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Computational Fluid Dynamics in Coronary and Intra-Cardiac Flow Simulation

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***Abstract*: Computational fluid dynamics (CFD) is a field of mechanical engineering for the analysis of fluid flows, heat transfer, and related phenomena, using computer simulations. CFD is a widely adopted methodology for solving complex problems in many areas of modern engineering. The merits of CFD are the development of new and improved equipment and system designs, and optimizations are performed on existing equipment through simulation, leading to increased efficiency and reduced costs.**

However, in the biomedical sector, CFD are still emerging. The main reason why CFD in the biomedical field lags behind is the enormous complexity in the workings of human body fluids. Recently, biomedical CFD research has become more accessible as high-performance hardware and software are readily available because of advances in computing. Every CFD process contains three main components that provide useful information, Pre-processing, formula resolution, and post-processing. Precise initial boundary conditions and geometric models are essential to obtain appropriate results. Medical imaging, like ultrasound imaging, computerized tomography, and resonance imaging can be used for modeling, and Doppler ultrasound, manometers, and non-invasive manometers are used for flow velocity and pressure as boundary conditions.

Many simulations and clinical outcomes are used to study congenital heart disease, coronary failure, ventricular function, aortic disease, arterial carotid, and intracranial cerebrovascular disease. With reduced hardware costs and faster computation times, researchers and healthcare professionals can use this reliable CFD tool to urge accurate results. A sensible and interdisciplinary approach is essential to performing these tasks. Open-ended collaboration between mechanical engineers and clinical and medical scientists is important. CFD is often an essential tool for understanding the pathophysiology of disease onset and progression, and for establishing and developing treatments within the cardiovascular field.

Keywords: Hydrodynamics; Viscosity; Cardiovascular diseases.

I. INTRODUCTION

The heart is fist-sized organ that pumps blood throughout the body. It's the first organ of the vascular system. The heart contains four main sections (chambers) fabricated from the muscle and powered by electrical impulses. The brain and nervous system direct the heart's function. The aorta is the main vessel through which oxygen-rich blood travels from the heart to the remainder of the body. It also delivers nutrients and hormones. These branches ensure that the nutrients reach the internal organs and the tissues.

The aorta is the primary source of oxygen and essential nutrients for several organs. An injury or disease can affect the blood flow and can increase many life-threatening diseases. These include aneurysm, internal bleeding, aortic dissection, renal disorder, stroke, attack, heart failure. Some conditions like congenital defects, genetic diseases and trauma, are difficult to forestall. But there are steps which can be taken to avoid other kinds of aortic diseases.

A. Coranary Artery Disease (CAD)

Coronary Artery Disease (CAD) is a heart disease, which is the major reason behind the death of round the world. This is often caused thanks to the narrowing of the aortic valve due to the build-up of plaque. This is often called atherosclerosis. CAD tends to develop when cholesterol builds up on the artery wall. If a chunk of plaque breaks off or rupture, platelets will cluster within the area in an attempt to repair in the blood vessel. This cluster can block the arteries and reduce or block blood flow, which might result in a coronary failure. An attack occurs when the heart muscle doesn't have enough blood or oxygen, when a clot develops from the plaque in one coronary arteries. This clot, if it's sufficiently large, can completely stop the availability of blood to the heart blood vessel. The explanation of coronary plaque relies not only on the formation and progression of atherosclerosis, but also on the vascular remodelling response. The local inflammatory response will simulate the formation of so-called vulnerable plaque, which is at risk of rupture with superimposed thrombus formation. Since the progression and development of vulnerable plaque is related to low wall shear stress and therefore the presence of expansive modeling, the measurement of those characteristics in vivo will enable risk stratification for the entire coronary circulation.

II. METHODOLOGY

The project started by compiling preliminary research data on the topic from journals and research papers. In the literature review, the author focused studies on patient-specific computational fluid dynamics flow simulation. Once an adequate understanding of the steps and software required to perform the project is acquired, a preliminary model is made using the Sim Vascular software. The model is generated from a CT scan image, a patient-specific model. The required parameters are specified here. Once this step is completed, the model is generated. Then, simulation is performed on the model.

After the simulation is performed, the results are analysed. The flow simulation results were studied and verified with the available data. Here, the results are discussed afterward.

III.DATA ACQUISITION

A. Importing Data

- The coronary artery can be imaged using intravascular ultrasound, MRI, CTCA, CT scan.
- The image is used to construct a 2-D and 3-D model of the organ.
- The image acquired is in VTI format.
- The image is opened using “SimVascular” software.
- SimVascular is open source software that gives a medical image data segmentation for patient-specific blood flow simulation and analysis.

B. Path Planning

- Creating an anatomic model supported medical image data requires construction geometry of the region using image segmentation.
- SimVascular uses approximate vessel centrelines called Paths to spot anatomical regions of interest within the image volume.
- These paths are later employed by the segmentation tools to construct a model of vascular anatomy.

C. Segmentation

- This is an operation used to identify objects or structures within an image in an automated way.
- 2D segmentation method has been incorporated in SimVascular.
- To create a 3D model from 3D imaging data, we generate a group of 2D segmentation along a given path.
- These 2D segmentations are often stitched together to create a 3D model.

D. Model Generation

- The solid model is employed as geometric representation of the volume of vascular anatomy.
- It’s created by joining together vessel surfaces fitted to a group of 2D segmentations.
- A solid model provides the data needed to generate a finite element volumetric mesh.
- The lofted surface created from groups of 2D segmentations is converted to a solid model.

E. Meshing

- The continuous volume enclosed by a solid model is divided into discrete tetrahedral elements using mesh generation software.
- A good mesh is integral to finite element simulation techniques.
- It enables a computer to numerically solve the governing equation and simulate the results.
- The mesh quality determines the accuracy, convergence and speed of the simulation process.
- Meshes are mainly of two types, they are

1) Surface Mesh

- A surface mesh uses 2D elements, which are typically triangles or quads to approximate the outer surface of a 3D body.
- Surface meshes are employed in manufacturing and rendering applications.

2) Volume Mesh.

- A volume mesh is also known as solid mesh, it uses 3D elements, typically tetrahedrons or hexahedrons, to define both the surface and interior surface.

F. Applying Boundary Conditions

- In this step, we will define the inlet and outlet parameters.
- The inlet condition is a steady velocity profile.
- We select the prescribed velocities and define the flow velocity.
- Based on the location of the geometry, different types of flow shapes are available in SimVascular.

G. Results

- After the simulation is performed, to view the results we need software named “Para View.”
- Para View is an open source, multi-platform and visualization application.
- This helps users to quickly build visualizations to investigate their data using qualitative and qualitative techniques.

IV. SIMULATION

After the model is generated we must assign the inlet and outlet conditions to the model. We specify the flow velocity, flow over a period time i.e., one cycle. We prescribe the flow as BC type with prescribed velocities where we prescribe the flow velocity and constant steady state at inlet.

For the outlet we select the BC type as “Resistance.” This represents that the impedance is caused by the down flow. The value can be determined clinically, can be based on the flow distribution, or can be studied from literature review. The wall properties are considered as rigid i.e., they do not deform.

We use Navier-Strokes equation to unravel the linear equations, the time-steps are determined accordingly and therefore simulation files are generated.

These files are created and viewed using Para View. It’s open source software, multiplatform and visualization application. This helps us to quickly visualize and analyse data using qualitative techniques.

V. RESULT AND DISCUSSION

We have performed a simulation and obtained results for pressure, direction of flow, velocity and pressure fields value at any particular location, surface displaced by the velocity vector, visualization of velocity globally, and also the visualization of fluid motion in the geometry. The results are shown below.

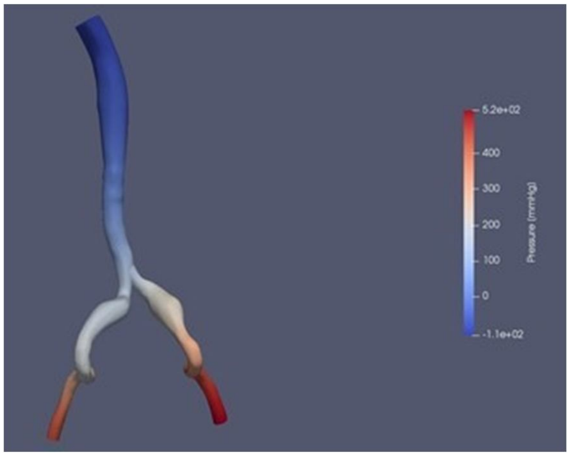

Figure 1 Pressure in mmHg

Figure 1 shows the values of pressure exerted by the fluid when it is flowing through the artery.

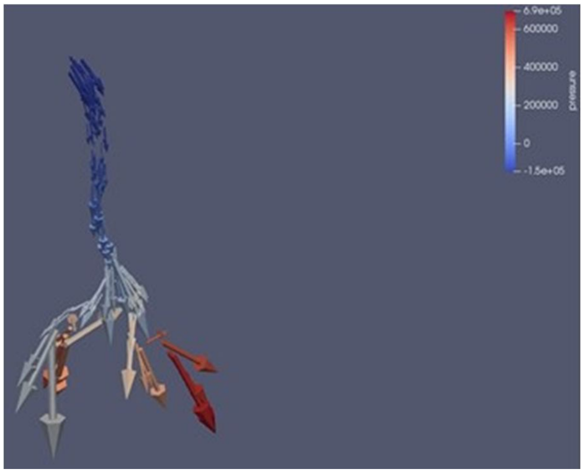

Figure 2 Glyph

Figure 2 shows glyph i.e., it represents the direction of flow of the fluid and also shows the values of the pressure exerted.

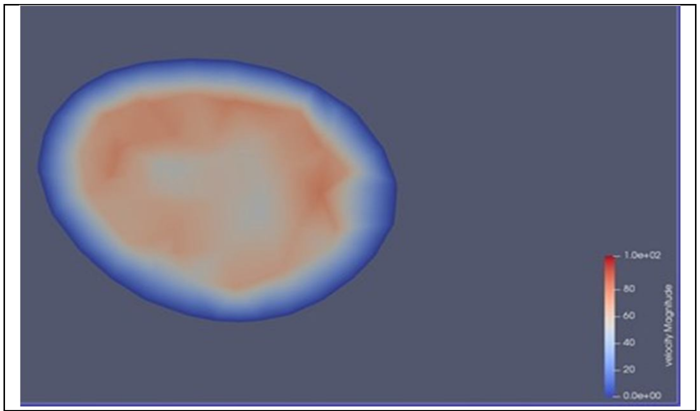

Figure 3 Slice

Figure 3 shows slice, i.e., it can slice the geometry at a particular location and study the velocity or pressure fields.

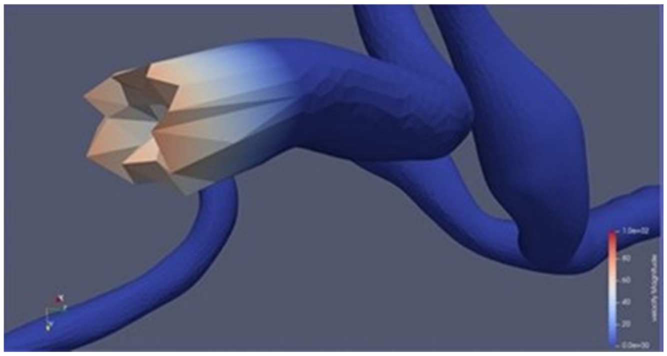

Figure 4 Wrap by vector

Figure 4 shows wrap by the vector i.e., how the surface displaced by the velocity vector when the fluid is flowing through the artery.

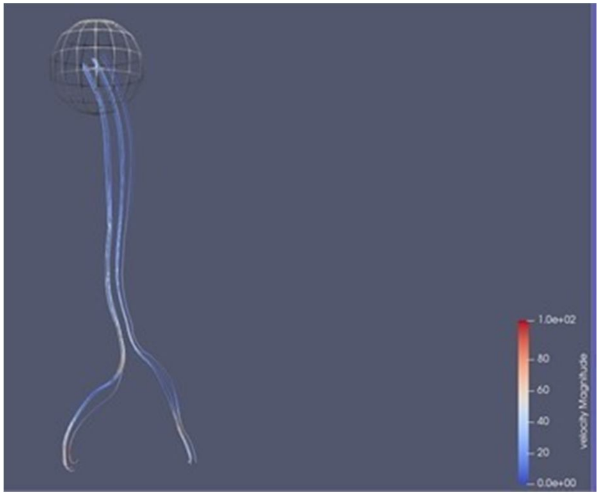

Figure 5 Streamline

Figure 5 shows the visualization of the fluid motion in the geometry.

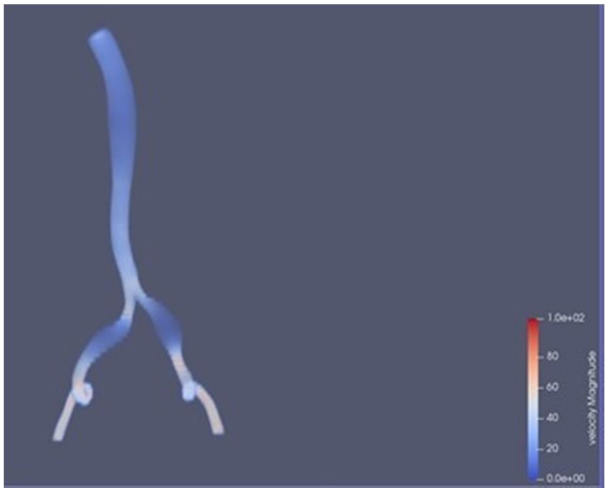

Figure 6 Resample to image

Figure 6 shows the visualization of flow globally.

VI. CONCLUSIONS

From the above simulation, we will see that we have created a patient-specific model of the aorta and have performed a flow simulation and gathered the values of pressure, velocity, flow direction, velocity or pressure fields at a specific location, the surface displaced by the velocity vector, velocity visualization globally, visualization of fluid motion within the geometry.

With the development in technology, we could model and develop a patient-specific model, with which we will be able to save many lives. This also helps reduce the cost of the surgery and improve the approaches used in the procedure.

The future scope of this work is to perform a simulation with plaques present in the arteries and help to remove the plaques using efficient methods.

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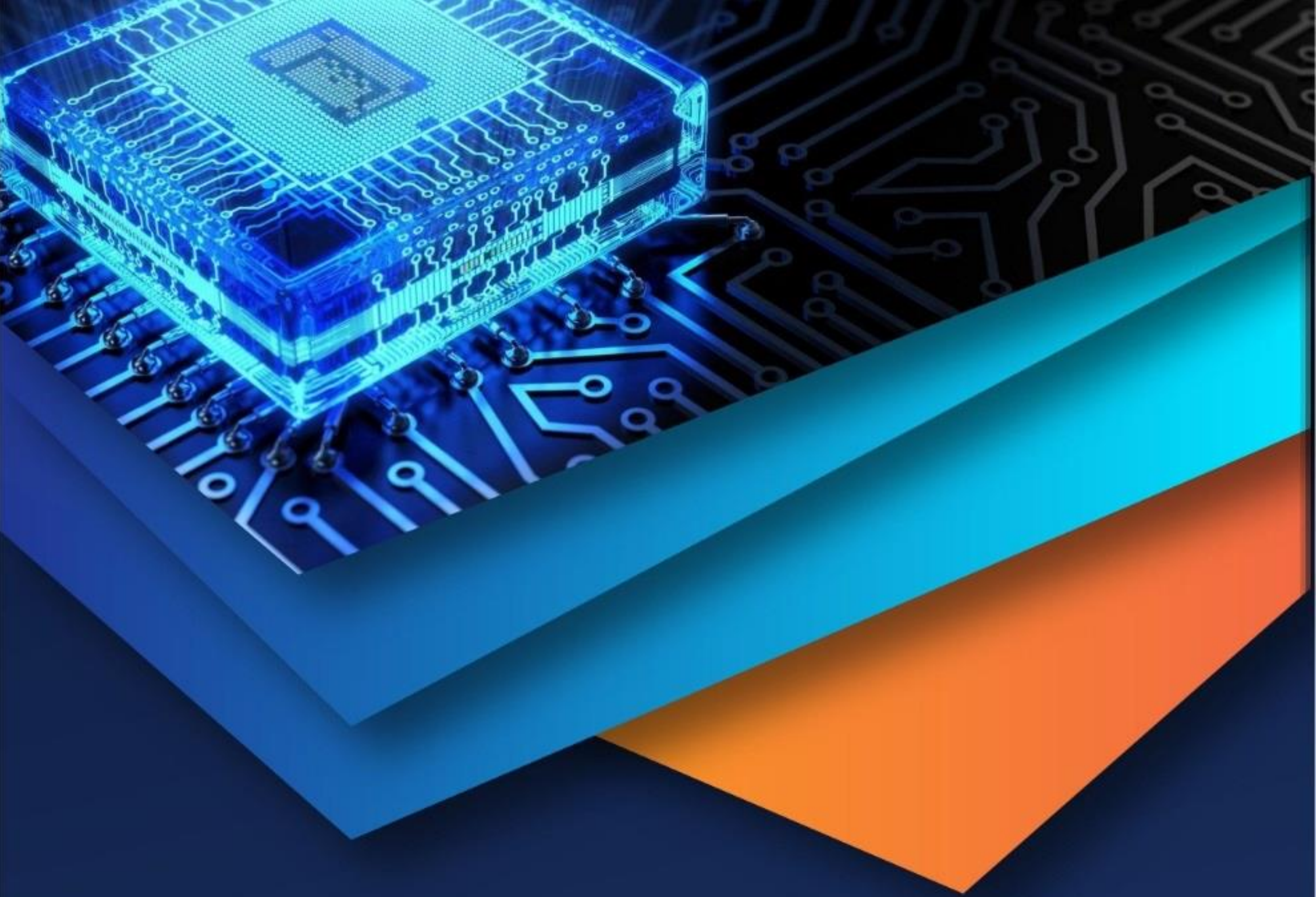

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