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COMPARATIVE STUDY BETWEEN EXPERIMENTAL AND COMPUTATIONAL SIMULATION ON HEART VALVE LEAFLET AND BLOOD FLOW CHARACTERISTICS ANALYSIS: A REVIEW

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ABSTRACT

The heart is the blood pumping unit for all mammals which involves transporting the blood throughout the whole body at a certain pressure, velocity, and frequency. This paper focuses on the review of the experimental and computational simulation study on the heart valve and fluid flow characteristics concerning the method, similarities, and limitations on the parameters involved such as heart structure design, fluid properties, and effect of heart valves. There are a few methods to study the working principle of the heart and valves. Many researchers are more familiar with the numerical method than the experimental method. However, experimental modeling of heart structure will give a better understanding and visualize of the heart muscle, valve movement, and fluid flow pattern in the heart chamber.

Keywords: biomechanics, heart experimental model, heart numerical model, valve leaflet, fluid flow.

INTRODUCTION

The heart is a myogenic muscular organ that regulates blood supply to all of the body's blood vessels. To maintain a unidirectional blood supply during the cardiac cycle, the majority of mammal hearts have four heart valves. Heart valves are passive tissues that open and close in response to blood pressure differences around the valves. Heart damage will result from the inability of the heart valve to function properly. Stenosis and incompetence are the two types of heart valve disease. Stenosis occurs when the heart valve fails to completely open due to stiffened valve tissue, while incompetence occurs when the heart valve fails to function well and induces backflow of blood into the heart [1-5].

The fluid velocity, flow rate, friction, continuity, and physical properties of the cavity would all have an effect on the fluid flow system in a cavity. The fluid flow pattern in the heart chamber is similarly affected. The properties of the blood and the composition of the heart would have a significant effect on the fluid flow pattern. The properties of the blood and the composition of the heart would have a strong effect on the fluid flow pattern. Based on the Reynolds number, fluid flow patterns can be classified into three types: laminar flow, transitional flow, and turbulent flow. During contraction, blood circulating through the human heart and lungs has high pressure and velocity, so the Reynolds number is relatively high and can be described as turbulent flow. However, since this flow pattern is difficult to handle and monitor, these fluid flow properties are normally neglected in the modeling experiment.

EXPERIMENTAL AND NUMERICAL SETUP

The fluid Flows Pattern and Behavior of Leaflet with Different Leaflet Thickness

The two-dimensional fluidstructurewas studied intensively in [6] which focuses on the aortic valve. Using numerical and simulation experiments, this paper included a fluid flow analysis after the aortic valve during diastole. Through applying rhythmic fluid flow to the structure, this simulation experiment investigated the relationship of the aortic valve with fluid flow. The leaflet thickness was manipulated in the simulation experiment by the researcher. In the experiment, the finite element approach was also used for fluid and structural computing. The researcher's goal in performing the theoretical analysis is to verify the simulation outcome of the fluid flow system with the experimental model shown in Figure-1. The researcher used two dimensionless parameters in the numerical analysis, which are Reynolds numbers about 800.

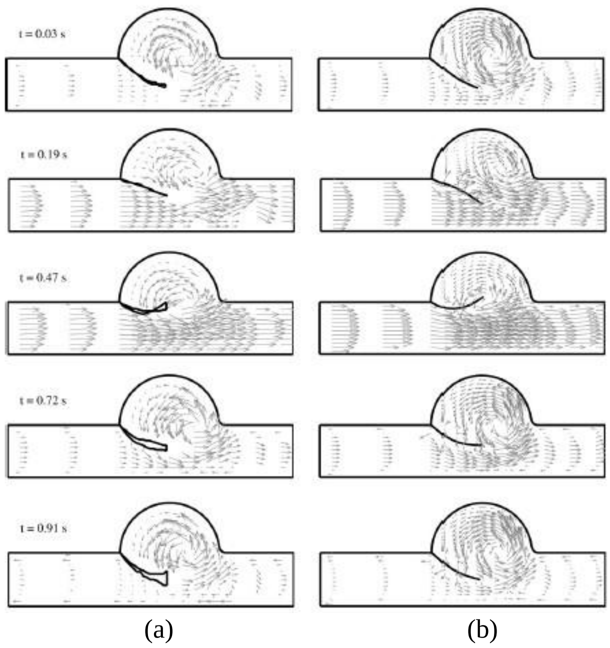

Figure-1. Comparison of experimental (a) and numerical (b) fluid flow vectors after the valve for leaflet thickness 0.16mm [6].

Experimental and Numerical Analysis of Blood Flow in the Left Ventricle

The research conducted in [7] used a mixture of computational and experimental methods to study the fluid dynamics structure. The dynamic ventricle wall, which is operated by a computerized piston system, drives blood movement within the cavity in the experiment model. The research would not have heart valves in the experiment. Backflow was prevented by installing two check valves at the mitral and aortic tubes. The results of the experiment revealed that computational and experimental modeling of vortex formation was identical. In comparison to the modeling experiment, the numerical analysis of vortex ring forming in Figure-2 generated a clearer finding. Both findings conclude that fluid flow in the heart chamber becomes more complex during the diastolic process.

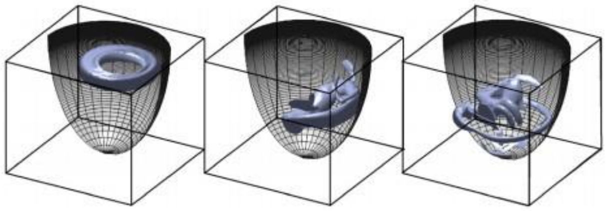

Figure-2. 3-dimensional vortex ring formation is shown in simulation [7].

Continuous Blood Flows through the Mitral Valve Model

The article [8] reflects on the comparison of numerical and experimental fluid flow structures. The authors used a digital camera to monitor the flow of a steady fluid flow through an open structure through the mitral valve. This differs from the real fluid flow in the human heart valve because blood flow in the heart is carried out in a close system with the pulsating flow. On the other hand, a computational analysis using fluid-structure interaction (FSI) on the same heart architecture had also been performed. The simulation outcome successfully demonstrated that the flows from both experiments are identical, as seen in Figure-3. However, the researcher used two parameters in the fluid-structure interaction (FSI) simulation, which are blood density and viscosity, but the parameters used in the flow model are unclear.

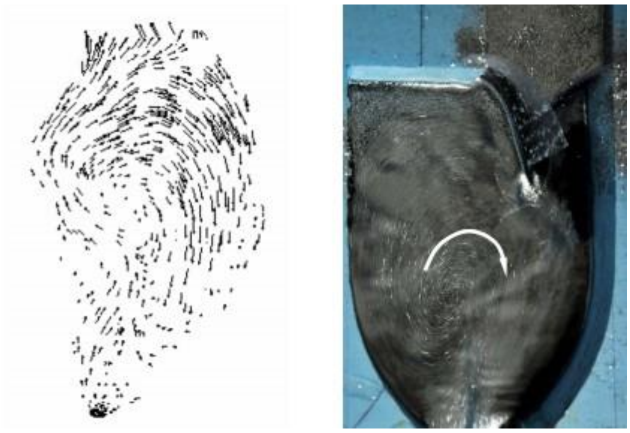

Figure-3. Comparison of MRI scan and modeling results on vortex formation in the left ventricle [8].

Left Ventricular Deformation and Recovery Detection using MRI

This paper differs from the previous experiments mentioned. The researcher [9] used magnetic resonance imaging to study the activity of the human heart contraction (MRI). The researcher made two hypotheses at the start of the study: the incompressibility of the myocardium muscle and that every point on the left ventricular wall would only travel in the normal direction to the original point. Since the MRI cine does not provide enough detail to correctly approximate all requirements during the cardiac cycle, the first and second assumptions are made. The researcher separated the heart into a few parts and used a pseudo-thin plate to interpolate the nodes on the segment to study the three-dimensional contraction of the heart muscle. These nodes serve as a point of reference for the motion of the ventricle wall. As shown in Figure-4, all node motions are depicted as vectors. To confirm the study results, the researchers performed the same study on a heart attack patient, and the MRI scanning was repeated on the same subject four months later, and the results of the ventricle wall deformation were well decided upon.

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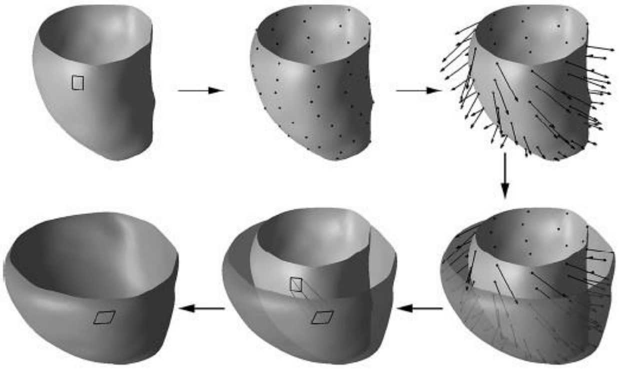


Figure-4. The left ventricle's node sample, vector, and deformation [9].

Cardiac Movement Detection using Echocardiogram (ECG)

From [10] focuses on the study about heart disease detection by using an echocardiogram. Heart dysfunction is divided into two categories: structural defects and motion abnormalities. The echocardiogram can diagnose all forms of illness. In this article, the researcher used scale-invariant features on the edge filtered motion magnitude mapping system to perform automated disease detection. The videos of echocardiograms are the basis of this process. The interesting point on the feature will be chosen from the edge-filtered features, and motion will be observed in two dimensions, as seen in Figure-5.

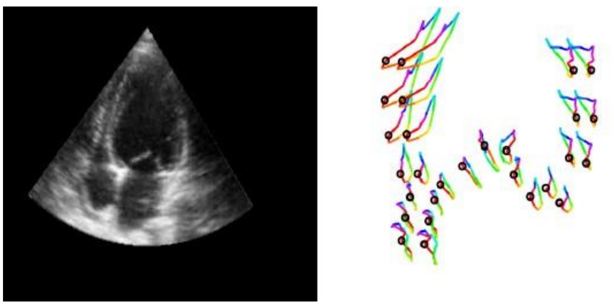
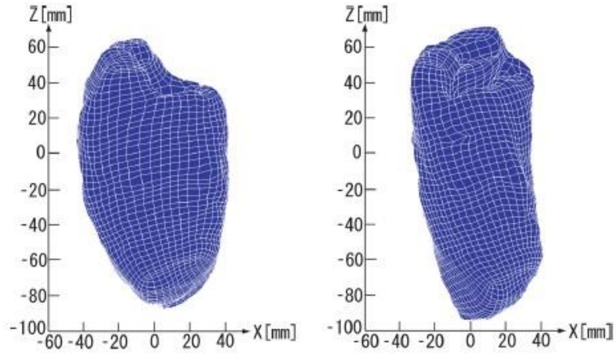


Figure-5. An echocardiogram of a healthy individual and the velocity movement profile of the left ventricle [10].

Simulation of cardiac motion using Finite Element Method (FEM)

The finite element method (FEM) was used in [11] to conduct a simulation of left ventricular movement. To obtain a similar shape as the human left ventricular shape, the author had used a set of MRI to extract a two-dimensional feature. To perform a three-dimensional simulation on the left ventricle, they applied a three-dimensional smoothing filter to generate three-dimensional image data. In this paper, they considered many components to obtain a result close to the actual heart movement such as the cell orientation in the ventricle and material properties of left ventricular tissue are some of the examples. The findings revealed that the contracting force varies depending on cell orientation. Figure-6 depicts the shape of the left ventricle deformation model using FEM software at the end of diastole and systole.



(a) (b)

Figure-6. Left ventricle (a) end-diastole; (b) end-systole deformation of simple cell orientation [11].

Coupling Simulation Method on Left Ventricular using FEM Solver and Circulation Simulator

The aim of this paper [12] is to forecast high-accuracy simulation results from a left ventricle sample. The author combined the simulations from the mechanical model and the circulation model to achieve a high precision outcome in terms of volume, strain, and contraction force over time. In this experiment, the coupling process will be the convergence calculation. Figure-7 depicts the basic principle of this coupling process. The experiment employs two primary equations, which are as follows:

a) $$\frac{dV_{lv}}{dt} = \frac{P_{lv} - P_a}{R_{lv\_a}}$$

b) $$C(P_a - P_{a0}) + (V_{lv} - V_{lv0}) + \frac{P_a}{R}.dt = 0$$

V_{lv} = Left ventricle volume
P_{lv} = Left ventricle inner pressure
P_a = Arterial blood pressure
R_{lv_a} = Resistance between left ventricle and aorta
P_{a0} = Left ventricle inner pressure before time *dt*
V_{lv0} =Left ventricle volume before time *dt*
R = Resistance vessel
C = Compliance

To obtain the coefficients needed in the measurement model, the FEM solver and circulation simulator (windkessel model) are used. The author had already specified the boundary condition for equations (a) and (b) during isovolumic contraction, ejection, isovolumic relaxation, and filling processes to solve the equation above.

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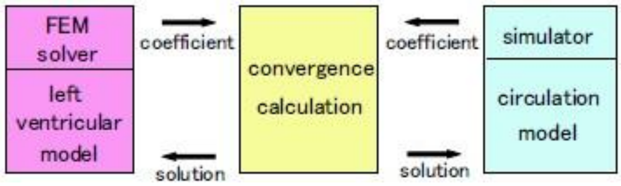

Figure-7. Simple system configuration [12].

Heart Cavity Profile Movement Study using Extract Image from Echocardiogram (ECG)

The reviewer of [13] concentrated on a stable cardiac cycle extracted ECG at the left ventricle. Several activities are included in the technique, including the processing of echocardiogram images, the computation of the optical flow area, and the retrieval of the activity profile. The optical flow field is calculated based on the image amplitude, which is the same approach used to interpret echocardiogram images. After determining the image amplitude, the author divides the left ventricular images into a few parts for better study. As seen in Figure-8, the effect is a displacement and path (angle) profile for various segments. By studying this result, we can enhance the development in the detection of heart abnormalities.

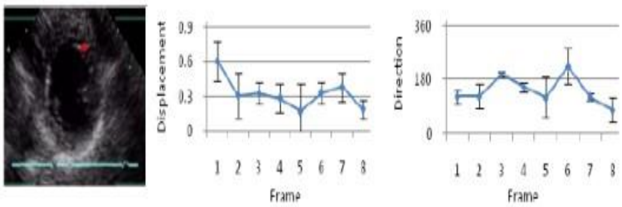

Figure-8. The section being evaluated in terms of displacement and position is represented by red marks in the echocardiogram images. [13]

Fluid Flow Formation in Left Ventricle using the Lagrangian Coherent Structure and MRI Velocity Mapping

Experimental research in [14] presents an analysis of 4D magnetic resonance velocity mapping and Lagrangian Coherent Structure (LCS) to measure vortex ring volume in the human left ventricle. The velocity in the heart during the cardiac cycle was measured using phase-contrast magnetic resonance. The velocity mapping result will then be coupled into LCS, and the fluid flow figure will be manually sketched by observers during diastole. The investigator conducted this experiment on a stable individual and a heart attack patient. As a consequence, the fluid flow structure during the cardiac cycle and vortex forming in the left ventricle during early fast loading during diastole can be observed. Figure-9 below shows one of the results from the normal healthy person and how does the LCS be implemented into this study.

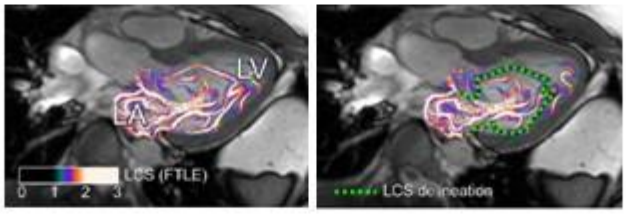

Figure-9. Vortex formation in the left ventricle for the normal person [14].

Mitral Valve Flow Prediction using CFD and Flow Loop Experiment

The author [15] used an experimental model and computational fluid dynamics (CFD) simulation to study the fluid flow velocity, flow rate, and pressure at the mitral valve during the cardiac cycle. However, the fluid flow patterns after the mitral valve are not being studied in this paper due to the limitation of the CFD and experiment modeling. The experiment was conducted in a closed system and the fluid in the experiment was circulated by pulsating flow pump. They used different shape orifices (round and rectangle) to study the pressure created at the mitral valve when the different flow rate was applied. The velocity and pressure readings from the measurement system at the orifices showed strong alignment with the CFD model as a result of this flow loop experiment, as seen in Figure-10. The CFD model's findings also revealed a velocity profile that was close to the spectral Doppler norm measure of peak trans-orifice velocity profile.

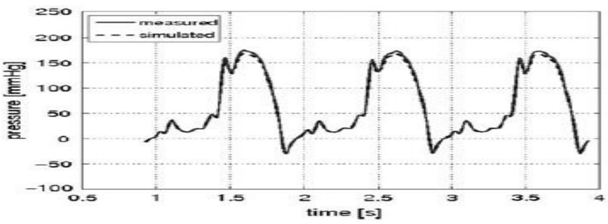

Figure-10. Agreement between simulated and measured pressure result for circular orifice [15].

Simulation of Blood Flow and Myocardium Muscle Motion of Left Ventricle

The movement of the left ventricle wall and the fluid motion were investigated in [16] which focuses on the left ventricle cavity during diastole. A commercial finite element software ADINA is used in the experiment. The author had constructed two different parts for doing the fluid-structure interaction simulation which are structural (myocardium) and fluid geometries as shown in Figure-11. To construct the solid model for myocardial muscle, they used six layers and each layer will have a different fiber orientation. Besides, the fluid used in this experiment will be considered as slightly compressible Newtonian fluid and the flow in the left ventricle is assumed as laminar flow. As the result of this simulation, we can obtain the pressure change and velocity profile on the fluid geometry.

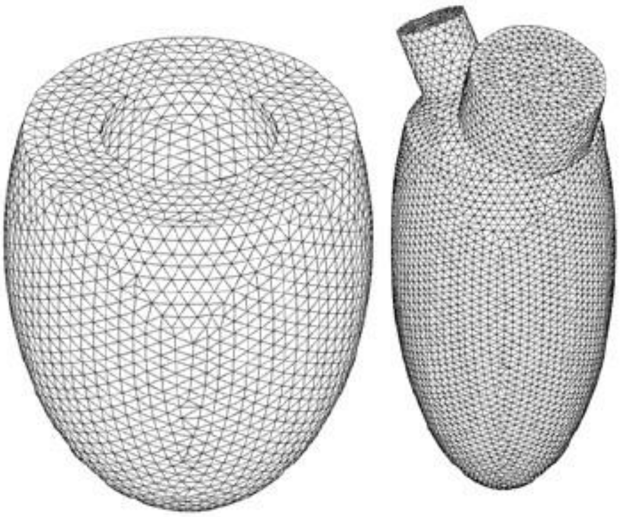

Figure-11. Meshes on ventricle wall and fluid geometries [16].

Direct Simulation of Blood Flows in the Left Ventricle

In [17], studied the intraventricular flow structure during the cardiac cycle using a numerical method. To get the actual anatomy of the left ventricle structure, the author had constructed the left ventricle from MRI. Besides, they also neglected the influence of myocardial muscle on the fluid flow structure. The endocardium (internal layer of the myocardium) was used as the structure profile for the left ventricle, implying that the left ventricle wall has just one layer. As a consequence of the simulation, we can see the creation of a vortex ring in the left ventricle, as well as the complexity of the fluid flow pattern at the end of the diastole, as seen in Figure-12. The author also provides several criteria in this article, such as end-systolic volume, end-diastolic volume, and stroke volume, which will be very useful in future research.

(a) (b) (c)

Figure-12. Vortex ring formation sequence (a) E wave; (b) end of diastasis; (c) end of diastole in left ventricle [17].

RESULT AND DISCUSSIONS

Heart research can be divided into three categories: research focusing on the structural deformation of the heart, research focusing on the fluid flow pattern in the heart cavity, and research focusing on valve deformation. However, the majority of the authors will conduct their analysis by investigating the relationship between the structural, fluid flow pattern, and valve. Figure-13 depicts the distributions of the priority problems.

Table-1. Summary of the interest issue studied from 12 journals.

	Type			Fluid Flow					Structure		Valve
Tittle	Modeling	Computational	Simulation	Fluid Flow Pattern in LV	Formation of Vortex	Laminar	Turbulent	Pulsate Flow	Structure Deformation of LV	Ability to follow heart anatomy	Valve Deformation
A Two Dimensional Fluid-Structure Interaction Model of The Aortic Valve	0	x	0	x	0	0	x	0	x	x	0
Combined Experimental and Numerical Analysis of The Flow Structure into The Left	0	x	0	0	0	0	x	0	0	0	x
Computer and Experimental Modelling of Blood Flow through the Mitral Valve of the	0	x	0	0	0	x	x	x	x	x	x
Left Ventricular Deformation Recovery From Cine MRI Using an Incompressible	x	0	x	x	x	x	x	x	0	0	x
Cardiac Disease Detection from Echocardiogram Using Edge Filtered Scale-Invariant Motion features	x	0	x	x	x	x	x	x	0	0	x
Model Generation Interface for Simulation of Left Ventricular Motion	x	x	0	x	x	x	x	x	0	0	x
Simulation Algorithm for the Coupling of the Left Ventricular Mechanical Model with Arbitrary Circulation	x	x	0	x	x	x	x	x	0	0	x
Cardio-Spatial Profile Extraction using Optical Flow of Echocardiographic Images	x	0	0	x	x	x	x	x	0	0	x
Vortex Ring Formation in the Left Ventricle of the Heart: Analysis by 4D Flow MRI and Lagrangian Coherent	x	0	x	0	0	x	x	0	0	0	x
A Three-Dimensional Computational Fluid Dynamics Model of Regurgitant Mitral Valve Flow: Validation Against In Vitro Standards and 3D Color Doppler Methods	0	x	0	0	x	0	x	0	x	x	x
Computation Of Blood Flow In The Left Ventricle with Fluid Structure Interaction	x	x	0	0	x	0	x	0	x	0	x
Direct Numerical Simulation of the Intra-Ventricular Flow Using Patient Specific	x	0	0	0	0	0	x	0	0	0	x
total	4	5	9	6	5	5	0	6	8	9	2
precentage (out of 12 journa	33.33333	41.666667	75	50	41.66666667	41.66666667	0	50	66.66666667	75	16.66666667

o- issue is covered in the experiment
x- issue is not covered in the experiment

Just 17 percent of the papers mentioned previously have examined the impact of valve influence on the flow in the heart chamber. Both tests of fluid flow in the heart must take the impact of the heart valve into account. The presence of heart valves can complicate the flow in the heart chamber because the valve leaflet becomes a disruption in the flow. Most authors, especially those conducting the numerical [3, 18-19] left ventricle analysis, had ignored these parameters. The cardiac cycle thesis is concerned with the fluid flow rhythm in the heart. Approximately 58 percent of the 12 publications examined had examined the flowing rhythm in the heart chamber. Almost all of the scientists examined the fluid flow in the left ventricle during the fast filling process, also known as the diastolic phase. The vortex ring will form in the left ventricle during this period. The study of myocardial muscle deformation is comparatively important since any contraction of the myocardium will affect the flow in the heart chamber. As a result, some of the authors simulated the fluid-structure analysis between the myocardium and the fluid flow pattern in the heart chamber.

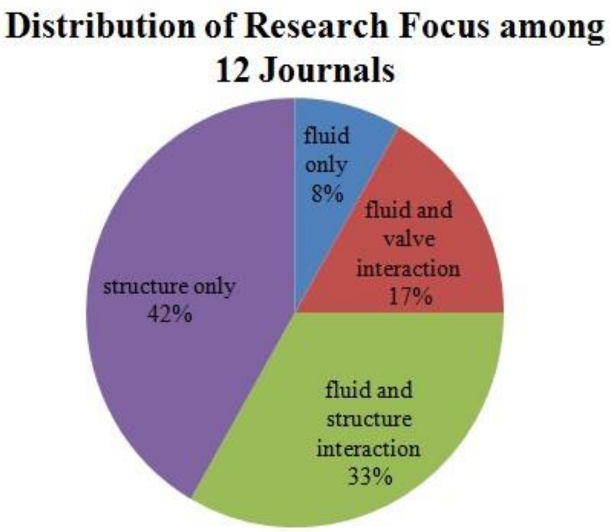

Figure-13. The distribution of research-focused issues among the 12 publications reviewed.

LIMITATION

Since the heart is a dynamic organ, doing some simulation procedure or creating a computational model that is identical to our heart is virtually impossible. We would deal with several heart parameters in this analysis, and some of the most significant parameters are still unknown today. Furthermore, all simulation software presented has drawbacks and accuracy. Since the simulation outcome may be correct or incorrect, the majority of studies performed modeling validation. The failure to build a device with pressurized pulsates flow is a common problem in modeling experiments. Since the heart has differing curvature and thickness in different areas, most simulation studies are unable to include the internal anatomy of the heart in their design. Furthermore, several criteria must be considered to provide a reliable outcome, such as blood viscosity, density, ventricle wall roughness, blood velocity, flow rate, muscle contraction signals, heart valve performance, and the dimensions of the aortic and mitral valves.

SIMILARITIES

The consideration of the rhythmic flow is also important to perform a result similar to the actual heart fluid flow pattern. But for the paper by [8], all of the articles that investigated fluid movement in the heart chamber used pulsate flow in their experiments or simulations. The flowing character, on the other hand, is a significant criterion for studying fluid flow in the heart chamber. Normally, blood runs in human arteries at elevated pressures (around 80 mm Hg to 120 mm Hg) [20], and the amplitude, hence the Reynolds number of the flow, would be comparatively high, indicating that the flow is turbulent. However, the whole paper that has analyzed fluid flow assumes laminar flow of blood into the left ventricle cavity. Furthermore, to acquire heart anatomy that is as similar to the actual heart structure as possible, most researchers derive the heart outline from an MRI or an echocardiogram. The motion profile, which will be represented in vector form, is the most common result obtained by the authors. This computational analysis is also widely used to predict heart disease.

CONCLUSIONS

In conclusion, cardiac structure and blood flow analysis is broad research areas. The majority of scholars who have analyzed fluid flow are only concerned with the fluid flow trend of laminar flow. Turbulent flow can also occur in the heart chamber as a result of the high pressure and volume of blood during rapid filling. The results of the heart analysis are important, but there would be certain drawbacks in the trial. The problem may be obtaining the human heart's real blood properties, internal surface roughness, dimension, and curvature profile.

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