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By

Christian Marinaro & Ritik Verma

Word Count: 2872
Number of Figures and Tables: 8
Number of Equations: 0
Number of Supplements: 0
Number of Citations: 17

Approved Michael Shorofsky Date 05/06/2024

Computational Flow Dynamics Predicting Pulmonary Blood Flow for Pediatric Congenital Heart Disease

Christian F. Marinaro[a]. Ritik Verma[a], Dr. Michael J. Shorofsky[b], Dr. Haibo Dong[c], Jiacheng Guo[c]

[a] Department of Biomedical Engineering, University of Virginia, Charlottesville VA
[b] Department of Pediatric Cardiology, University of Virginia, Charlottesville VA
[c] Department of Aerospace Engineering, University of Virginia, Charlottesville VA
[1] Correspondence: Christian Marinaro: cfm3fcb@virginia.edu, Ritik Verma: rv9awx@virginia.edu

Abstract

Congenital heart defects (CHD) are a group of conditions that affect the functionality of a patient's heart beginning at birth, and it affects about 40,000 births in the United States each year. Two of the key tools cardiologists use to diagnose and assess the severity of these conditions are computed tomography (CT) scans, and nuclear lung perfusion (NLP) scans. CT scans give the 3-D structure of the heart with a series of X-ray images, and NLP scans give the percentage of blood flow to different sections of the lungs. This project aims to find an alternative to NLP scans by utilizing computational flow dynamics to predict blood flow to each part of the lungs using a CT scan. The goal was to convert the patients' CT scans into 3-D models, and run flow simulations on this model that produce the same output as a NLP scan. A pipeline to convert CT scans into models compatible with flow simulations was successfully created, and initial flow simulations were performed. The simulations were not able to run to 100% completion due to computational abnormalities discussed in the results, but the success of this project lies in the fact that it established a pipeline to go from CT data to a flow dynamics output, paving the way for future work.

Keywords: Computational Flow Dynamics (CFD), Congenital Heart Disease (CHD), Pediatric cardiology, Interventional cardiology, CT Scan, Nuclear lung perfusion scan

Introduction

Congenital Heart Disease

Congenital heart disease (CHD) is a genetic disease that refers to a range of structural abnormalities in the heart that are present at birth.[1] These defects can affect the heart's walls, valves, or blood vessels, disrupting its normal function. Pediatric congenital heart disease is a heterogeneous field with complex medical anatomy, surgical procedures and catheter based interventional care. Congenital heart disease affects 1% – or about 40,000 – births in the United States every year.[2] These patients hardly ever have the same treatment course and thus the surgeons, cardiologist, and interventional doctors must tailor their treatments and procedures to the individual patient. While some cases have a known genetic basis, others occur sporadically without a clear familial link. Maternal factors such as maternal age, certain medications, infections during pregnancy, and exposure to toxins or radiation may also increase the risk of CHD.[3]

The spectrum of CHD is broad, ranging from simple defects that may not require treatment to complex malformations that can be life-threatening without surgical intervention. Common types of CHD include atrial septal defects (ASDs), ventricular septal defects (VSDs), patent ductus arteriosus (PDA), Tetralogy of Fallot (TOF), transposition of the great arteries (TGA), and Pulmonary Artery Stenosis.[4] Symptoms vary depending on the type and severity of the defect but may include cyanosis (bluish discoloration of the skin), rapid breathing, poor feeding, failure to thrive, and recurrent respiratory infections.[5]

Early diagnosis and intervention are crucial in managing CHD. Treatment options range from medications to surgical procedures, including open-heart surgery and catheter-based interventions.[6] Advances in medical technology and surgical techniques have significantly improved outcomes for individuals with CHD, with many able to lead relatively normal lives with appropriate medical management.

However, CHD remains a significant cause of morbidity and mortality, particularly in low-resource settings where access to specialized care may be limited.[7] Long-term follow-up care is essential to monitor for complications, ensure optimal growth and development, and address any ongoing cardiac issues. Multidisciplinary

teams consisting of pediatric cardiologists, cardiac surgeons, nurses, and other healthcare professionals play a critical role in the comprehensive care of individuals with CHD, supporting them from infancy through adulthood.

Diagnosis and Treatment Plans

Currently, doctors rely heavily on subjective judgment when looking at CT angiogram scans and various other imaging techniques to determine further steps of care for patients, specifically when it comes to catheterization procedures.[8] CT scans, or computed tomography scans, use X-rays and computer processing to create detailed cross-sectional images of the body.[9] They are commonly used in medical diagnosis to visualize internal structures such as organs, tissues, and bones with high resolution.

Another important diagnostic tool for cardiologists is the nuclear lung perfusion scan. For this scan radioactive contrast is injected intravenously, and a gamma camera is used to take scans at multiple angles.[10] Doctors are able to see the percentage of blood perfusion to each part of the lungs based on this scan, and this is essential for diagnosing CHD conditions such as pulmonary artery stenosis where a pulmonary artery narrows very rapidly therefore causing a part of the lungs to not get enough blood.[11] This scan is often done before a catheterization procedure to understand diagnosis and what needs to be fixed, as well as a couple weeks after the procedure to determine if the problem was fixed successfully.

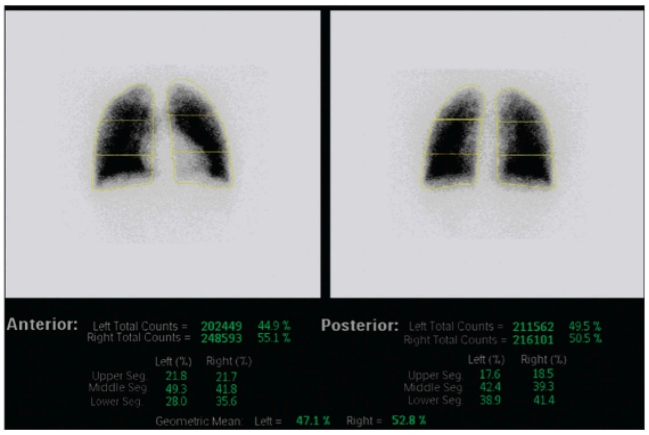

Fig. 1. The figure above shows an example of a nuclear lung perfusion scan with the number at the bottom illustrating percent blood flow to each labeled section of the lungs.

Cardiac catheterization is a diagnostic and therapeutic procedure used in the management of congenital heart disease. In this procedure, a thin, flexible tube (catheter) is inserted into a blood vessel, typically in the groin, and threaded up to the heart under X-ray guidance.[12] As shown in figure 2, It allows for the measurement of pressures and oxygen levels within the heart chambers and blood vessels, assessment of the severity of the CHD, and may also involve interventions such as balloon dilation of narrowed blood vessels or closure of abnormal communications, providing crucial information for treatment planning in individuals with CHD.[13]

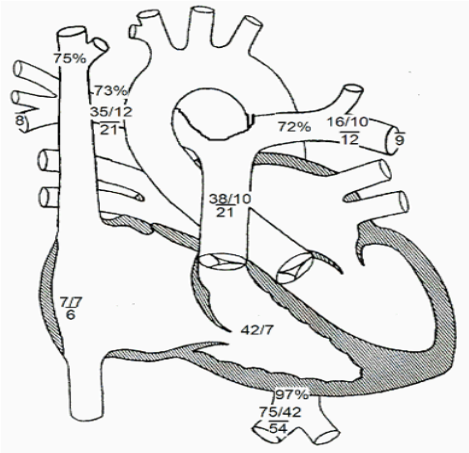

Fig. 2. Heart diagram for patient 1 from cardiac catheterization procedure illustrating pressures and blood flow in various locations.

Problem Being Addressed

The problem identified by Dr. Shorofsky with this current treatment process is that nuclear lung perfusion scans are tedious and expose patients to radiation. Cardiologists seek the ability to quickly determine pulmonary blood flow percentages before and after catheterization procedures without the use of these scans. Being able to quickly see flow characteristics without the use of the perfusion scan can greatly save patient cost and the need to redo catheterization procedures. Currently, there exists no clinical computational flow dynamics (CFD) method that can predict blood flow metrics from only a CT scan. This project aims to investigate an alternative to nuclear lung perfusion scans by creating a pipeline to develop flow simulation compatible models from a CT scan, and to run simulations that will output the percentage of blood flow leading to different sections of the lungs. More specifically, the project explored three major aims: 1) to segment CT angiograms into 3D models that can be used to test flow, 2) to develop a pipeline capable of performing CFD on CT angiogram data, and 3)

to compare CFD data to Nuclear Lung Perfusion scans to determine efficacy of the process.

Results

This project had the ultimate goal of investigating an alternative to nuclear lung perfusion scans by using flow simulations on patient CT models to predict the percentage of blood flow to different sections of the patients' lungs.

The product of aim 1 involved segmenting the patient CT scans into 3D models using the software Eclucis. The method for doing this is highlighted in the Materials and Methods section, but these 3D models of the pulmonary arteries and heart allowed us to continue onto aim 2.

The product of aim 2 was the pre-processing pipeline that turned the 3D models created in aim 1 into viable flow models. This process is highlighted in the Materials and Methods section, but the output of this large chunk of the project is what led us to aim 3 where flow simulations were run on each patient to visualize theoretical blood flow in the pulmonary arteries.

Aim 3 was not successfully completed in full as explained in the discussion, but flow was able to be visualized and examined through our analysis. The simulations run for each model were not able to reach a steady state equilibrium before crashing which led to no percentage blood flow from each artery outlet, but the analysis generated flow data visualized in the following figures.

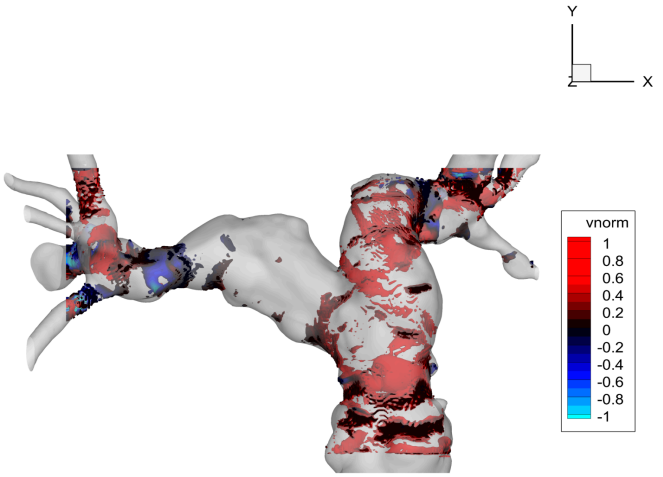

Fig. 3. Q-criterion (method of identifying vortices in 3D) isosurfaces colored by normalized vertical flow speed (vnorm=v/v_inlet) for patient 1.

First, Q-criterion behavior, which are areas where the vorticity magnitude is greater than the magnitude of the rate of strain (turbulent flow), was examined with respect to blood flow velocity as shown in figure 3.[14] Flow velocity is imperative to understanding how much blood flow is going to a certain location because flow speeds affect volume of blood delivery. Fast velocities in one area will lead to an unbalanced volume of flow in a certain location. Flow simulation results showed a far greater flow velocity in patient 1(right artery from figure perspective) as seen through the colorized results in figure 3. This led to an uneven volume of flow through the left branch, and had this simulation come to a steady state the results would have shown a large percentage of blood flow leading to every section in the left lung. In the case of patient 1, this is not surprising due to the patient having arterial stenosis (narrowing of the artery) in the right pulmonary branch, preventing as much blood from traveling there.[15] Other patients in the data set with similar diagnosis presented similar results.

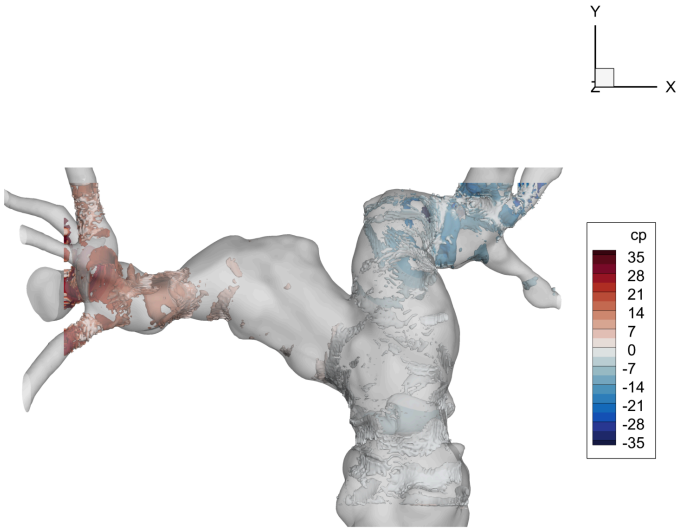

Fig. 4. Q-criterion isosurfaces colored by pressure for patient 1.

Second, pressure behavior was evaluated within the model as shown colorized in figure 4. This data checks out with what we would expect for patient 1 based on the diagnosis of arterial stenosis and flow velocities. There is a lower pressure seen in the left pulmonary branch and much higher pressure seen in the right branch as evident in figure 4. The area of higher pressure makes sense since that is where the narrowing of the patient artery occurs and this

would stifle flow entering that region. The velocity model also validates these observations due to higher flow velocities seen in the areas of lowest pressure, and lowest velocities seen in the areas of highest pressure. This is validated through Bernoulli's principle which states: an increase in the speed of a fluid occurs simultaneously with a decrease in pressure or a decrease in the fluid's potential energy.[16] This confirmed that our flow results did in fact represent what theoretically should happen in the body. Other patients with similar diagnosis exemplified the same behavior.

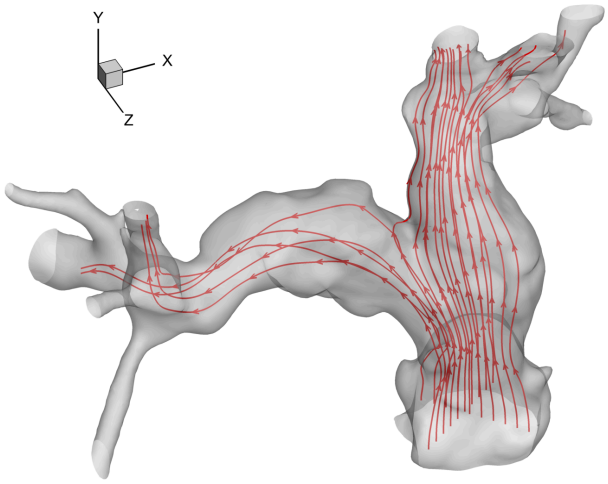

Fig. 5. Streamtraces of blood flow through pulmonary arteries for patient 1.

Lastly, we analyzed the streamtraces of blood flow through the pulmonary arteries, essentially being able to visualize the path that volumes of blood will take. These lines are tangential to the instantaneous velocity direction.[17] This visualization is just another way to show flow modeling capabilities, and it validates the data seen in the velocity and pressure figures. There is a large quantity of blood flow going towards the left pulmonary branch due to the stenosis occuring in the right pulmonary branch. As mentioned previously, this leads to lower pressures and higher velocities in the area of more volumetric flow.

Despite the flow simulations being unable to reach a steady state and complete 100%, thus not allowing an accurate generation of blood flow percentages to each part of the lungs, these results proved that a CT scan to flow data pipeline is possible. The flow characteristics produced proved to be logical given the physiological parameters and arterial geometries, and future work will iterate upon this to achieve higher accuracy outputs.

Discussion

Although we were unable to get an accurate percentage blood flow measurement to each part of the lungs, the success of our project lies in the fact that we created the pipeline to go from CT scan to flow data, and proved that it is possible to model flow from only CT scans.

Aims 1 and 2 were successfully accomplished in full. With aim 1, each patient CT scan was segmented into viable 3D models allowing manipulation to be performed to run flow simulations on them. Aim 2 was also accomplished with the development of the flow dynamics pipeline, with each step highlighted in the materials and methods section. This detailed pipeline will provide a base for future research to replicate and test on a larger patient set.

Despite using Dr. Dong's lab's proprietary CFD algorithm, aim 3 was not accomplished in full due to flow simulations on each patient not being able to reach a steady state outputting flow results from each pulmonary artery. The models for patient 1 and patient 4 reached the furthest time steps with the algorithm running to 98% completion. This was due to the favorable geometries of those patients' pulmonary arteries allowing pressure boundary conditions to stay close to a normal range. Our team theorizes the reason the simulations would fail was because of pressures being unusually high or low near the outlets of the model as shown in figure 4. Additionally, when running flow simulations, oftentimes blood flow would highly favor one pulmonary artery branch over the other. Many attempts were made to remedy this including attempting to model more turbulent flow to equally distribute flow across each artery, but this was unsuccessful. Given the time constraints and novel nature of the project, a robust solution was unable to be implemented to solve these issues, but this is where future work should pick up on. Future steps should attempt to create pressure boundary conditions built into the flow algorithm to keep flow pressures within a reasonable range. This theoretically could force the system to converge to a steady state and give accurate blood percentages out of each artery. Fixing the issue of modeling correct blood flow to each pulmonary artery branch is also imperative as that would significantly affect blood percentage predictions to each part of the lungs.

General limitations of the project included software licensing delays and the tedious manner of

performing pre-processing on the patient models. Firstly, segmenting the patient models was delayed due to the license for Elucis, the 3D segmentation software used to turn CT scans in models, being expired and therefore Dr. Shorofsky had to go through a month-long process for its renewal. Secondly, a downside to this method of flow dynamics is that in order to get each model prepared to be run in the algorithm, each step highlighted in the materials and methods section had to be done by hand. This included tasks like repairing the surface mesh on the models at a very small scale, re-cutting the model if it did not fit into the flow domain, and trying many iterations of parameters to create a flow mesh that worked. When added up over a group of patients, this process becomes tedious and unreasonable for a large future testing group.

As mentioned above, future work should build upon this created flow dynamics pipeline to achieve a percentage blood flow output to each part of the lungs. This work should aim to replicate the results of a nuclear lung perfusion scan to a degree of 2% error in order to be clinically viable. Within the clinic this type of software would have a drastic effect in the way catheterization procedures are performed. In an ideal scenario, a cardiologist would use this software to determine blood flows to each part of the lungs before a catheterization procedure to hone in their diagnosis. Then, after the procedure has occurred the cardiologist can run this software again with the imaging data from the catheterization procedure before closing the patient up to determine the procedure success. In the case of a common congenital defect such as pulmonary artery stenosis where the rapid narrowing of a pulmonary artery leads to a section of the lung lacking blood flow, being able to run this software after the procedure is extremely useful to the doctor as they can see if the problem has been repaired. Dr. Shorofsky mentioned that oftentimes after seeing the results of the nuclear lung perfusion scan post-catheterization procedure, the patient has to undergo another procedure to further fix the problem. If this could be measured before the patient is ever closed up during the first procedure, this software has the potential to drastically save patient cost and generate better clinical outcomes.

As mentioned in the limitations, the pre-processing steps for each model can be tedious. For testing on large patient sets, future work should focus on automating this pipeline. If the man hours of pre-processing each model is cut down drastically, algorithms and parameter refinement to closely match nuclear lung perfusion scans can occur at a much faster rate. Additionally, for this method of flow dynamics to be viable in the clinic, the pre-processing needs to occur in real time so it does not take long to get a flow output after a CT scan is taken.

Once these steps are taken, this system can follow the 510(k) de novo pathway for FDA approval and be marketed to hospitals and cardiologists. This system ultimately would serve cardiologists and patients to more seamlessly and effectively diagnose, treat, and monitor pediatric congenital heart disease.

Materials and Methods

This project required the implementation of a series of preprocessing steps to prepare the patient models for simulations. Anonymous patient data was provided by Dr. Shorofsky and the UVA Department of Pediatric Cardiology. Each step was refined and individualized for every patient model to complete the specific aims for this project. The steps taken for each patient model were 3-D segmentation of the CT scan, cutting and meshing the model, creating the flow domain, applying the flow domain mesh, and finally running the simulations.

Segmented and Preparation of Five Patient Models

Each patient model was created using the 3D segmentation software Elucis. This software allowed the models to be created in a virtual reality environment, by selecting the inner lumen of pulmonary arteries on each layer of a patient's CT scan, which would then convert the selected areas into a 3D mode, which can be seen below in figure 6.

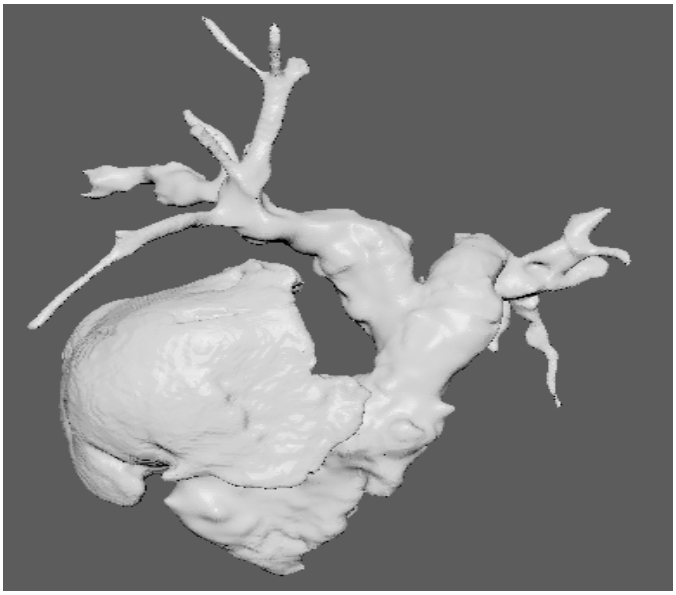

Fig. 6. The initial model after the segmentation of the CT scan provided for patient 1.

These models were then exported as STL files to be further processed using Autodesk Fusion 360. The first step for processing was repairing the surface mesh ensuring that there were no holes or imperfections in the model. The mesh allows the computer to visualize and quantify the surface in preparation for flow simulations. After this repair, the model was remeshed with a uniform mesh to be compatible with the simulation software. After the mesh was redone, a series of plane cuts were done to create flow inlets and outlets on the model, at the base of the pulmonary artery just above the pulmonary valve, and at branches of both the left and right pulmonary arteries before they reach the lungs, seen below in Figure 7**.**

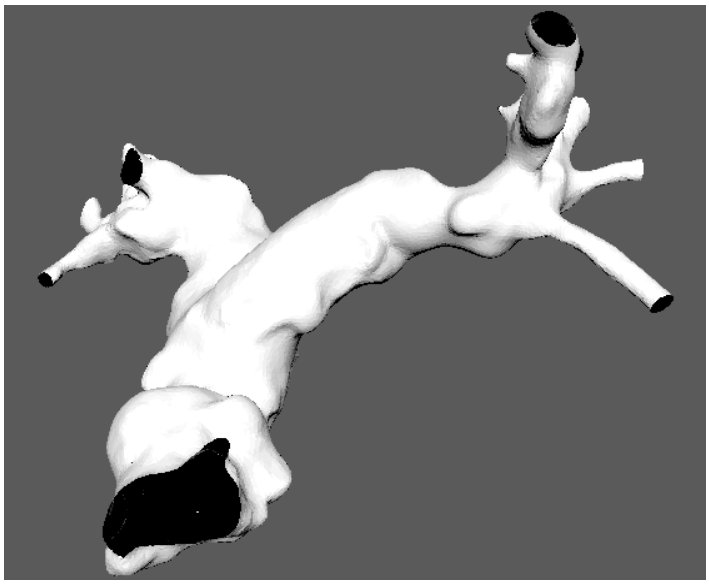

Fig. 7. Image of the first patient model after it has been remeshed and trimmed down using plane cuts.

Establishing the Flow Domain

After each model was meshed and trimmed down, the next step was defining the flow domain around each model. This is the area that defines the boundary conditions of the simulation. This required creating a box around each model in Fusion 360 with each inlet or outlet protruding completely from one side of the flow domain. This process required multiple iterations, cutting the model at different points on the inlet and outlets, as well as adjusting the model's orientation within Fusion 360, so that the simulation could run correctly. A model within its flow domain is depicted in figure 8.

Preprocessing the Model for Simulation

The models were imported to Autodesk Maya to generate the output files needed for preprocessing. A Maya script was used to create the obj and mtl files necessary. Both of these files were put into a program provided by Dr. Dong's lab called wingVertex_no_uv.exe, which outputs a specialized file called a dfly, containing the number and position of the vertices and planes of our model. The model was then moved and scaled so that the size of the inflow standardized using a program from the lab called preprocess_gui.exe. The output of this step is an unstruc _surface.dat file needed for simulations. Tecplot, a visualization and analysis tool for computational flow dynamics, was used to visualize the results. This process required multiple iterations to have the model correctly oriented and scaled for the simulations.

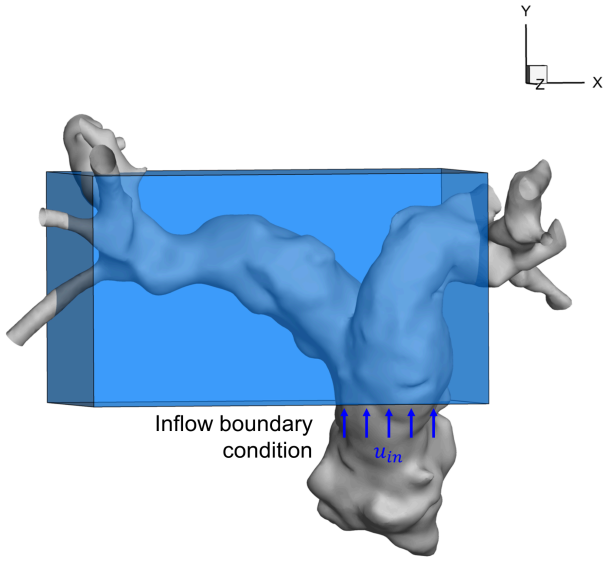

Fig. 8. Final patient model overlaid with the flow domain. The input condition is shown with blue arrows along with u_{in} the symbol for input velocity.

Running Flow Simulations

To run simulations, UVA's high power computing system, Rivanna, was needed. WinSCP, a file manager, was used to organize directories and transfer them from local directories to the high powered computing system. The Putty terminal was used to run programs provided by the lab. The first step was defining the flow mesh within the flow domain for each model within WinSCP using the Putty terminal. Multiple iterations had to be done with each model to get the dimensions of the mesh cells to the proper size and the correct area of the model, and each attempt was visualized using tecplot. The x y and z grid files for the flow cells were generated by running a program called a.out in the Putty terminal. Before running a.out, the inputs had to be adjusted to size the flow cells for each model in a file called input_mesh_ twolayers.dat.

To run the simulation, the outputs from the x y and z grid files were then put into a simulation folder in Rivanna along with the unstruc_surface_in.dat file, which was created for the patient during preprocessing. The file input.dat had to be adjusted to match the number of cells in the x y and z directions, and the number of faces and vertices from the unstruc_suface.dat file had to be put into a file called canonical_body_in.dat to define the surface for simulation. After these files were put in the simulation folder, the flow simulation program provided by Dr. Dong's lab, picar3d, was executed using the Putty terminal. This program outputs the flow data into an output file in WinSCP, and the results were interpreted using Tecplot. Examples of flow results are seen in figures 3, 4, and 5 in the results section.

End Matter

Author Contributions and Notes

Dr. Shorofsky and Dr. Dong designed research needs, Ritik Verma, Christian Marinaro, and Jiacheng Guo performed research, Dr. Dong's CFD software was used, Ritik Verma, Christian Marinaro, and Jiacheng Guo analyzed data; and Ritik Verma and Christian Marinaro wrote the paper.

The authors declare no conflict of interest.

Acknowledgments

We would like to thank Dr. Shorofsky for providing us with the patient data and layout of the project. We would also like to thank Dr. Dong and his lab for providing us with his computational resources and guidance. We would especially like to thank PhD student Jiacheng Guo for providing us with guidance throughout the entire computational side of the project.

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