same concept should follow with blood vessels. Using the gathered data, we could relate our results to the modeled concept: The circulatory system. Since a narrower straw requires more pumps to transport the same amount of liquid, we expected that narrower blood vessels would require the heart to pump more to transport the same amount of blood. Therefore, our study provides insight into how the heart must overcompensate to transport blood through narrow vessels.

When conducting the experiment, for 3 of the 4 straw diameters, the replicates contained varying answers (**Figure 2**). While variation within replicates is common, it could have been a result of our muscles getting tired. With the observed variation, the accuracy of our results come into question, as it should ideally take the same number of pumps to transport the liquid in all 4 replicates. Additionally, the straws contained different materials — plastic, paper, and silicone — for each of the diameters. The varying materials could have altered the results by affecting the way the water is transported through the straw. For example, the 0.6 cm straw material was paper, which absorbs moisture more than plastic straws. Differing straw materials could have increased the number of pumps, as some of the water traveling through the straw was absorbed rather than deposited into the second bottle. Thus, the difference in materials could have affected the ability for the water to transport through the straw, altering the results. Furthermore, although a different water bottle was used for each of the different diameter straws, the same bottle was used for all 4 replicates. As the bottle is in better condition during the first replicate, it could have taken less pumps to transport the water in the replicates. However, for the 1 cm diameter straw, in which the same bottle was used for all 4 replicates, the number of pumps did not differ. Our data suggests the damage of the bottle was not substantial to influence our results. Additionally, to account for the potential damage that could have affected our results, we waited for the bottle to inflate again after each pump, returning it to a similar shape as before the pump. Using this strategy helped to minimize the damage of the water bottle.

A final aspect that could have led to a source of variation was in controlling the pumps. While the pumps are intended to be a controlled variable in terms of strength and frequency, this may not have occurred. To elaborate, the strength of the pump was determined by the two sides of the bottle touching. However, the bottle could have been squeezed slower or quicker than previous pumps and still have touched the two ends. Squeezing the bottle at different speeds would change the amount of pressure of each pump, ultimately controls the strength. Thus, to control the intensity, a timer could be used to ensure every pump is the same strength.

While the power could have impacted our results, the inflation after each pump was a controlled factor. A pump only occurred once the bottle inflated again, which determined the frequency. The inflation of the bottle did not affect the results and contributed to controlling the experiment by restoring the bottle back to its original size before the next pump.

Our study provides insight into how narrow blood vessels impact the circulation of blood. While a simpler representation of the intricate circulatory system, the model highlights the general concept. We chose to transport 200 mL of water due to its substantial amount, which allows for many pumps without providing significant room for error. Additionally, we calculated flow rate to give us a better idea of how much water is transported with each pump, and to what degree the number changes with different straw diameters. While our calculated flow rates do not directly correspond to blood vessels, our data gives a general idea of how much less blood would be transported during vessel constriction. For example, from 1 cm to 0.8 cm, the amount of water transported decreased by almost 37%. Decreasing the flow rate at this amount stresses the importance of why even mild constriction should be taken seriously, as a 37% decrease in blood flow would deprive the body of the oxygen and nutrients it needs to survive. For our experiment, four different diameter straws were used. We chose the sizes to give us a better idea of how the percentages mentioned in the Circulation journal article affect blood flow (10). For example, the 1 cm straw represents a blood vessel with no obstruction, while the 0.4 cm straw represents a vessel 60% narrower, which would require surgery. The other 2 diameters (0.6 cm and 0.8 cm) further display how the pumps are affected, while also providing data as to whether the relationship between the number of pumps and straw diameter is linear. Thus, our model highlights how constricted blood vessels can affect the number of pumps needed to transport blood.

As a next step, our model could be used to examine different aspects of the circulatory system. For example, we could analyze how varying strengths affect the number of pumps to transport 200 mL. The speed at which the pumps occur is another variable that would be interesting to test. With our experiment, we waited about 2 seconds between each pump to allow the bottle to inflate. However, we could use our model to measure how blood circulation is affected when the bottle pumps at a much quicker pace. Implementing these developments would account for different variables of the circulatory system, such as heart rate.

Other researchers share similar goals, creating complex models of the circulatory system. Researchers created a mock circulatory system to measure flow rates and arterial pressures (12). The system consisted of two MicroMed DeBakey pumps, a bronchial shunt, a test fluid of 35% glycerol in water, and other elements to represent the system. Another set of researchers used a mock circulatory loop to study a type of graft (13). One component of the loop was the pulsatile pump, which produces physiological ventricular pumping behaviors. The loop also contains an expansion chamber and pinch valves to generate peripheral resistance.

The two models include sophisticated equipment and complex designs. For changing our model, future experiments could include a more accurate prototype, demonstrating the whole circulatory system. The development would require more sophisticated supplies, such as a larger range of diameters or a more accurate test fluid, to better represent the components of the system. Improving our model would help better the understanding of how the heart behaves with blood vessels of varying sizes.

Our study highlights the relationship between the pumps needed to transport water and the different diameter straws. Our results relate back to the circulatory system, depicting how the heart reacts when vessels narrow. Thus, our study focuses on modeling a real-world situation in a simple way to better understand how the heart is affected when blood vessels narrow.

MATERIALS AND METHODS

A plastic, 16-ounce water bottle was filled with 200 mL of tap water mixed with McCormick Red Food Color to model the heart. Using a pair of scissors, a small hole was made into the cap of the bottle, providing a place for a ICONIQ silicone straw with a 1 cm diameter to be put through. The same was done with a second bottle. Before placing the straw through the cap, the short part of the 1 cm straw was taped to the short part of a second 1 cm straw, making an upside down "U" shape. The long end of the first straw was then placed 15 cm deep into the first water bottle. An AdTech Mini Hot Glue Gun was used to glue the circumference of where the straw meets the cap, to avoid letting air escape. The second water bottle was filled with 200 mL of water, with a line drawn on the bottle where the water fills up to. The water was then poured out. The long end of the second straw was placed through the cap of the second water bottle, and a hot glue gun was used to glue to straw to the cap. The first water bottle was squeezed from the part where it indents inward, until opposite sides of the bottle touched. This process was repeated after the bottle inflated again. The number of pumps was counted until the water in the second bottle reached the marked line. The number was recorded, corresponding to the diameter of the straws used (1 cm, 0.8 cm, 0.6 cm, or 0.4 cm). Using the same 1 cm straws, this procedure was repeated 3 more times, recording the data, and then calculating the average number of pumps for the straws with this diameter. The same process was completed with straws with diameters of 0.8 cm (unbranded plastic straw), 0.6 cm (OL-A paper straw), and 0.4 cm (Da Boom plastic straw). Using the 4 replicates from each diameter, a scatter plot graph was made. A trendline and error bars representing the standard deviation were placed on the graph. Afterwards, a flow rate for each of the straw diameters was found. Using the model with the 1 cm straw, the bottle was squeezed once. The water transported into the second bottle was measured and recorded. This procedure was repeated 4 more times, and then an average flow rate (mL/pump) was calculated for the 1 cm straw. The same process was completed for the 3 other diameters (0.8 cm, 0.6 cm, and 0.4 cm). This data was then compiled into a bar graph with error bars representing the standard deviation. A one-way ANOVA test with post-hoc testing was calculated. The f-ratio value and p-values were then added to the bar graph.

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