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Modeling Fluid Flow Dynamics and Blood Clotting Using Simplified Replicas of Mechanical Heart Valves

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ABSTRACT

About 2.5 percent of Americans have a form of valvular heart disease, with more than 200,000 of individuals having artificial heart valves. Prosthetic heart valves allow blood to flow through the heart in one direction while preventing backflow, thus becoming integral pieces for restoring cardiac function for patients with valvular diseases. Some complications with these heart valves are thrombosis and pannus formation, both of which block natural blood flow. This study aims to explore how different shapes, materials, and the addition of biomimetic features influence the overall performance and hemodynamic function of the valve. To achieve this, the St. Jude's valve, Medtronic-Hall disc valve, and Starr Edwards valve were reviewed with a variation of materials and presence of biomimetic features. They were crafted using a variety of household materials to recreate static model valves. To test the valves, a flow-controlled tubing system that mimicked physiological conditions was used and a vicious liquid tested for possible clotting areas. The results show that the St. Jude's valve had the highest flow value in comparison to the two other valves with biomimetic features playing no significance in the results. Lastly, areas of possible clotting were most seen around the St. Jude's valve although the Starr Edwards valve had the most buildup of agave syrup. Discovering the relationship between shape, design, and biomimetic features of mechanic heart valves and their impact on fluid flow and thrombogenicity provides valuable insight for future designs that can improve the quality of life for many individuals.

Introduction

With the improvement of modern medical technology and surgery, more than 200,000 heart valve replacements are performed annually around the globe. These medical procedures have increased the quality of 2.5 percent of patients' lives who have struggled from valvular heart disease for over 50 decades. However, prosthetic heart valves do not completely resolve complications and can often result in prosthetic valve disease (Pibarot & Dumesnil, 2009). Prosthetic valve disease is the complications that could happen due to problems within the valve such as blood clotting. One of the attributes that most affects patient outcome is hemodynamics. To allow blood to flow smoothly through the artificial valve, patients are required to take anti-clotting medication that decreases the risk of clotting while increasing the risk of bleeding. Therefore, a significant factor in making the ideal prosthetic valve is the ability to allow for efficient blood flow. It is thus necessary to identify the prosthetic heart valve designs that lower the risk of complication due to interrupted hemodynamic flow.

The main function of the artificial valve is to mimic the natural behavior of a healthy heart valve as well as to prevent clotting and maintain durability for as long as possible. However, current patients are required to adhere to lifestyle changes such as taking blood-thinning medication, routine checkups, and refraining from intense workouts (Frankel & Nguyen, 2001). These requirements also risk other illnesses such as increased bleeding if blood-thinning medication is not taken consistently. Nonetheless, mechanical heart valves are usually recommended for younger patients due to their durability and longevity compared to bioprosthetic valves. Nevertheless, these benefits are rendered futile if the design of mechanical heart valves is not improved to prevent complications and illnesses.

Many types of valves have been developed and implanted into patients which fall into two categories: bioprosthetic and mechanical. Bioprosthetic valves come from living tissue that is less durable while mechanical valves are made out of metal but also introduce a higher risk of blood coagulation (David, n.d.). Blood clotting within the valve is the most common issue due to uneven blood flow where blood is blocked and becomes stagnant, which can lead to a stroke and other health failures (Murphy, 2021). Mechanical valves have three common types: the Starr Edwards valve, St. Jude's valve, and Medtronic-Hall tilting disc valve. The Starr Edwards valve consists of a ball in a cage that allows blood to push the ball to go through, then pushes the ball back to block backflow. This valve is not currently being implanted today due to high risk of blood clotting but was highly successful in comparison to the field when it first came out. The St. Jude's valve is the most common type of mechanical heart valve and has been used since 1977. It involves two semicircle leaflets that open and close to allow blood to flow one way. The Medtronic-Hall tilting disc valve was introduced at the same time as the St. Jude's valve, but it has been discontinued since September 2009. It similarly uses a leaflet to open and close making the blood flow one way; however, it utilizes a single circle leaflet that tilts to open and close. These three valves effectively allow blood through the valve without back flow while maintaining durability for at least 20 years; however, they still lack complete absence of thrombogenicity, the ability of a clot to form when in contact with material. The addition of biomimetic features into these mechanical valves may be an effective combination of bioprosthetic and mechanical heart valves that could reduce blockages in blood flow. This current study aims to explore how different designs and whether the addition of biomimetic features of mechanical heart valves would affect the fluid flow and the hemodynamics within the heart.

Methods

System Setup

All the valves were tested in a flow-controlled system that closely mimicked physiological conditions consisting of a water hose (3 cm diameter) and opaque tubing (3.5 cm ID, 1 ft length). These materials were used to replicate the size of a heart's aortic valve where the valves would be inserted and to see how well the valves allowed liquid to constantly flow through. At the end of the tubing was a bucket (28.5 cm ID) to contain the water.

Water Flow Rate Measurement

Without any valves inserted in the tubing, the hose was turned on at ~2 psi for 30 seconds. After 30 seconds, the hose was turned off and the amount of water in the bucket was measured with a ruler. Then individual valves were sewed in between two halves of the tubing. The method of measuring the flow rate was repeated on all three valve types ten times each for a total of thirty trials. Flow rate was calculated using the equation $Q = \frac{V}{t}$
where Q is the flow rate, V is the volume, and t is the amount of time.

Clotting Assessment

The valves were removed from the tubing, and agave (KIRKLAND) was poured on the valves to determine how many points of possible clotting can occur and where. Clotting was assessed through visual analysis and photographs were taken (Figure 1).

Design of Valve Types

Valve types were created using a hair tie (Bessrung, 3.81 mm diameter) to mimic the suture ring and copper aluminum wire (TecUnite, 0.15 cm diameter) and cardboard (0.5 cm thickness) to construct the frame and base of the valve, all of which are held together by super glue (LOCTITE) and/or masking tape (Scotch). The wires were bent into a circle with a diameter of 3 cm that was put into the crevice of the hair tie to hold the structure of the ring. Then a strip of cardboard was bent into the inner ring and the ends were connected with either super glue or masking tape to create a circular shape. All cardboard pieces were painted over with rubber cement (Elmer's) to prevent the cardboard from becoming wet and weakened.

St. Jude's Valve

The valve leaflets were made out of a circular cardboard piece that can fit inside the cardboard ring and then cut in half to create two identical semicircles. A wire was inserted through the cardboard and superglued together to hold the leaflets in place. The cardboard ring was punctured with two holes one cm apart with another set of holes directly parallel on the opposite side to attach the wires to the cardboard ring. The leaflets on the wires were placed with the flat edge facing upwards. The wires were then glued to the cardboard ring, and the cardboard ring was glued to the suture ring (Figure 2).

Medtronic-Hall Disc Valve

The leaflet of the valve was the same size as the inner diameter of the cardboard ring with a hole in the middle to fit a wire through. The middle wire was made out of two wires that are glued together and bent on one side with a bump that is created from aluminum foil (Reynolds Wrap) and masking tape to allow the leaflet to open at 90 degrees in place. The leaflet is fed through the wire through the straight side. The cardboard ring was punctured with two holes across from each other to attach the wire to the cardboard ring. The wire was then glued to the cardboard ring which was glued to the suture ring (Figure 2).

Starr Edwards Valve

The ball for the valve was made out of aluminum foil that was shaped with a hammer to make a sphere with a 2 cm diameter. The cage to hold the ball was made out of two identical pairs of wires that were connected together with glue and then bent. The cage wire arcs were then put together perpendicularly and glued at the top. The ends of the wire arcs were inserted into the cardboard ring with the ball inside the wire cage. The cardboard ring with the cage and ball was then glued to the suture ring (Figure 2).

Additional Experiment

The St. Jude's valve and the Medtronic-Hall valve were identically created with the leaflet component replaced with sandpaper (HSMYQ, 1500 grit) to test the effectiveness of biomimetic features. The valves with the substituted parts were then tested again using the same method for the same number of trials.

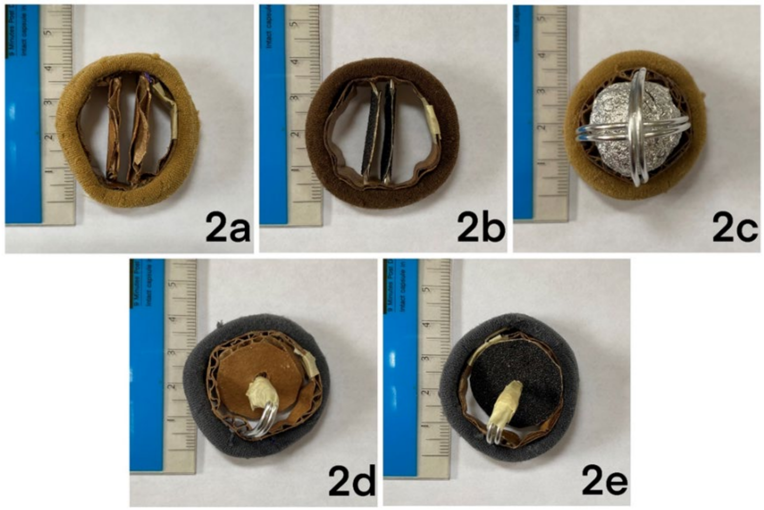

Figure 2. Types of mechanical heart valves that were tested. St. Jude's (2a), St. Jude's replaced with sandpaper (2b), Starr Edwards (2c), Medtronic-Hall (2d), Medtronic-Hall replaced with sandpaper (2e).

Results

Flow Rate Experiment

Results from the flow rate experiment are listed in Table 1 and Figure 3. The average flow rate of the control group was 9186.34 cm^3/min ± 268.24, the St. Jude's valve had an average flow rate of 6889.74 cm^3/min ± 1109.94, the Medtronic-Hall tilting disc valve had an average flow rate of 6124.22 cm^3/min ± 701.84, and the Starr Edwards valve had an average flow rate of 6506.98 cm^3/min ± 612.31. In the second experiment where the addition of biomimetic features was tested using sandpaper, the St. Jude's valve had an average flow rate of 7017.34 cm^3/min ± 804.19 and the Medtronic-Hall tilting disc valve had an average flow rate of 5741.46 cm^3/min ± 382.96.

Table 1. Data set from the flow rate experiment.

Valve type	Mean Water Height (cm)	Standard Deviation of Water Height (cm)	Flow Rate (cm^3/min)
Control (none)	7.2	0.21	9186.34
St. Jude's	5.4	0.87	6889.74
St. Jude's (sandpaper)	5.5	0.63	7017.34
Medtronic-Hall	4.8	0.55	6124.22
Medtronic-Hall (sandpaper)	4.5	0.32	5741.46
Starr Edwards	5.1	0.48	6506.98

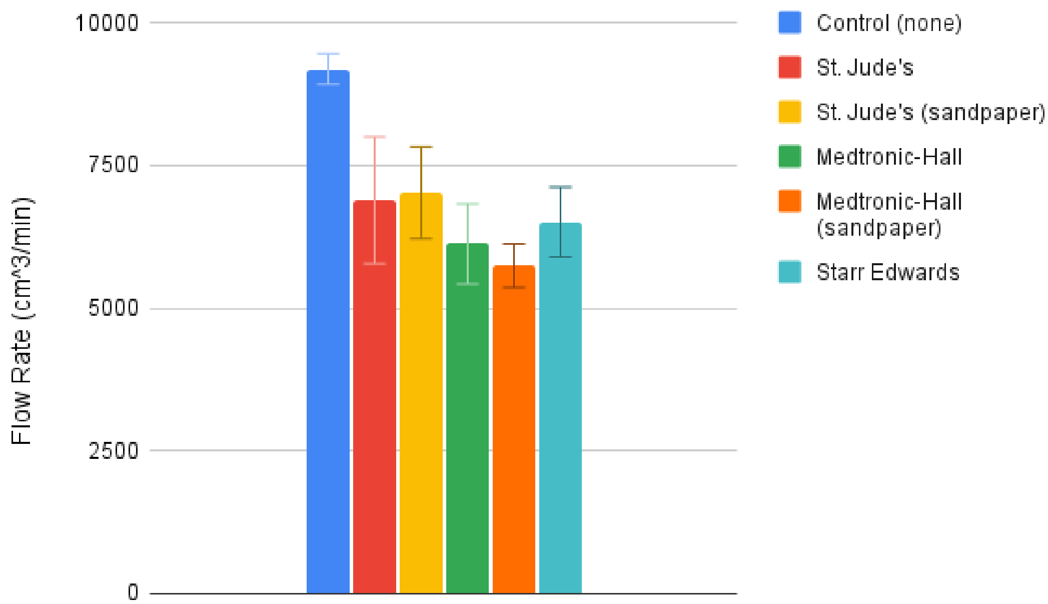

Figure 3. Comparison between the flow rates of the different valves. Standard deviation is shown using error bars.

Points of Possible Clotting Experiment

Pictures from the clotting experiment are shown in Figure 1. The St. Jude's valves have four points of possible clotting around where the leaflets attach to the frame. Likewise, the Medtronic-Hall tilting disc valves have two points of clotting where the central frame connects to the ring frame and an additional point of clotting around the curve of the central frame. In the Starr Edwards valve, the agave syrup appears most often around the tip of the cage and in between the ball and the cage.

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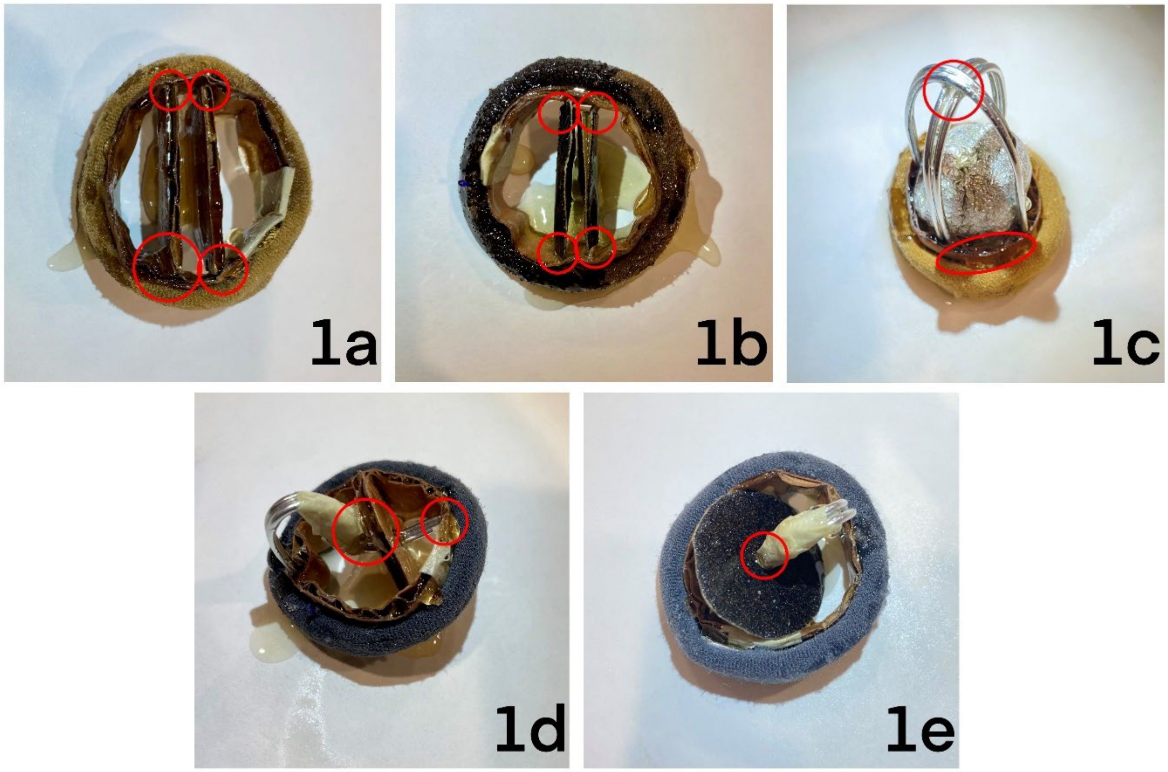

Figure 1. Valves after being poured with agave syrup. St. Jude's (1a). St. Jude's replaced with sandpaper (1b), Starr Edwards (1c), Medtronic-Hall (1d), and Medtronic-Hall replaced with sandpaper (1e). Points of possible clotting are circled red.

Discussion

Flow Rate Experiment

This experiment examined the flow rate of the three valves, with the St. Jude's valve having the closest average flow rate most similar to the control and the Medtronic-Hall valve having the least similar. The control represents a perfect circulatory system where blood flow is not obstructed; thus, the St. Jude's valve is the most efficient in maintaining consistent blood flow and preventing the least amount of clotting. This is due to its design having the least amount of blockage in the middle of the valve. The St. Jude's valve is the most common mechanical heart valve currently being implanted today, which is consistent with the results of the St. Jude's valve being the most efficient out of the three valves. The Medtronic-Hall valve was developed later than the Starr Edwards valve and it contains less obstruction to blood flow so the result that the Starr Edwards valve scored better is uncommon in respect to past patients' performance. However, the Medtronic-Hall valve had fewer points of possible clotting which also plays a role in fluid flow. Although the Medtronic-Hall valve has a worse fluid flow than the Starr Edwards valve, the experiment was tested using water instead of a liquid with a consistency similar to blood, such as an aqueous-glycerol solution, which could have affected the results. The water pressure and tubing could have also played a factor in the results since they are only models and not actual aortas. By understanding how various design choices affect blood flow and thrombogenicity, mechanical heart valves can be developed and better suited to address these health problems and reduce the risk of illness from these valves.

Addition of Biomimetic Features

The second experiment addressed how the addition of biomimetic features affects the fluid flow; however, the data showed that biomimetic features did not play a part in affecting the efficiency of the valve. The St. Jude's valve with sandpaper did better than the one without, but the Medtronic-Hall valve without sandpaper to replicate biomimetic features performed better. The data did not support my hypothesis that the addition of biomimetic features improves the hemodynamic performance of the valves, rendering the addition of biomimetic features ineffective. Mechanical heart valves do not have any biomimetic features and mainly include smooth metals and plastic, which is why the addition of those features had little difference compared to the alternative. However, further research would need to be done since the valves with and without sandpaper were not perfect duplicates. This data allows current research to continue to use the same or similar materials in its valve without the need for adding biomimetic features.

Points of Possible Clotting

The third experiment observed where possible points of clotting can occur by determining where the flow was uneven. The places that held bits of agave syrup represented areas where blood could also be trapped. Agave syrup has higher viscosity compared to blood, 212 cP and 4.5 cP respectively, thus facilitating the visualization of clotting points. By having more areas of agave syrup, the more areas blood can clot and therefore have an increased likeliness of blood clot formation. Although the St. Jude's valve had the most areas of possible clotting, more agave syrup was within the Starr Edwards valve. More agave buildup correlates to more blood buildup, which can be more critical than areas of possible clotting due to the buildup blocking more blood and therefore increasing its size. More areas of clotting does not necessarily imply an increased likelihood of clotting, as seen with the St. Jude's valve's efficient fluid flow. However, this may not be accurate by how water is used instead of blood which can clot unlike water. Because clotting and areas of clotting correspond to uneven flow due to blockages, it also affects the flow rate and fluid flow of the valves. Understanding these principles can direct future research to focus on minimizing areas where uneven blood flow can occur, and thus lessen the likelihood of blood clot formation.

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