COMPUTATIONAL MODELING OF POST-SURGICAL

HYPERTROPHIC HEART FOR

SURGICAL PLANNING

by

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ABSTRACT

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Hypertrophic cardiomyopathy (HCM) is a clinically prevalent disease in people around the world, with potential outcomes ranging from sudden cardiac arrest and/or heart failure to the normal life expectancy of the patients. HCM is a condition where the interventricular septal wall becomes abnormally larger, making it difficult for the heart to pump blood from the left ventricle. The current gold standard for the treatment of HCM is Cardiac Myectomy, in which the overgrown tissues are resected to correct the heart and restore the blood flow. Due to the complex anatomy of the heart and anatomical differences in the internal structures from one patient to another, myectomy comes with significant risks and needs very experienced surgeons in the field. Surgeons often have to improvise during the surgery due to unexpected conditions or structures in a patient's heart. The 3D models fabricated can be used in surgical planning. It has been shown that having a 3D

model decreases the time to perform a Myectomy and increases the chances of success. To further understand the anatomy of the Heart and blood flow pattern post-surgery, I used ScanIP software to create 3D models of how a hypertrophic heart might look after surgery. These models can be used to study blood flow patterns and establish an optimum amount of tissue in the interventricular septum needed to be removed during myectomy.

For the senior design project, my team created 3D models of a heart from CT scans of a patient and printed physical models of the heart to provide surgeons access to the internal structures for presurgical planning. The 3D model was generated using Simpleware ScanIP using automated and manual segmentation. The 3D models provided accurate physical models that surgeons planning the surgery can use. After the completion of 3D modeling, the study of blood flow patterns in the left ventricular outflow tract (LVOT) using ANSYS can help in understanding physical stress in the heart due to hypertrophy. Running simulations on the heart models after surgery can help access the correction of the heart and study the long-term effect. So, suppose we can have heart models which mimic the post-surgical heart. In that case, surgeons can have access to the simulation results, which can help them optimize the amount of tissue resection needed during myectomy.

The post-surgical model was developed in Simpleware ScanIP software. ScanIP is an FDA-approved software for use in clinical use. ScanIP allows both automated and manual segmentation for 3D modeling. Automated segmentation is not always helpful as the threshold values that represent surrounding tissues and heart tissues are not significantly different. Manual segmentation was used in the process to create the 3D

models. The 3D models were developed in halves to visualize the hypertrophic growth better.

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CHAPTER 1

INTRODUCTION

Hypertrophic cardiomyopathy (HCM) is a highly prevalent disease, with one in 500 people being impacted by it [1]. HCM is common heritable cardiomyopathy which is one of the major causes of heart failure, arrhythmic cardiac death, and arterial defibrillation [1, 2]. HCM is a condition with abnormal enlargement and thickening of the cardiac wall and is diagnosed when the wall thickness $\geq$ 15mm is seen in diagnostic images without any secondary cause [2, 3]. HCM obstructs the left ventricular outflow tract (LVOT), leading to life-threatening heart conditions. Because of its genetic nature, it affects all age groups. The diagnosis of the condition is difficult as it can be completely asymptomatic. Even asymptomatic young patients can have life-threatening effects from HCM in the long term. In most cases where medical treatment does not work, left ventricular cardiac myectomy is the procedure of choice. However, due to highly variable anatomy and complex physiology, cardiac myectomy is often a difficult procedure [4]. Figure 1.1 shows the anatomical difference in the normal and hypertrophic heart; the ventricular wall and septal wall thickening are visible in the hypertrophic heart. Such growth can vary from patient to patient, making each condition unique and making myectomy a high-risk surgery.

A readily available 3D model of a patient's heart can significantly help in surgically planning. The 3D model will have the same dimensions and anatomical structures as a patient's heart. Surgeons can have a physical model of the heart to work with during surgical planning. It has been found in similar research that with the help of a 3D model as

a tool during surgical planning, the time of surgery decreased by 20%, helped in sufficient resurrection of LVOT, reduced bleeding, and increased patient satisfaction as a surgeon could explain the procedure using 3D model [4].
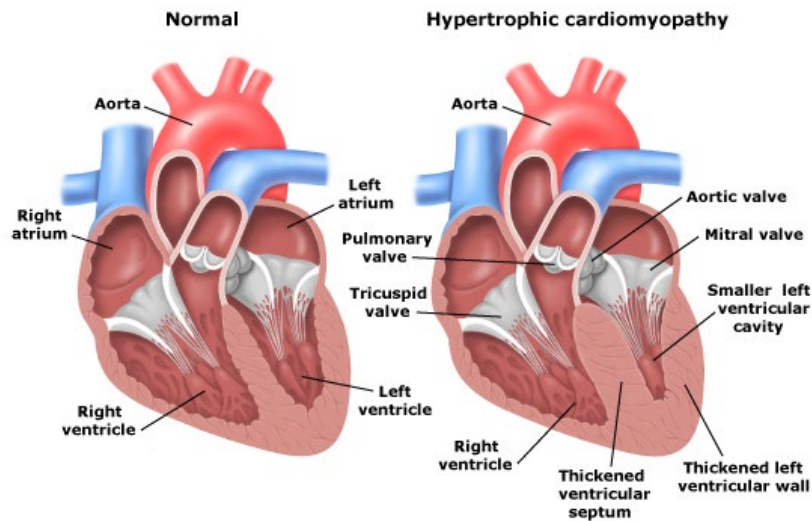
Figure 1.1: The illustrations show the anatomical differences between a normal heart and a hypertrophic heart. The thickening of the interventricular septal wall and ventricular wall can be seen in the hypertrophic heart.

In this study, I will further the computational modeling of the Hypertrophic heart by developing a model with corrected hypertrophy that mimics the post-surgery heart. Firstly, the procedure of myectomy was researched to understand the procedure. The 3D reconstruction of the heart was developed again to mimic the corrected heart. The hypertrophy/abnormally grown tissues were manually removed using ScanIP. The model helps understand how much tissues should be removed during cardiac myectomy. After the successful 3D reconstruction of the corrected heart, running computational fluids dynamic (CFD) simulation can help study whether the blood flow is restored. I also propose doing a blood flow analysis to see if the stress level in the heart has changed. This can help surgeons decide the amount of tissue needing removal during surgery. This will help take

our project further by helping to compare pre-and post-surgical stress in the diseased and corrected heart. It will be like a virtual myectomy which will help access the correct amount of tissues to be removed to restore the LVOT.

1.2 Significance

Hypertrophic Cardiomyopathy is a highly prevalent disease, and improving surgical planning can improve surgical outcomes. Many patients can directly benefit from better surgical planning as the success rates of the myectomy can increase. My senior design project for the department of Bioengineering was about the computational modeling of the hypertrophic heart. Through my honors research, I added additional value to the project as we are now able to compare the diseased and corrected hearts. The corrected 3D model can be used to perform a blood flow simulation to find out the exact amount of septal wall to be removed for the best result. Different amounts of muscles in the ventricular walls can be removed to see which one is sufficient to restore the LVOT and minimize the stress level on the muscles.

1.3 Physical and Functional Requirements

The project must need few physical and functional specifications for the project to be significant. The 3D reconstructed and corrected models must be accurate and have all the internal anatomy visible. The surgeons must be able to distinguish the anatomical structures in the heart and be able to measure the hypertrophic growth precisely. For the purpose of simulation, the models must not have different holes on the walls.

CHAPTER 2

METHODOLOGY

2.1 Materials and Systems

CT images of a patient with HCM were provided from UT Southern Medical Center with approval from Institutional Review Board (IRB). For this research, only one sample of the CT images were used.

2.1.1 Computational Requirements to run ScanIP
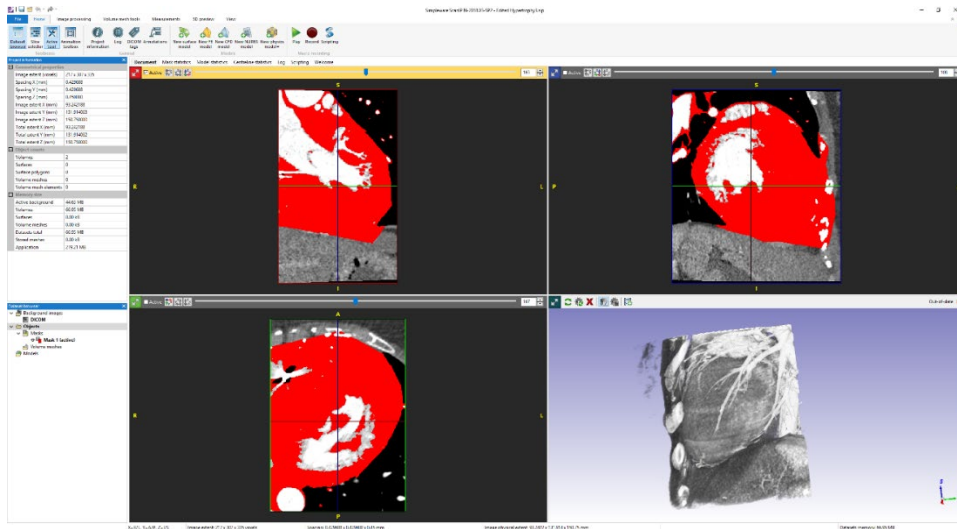
Figure 2.1: The image shows the user interface of ScanIP with the CT images loading in it. The images of sagittal, coronal, and axial views of the CT images and automatic 3D rendition can be observed in the image.

The computational requirements of the ScanIP to run include 64-bit operating systems. The processor must be Intel Core i7 or equivalent and memory (RAM) of 16 GB or more. The graphics card must be an openGL 3.2 compatible graphics card with 1024 MB VRAM. Screen resolution should be 1920 x 1080 and true color (32but) or more. The

disk space has to be 100 GB or more. Figure 2.1 shows the user interface of the Simpleware ScanIP software. The user interface shows four different views: the views of the CT images in three different planes and a view of automated 3D rendition. The approximate processing time was about 8 hours for 335 slices (Coronal view) x 418 (Sagittal View) x 335 (Transverse).

2.2 3D Modeling of Hypertrophic Heart

3D reconstruction of anatomical structures is rapidly growing in the medical field. There are several software programs such as ScanIP, Mimics, and Amira. ScanIP was the software used in this study as it was already available in the lab. The model of the hypertrophic heart was developed to represent the anatomy from the CT images. The CT images had 335 slices (Coronal view) x 418 (Sagittal View) x 335 (Transverse). The CT images were loaded in the ScanIP. ScanIP gives the automated 3D models upon loading of the images. The 3D model was cropped to remove the maximum amount of the surrounding tissues. Then the model was segmented using the automated segmentation using thresholding. However, the model contained extra tissues and bones from surrounding areas. The unpaint feature was used to go through each slice and remove the extra tissues and bones to get the segmented heart without surrounding tissues. The 3D editing features were used to get a smoother model and fill the holes created due to the pacemaker.

2.3 Reconstruction of Post-Surgical Model

The CT images were read to precisely locate the hypertrophic cardiomyopathy. The volume and the amounts of tissue overgrowth were determined in the CT images. The amount of the tissue to remove was determined by researching how a myectomy is performed. The septal wall thickness of the hypertrophic heart in the patient was around

43 mm. A thickness of higher than 15 mm is diagnosed as hypertrophy. Then, going to each slice of the CT images containing the abnormal growth, the hypertrophic tissues were removed from the heart model using the unpaint feature in ScanIP. One of the biggest challenges in using this method will be to determine the amounts of muscles to remove. Since threshold values for the normal tissues and abnormal growth will be the same, there are no visual cues to help determine where to cut the muscles. Another challenge is to determine how much to cut from a slice. The anatomy of the heart is very complex and the amount of cut from slice to slice has to be different.

<div align="center">2.4 Testing of the Model</div>

As the accuracy of the models is vital in the study, the 3D models will be tested by measuring the thickness of the septal wall at five different locations. The values will be averaged, and statistical data analysis will be done. Apart from the wall thickness, the overall dimensions of the models will be compared with the dimensions on the CT images to validate the accuracy of the 3D reconstructed models. For the overall validation of the 3D model, the dimension of height, width, and diameter of the aorta will be measured.

CHAPTER 3

RESULTS

The 3D reconstruction successfully got rid of all the surrounding tissues and had smooth surfaces. Figure 3.1 shows the 3D model before and after the 3D modeling. In the initial 3D model on the left of figure 3.1, we can see different extra tissues and bones surrounding the heart. In the 3D reconstructed model, the extra noises were successfully removed to get a better model with a smooth surface. The reconstruction done in two halves (anterior and posterior halves) provided better visualization of the internal anatomy of the heart as opposed to the models reconstructed as a whole. With the models developed in haves, it gave more freedom to work in segmenting and correcting the internal structures.
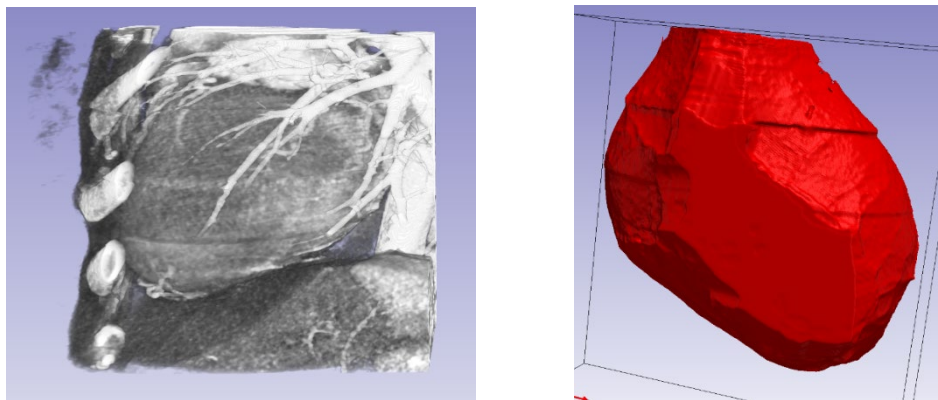
Figure 3.1: The 3D model before the reconstruction is shown on the left, and the model after reconstruction is shown on the right.

Figure 3.2: The image is the 3D reconstructed model of the anterior
half of the Hypertrophic heart before the manual
correction.

Figure 3.2 above shows the initial model of the anterior half of the heart. In the image, we can visually observe that the wall thickness of the heart is very large. The thickness at the location measured in the heart is 50.45 mm, which is very high. Due to the issues with access to the lab computer, more dimensions could not be measured to validate the data.
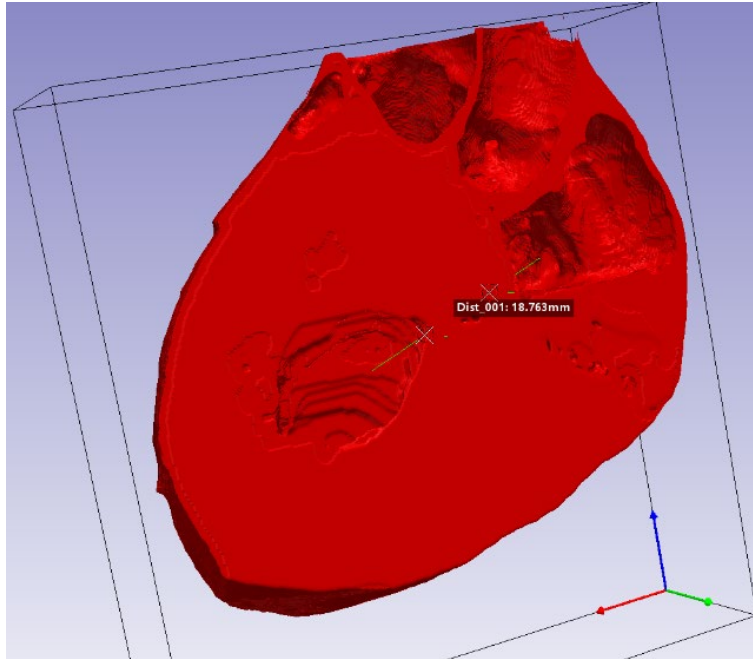
Figure 3.3: The image is the 3D reconstructed model of the
anterior halves of the Hypertrophic heart after
the manual correction for the post-surgical
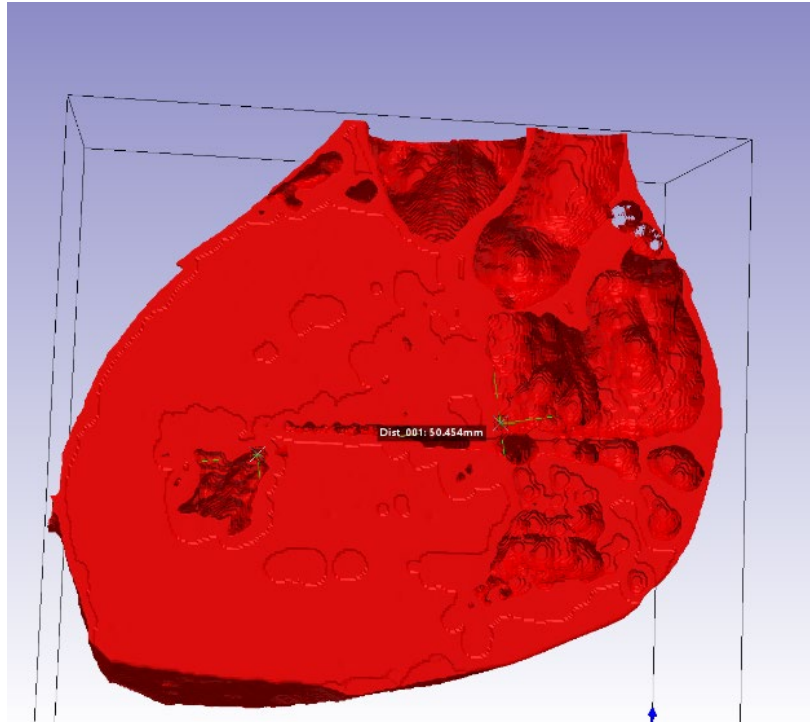model.

However, Figure 3.3 shows the post-surgical model which was developed in ScanIP. The difference in the thickness of the interventricular septal wall is clearly visible. The thickness of the wall in the model at the location measured in the image was 18.76 mm, which is significantly lower than the initial measurement. At the same location where the measurements in Figures 3.2 and 3.3 were taken, five measurements were taken of the thickness of the interventricular septal wall. The averages of the measurements were 47.97 mm before the correction and 19.25 mm after the correction. From the study, it can be concluded that the resected models can be developed from the CT images. However, more data will be needed to validate these findings and validate the possibility of using these models for fluid flow simulations.

Table 3.1: The comparison of the average dimension of the major anatomical structures of the heart in Dicom Viewer (CT images) and the 3D reconstructed model.

	DICOM VIEWER (CT Images) (a)	3D Reconstructed Anterior half (b)	Differences (|a-b|)	Percentage Difference ((|a-b|)/a) *100
DIAMETER OF AORTA	29.63mm	29.16mm	0.47mm	1.6
WALL THICKNESS	38.11mm	39.40mm	1.29mm	3.4
HEIGHT	116.33mm	121.20mm	4.87mm	4.2
WIDTH	130.47mm	126.10mm	4.37mm	3.3

Table 3.1 shows the comparison of the dimensions to measure the 3D model's accuracy compared to the dimensions in the CT images. We can see that the measurements are accurate, with less than 5% percentage differences for all measurements. Appendix B shows that each dimension was measured 15 times and averaged to get the measurements. In the study, the wall thickness needs to be very accurate to meet the functional requirements. In table 3.1, the average wall thickness in the CT image was 38.11 mm and, on the 3D reconstructed model, was 39.40 mm, with a percentage difference of 3.4 %. This meets the need of the project.

CHAPTER 4

DISCUSSION

Congenital cardiovascular diseases come with very complex anatomy and unique geometry, and it is often difficult to understand the extent of the disease using 2D images (6). In such situations, 3D models can provide comprehensive information about the anatomy and help in functional evaluation. The 3D models of the heart reconstructed from patient data have already proven effective. In a similar study, 3D models of the livers were used in surgical planning, and it was found that the median correct response rate after surgery for using 2D images was 40%, while the median correct response for using 3D models was 60% [7]. The surgical time needed while using 3D models was significantly lower than while using 2D images.

In the future, 3D modeling of the post-surgical heart can help in surgical planning. The post-surgical modeling can be done with different amounts of the tissues removed. The developed models can then be used to run the CFD simulation to study the stress and blood flow patterns to find the optimum amount of tissue to remove. The optimum amount of the tissues needed to be removed can give the best possible restoration of the blood flow without compromising the mechanical strength of the heart.

Combining the high-resolution imaging system, image processing technology, 3D modeling software, and rapid 3D printing technology can help rapidly produce patient-specific cardiac models, which can offer important additional knowledge on the disease condition (6). Implementation of such technology can not only help in procedural planning

but also can be used for educational purposes and for better patient communication in terms of needed treatments.

<div align="center">4.1 Limitations and Future Prospects</div>

The major limitation of this study was the limited number of samples. Only one sample of CT from a patient was used for the study. During the 3D reconstruction process, the resolution of the images is an important factor in the accuracy of the anatomical structures. Hence, it is crucial to validate anatomical accuracy using different CT images from different imaging technologies. Also, there can be errors in the 3D modeling. So, multiple software programs need to be studied before finding the accurate one.

There is a vast prospect of 3D modeling technologies in the cardiovascular field in the future. Currently, the use of 3D printed models in surgical planning is limited, and the use of the post-surgical models is even more limited. However, we can expect such technologies to be developed and marketed in the near future. The idea of manually corrected 3D reconstruction can be extended to develop patient-specific cardiovascular prostheses developed directly from the patient data with some manual correction.
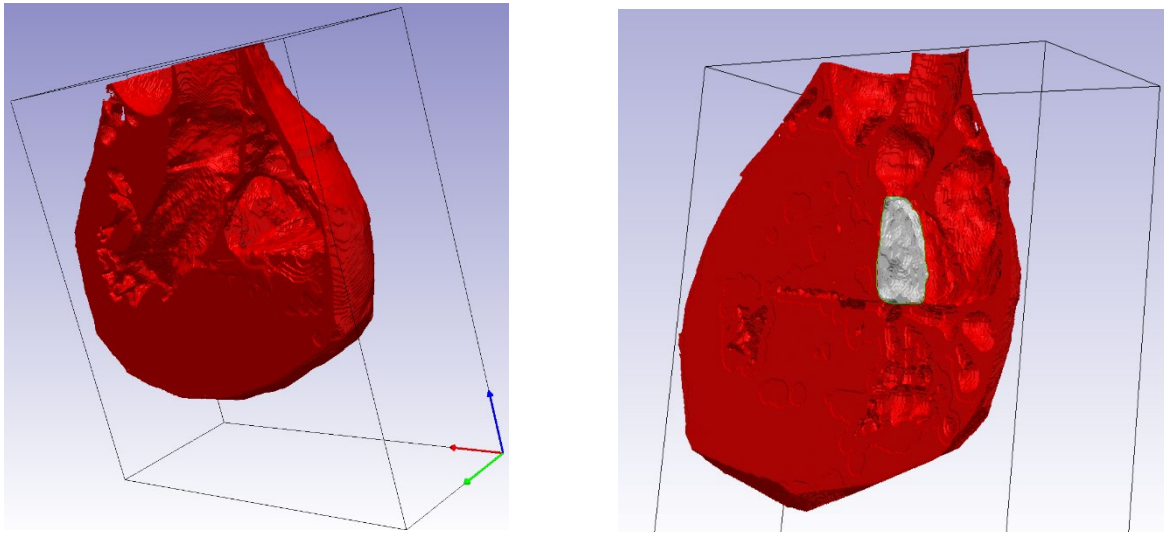
APPENDIX A

IMAGES OF 3D RECONSTRUCTED MODELS

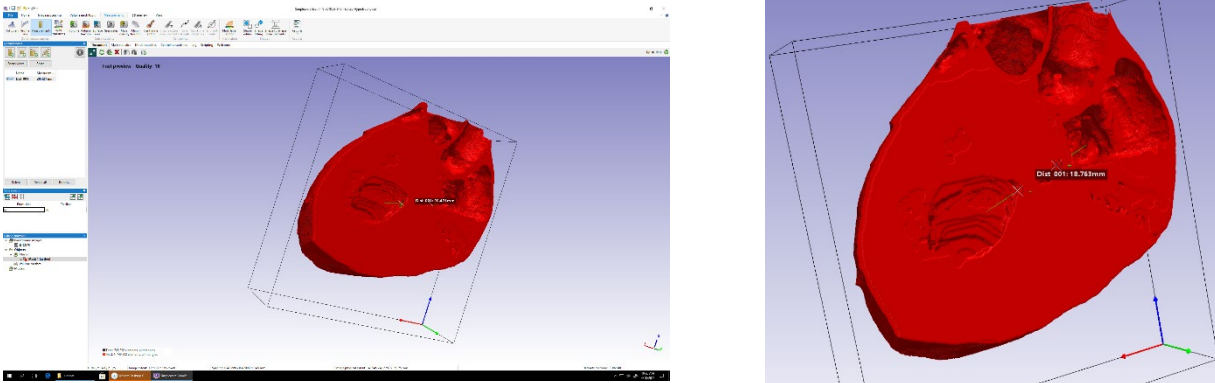Figure A.1: The images show the stages of the 3D reconstruction of the CT images.

Figure A.2: The images showing the measurements of the septal wall in the post-surgical models.

APPENDIX B

MEASUREMENT DATA OF DIMENSIONS

Table B.1: Table demonstrating the five measurements of the septal wall thickness in the original CT model and on the post-surgical model

Septal Wall Thickness in the original model	Septal Wall Thickness in the post-surgical model
50.454	18.534
47.926	20.999
49.479	18.997
43.985	19.463
46.053	18.268
Average= 47.579	Average= 19.252

Table B.2: The table showing the data collected during the testing, which shows the comparison of the dimension in CT images to the dimension of the 3D model

Dimensions in CT images			Dimensions in 3D model		
Height	Width	Aorta Diameter	height	Width	Aorta Diameter
104.02	129.49	29.53	104.02	128.08	30.31
104.32	130.42	29.7	103.89	128.72	30.15
104.37	129.89	30.09	104.43	129.68	30.26
103.97	130.24	29.43	105.46	128.25	29.8
104.12	129.56	29.48	104.73	128.94	30.3
104.5	130.23	29.73	103.96	129.68	29.44
103.94	131.07	29.44	105.24	128.99	29.44
104.26	130.19	29.44	105.15	128.57	29.53
104.25	129.61	30.02	104.59	128.64	29.59
103.66	129.61	29.44	104.55	128.56	29.28
103.93	129.67	29.45	104.52	128.62	30.03
104.23	130.31	30.01	104.84	128.96	29.5
104.57	128.21	29.69	104.63	129.41	29.21
103.4	129.45	29.39	104.42	129.05	29.65
104.78	130.14	29.43	104.17	129.53	29.58
Ave= 104.15	Ave= 129.87	Ave = 29.618	Ave= 104.57	Ave=128.91	Ave= 29.74

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BIOGRAPHICAL INFORMATION

Sudhir is a Senior in Biomedical Engineering, graduating in May 2022. During his time at the University of Texas at Arlington, he has worked in different leadership roles like Supplement Instruction Leader and Peer Academic leader. He also worked as the Nepalese Students Association's President for Spring 2022. Currently, he is working at the University of Texas at Arlington Research Institute (UTARI) on a research project with funding from the Undergraduate Research Opportunity Program (UROP). After graduation, he will be going into the industry to gain some experience. He is seeking a job in the medical device industry. Sudhir plans on going back to school to get a master's degree.