Standardization of Pediatric Cardiovascular Anomaly Anatomy Reconstructions

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***Abstract*— *In the realm of congenital cardiovascular diseases, the understanding, modeling, and visualization of such diseases as they develop during the neonatal growth period continues to be a challenge despite the current technological advancements. Moreover, such diseases as vascular abnormalities pose further risks due to their implications for a proper standardized method for three-dimensional visualization for planning and growth monitoring. This study uses imaging and computational techniques to create multiple models that relate the diseases as they progress from the initial phase toward the late growth stage for newborns' cardiovascular systems. Three-dimensional modeling of patients would be created from patient-specific scans coupled with image processing algorithms. This study also aims to use the working principles of already existing tools for diagnosing aortic & brain aneurysms and pulmonary hypertension for cardiovascular development. To comprehensively understand such diseases and how their physical morphology may be standardized.*

Keywords*—Cardiovascular System, Congenital Heart Diseases, Three-Dimensional Modelling, Disease Modeling, Geometric Visualization.*

I. Introduction

The main objective of this study is to generate a better understanding of congenital heart disease and the development of such diseases to aid in the prevention of disease development from an early stage. Through complex congenital heart disease modeling, the concepts of geometric characterization, computational simulations, and machine learning tools would be implemented to reach the goal. Another long-term goal for this project resides in confident suggestions for treatment procedures and operations backed by results obtained from this study. Furthermore, this study aims to create two main frameworks: a treatment planning one and a cardiovascular system growth framework. Both would be intertwined to function together to reach the end goal of the project. That is a framework that makes use of medical image segmentation, simulations, geometrical characterizations, and machine learning.

Another framework uses the information obtained from the first framework's geometrical analysis of the vascular tissue material behavior, features, and overall morphometric shape to model the growth pattern of different diseases.

II. Background

A. Cardiovascular diseases

It is estimated that 32% of all worldwide deaths are caused by cardiovascular diseases [1]. Since the heart is a complex organ, any kind of disease that affects the cardiovascular system is considered very critical. Conditions that affect the heart and the vessels are considered CVDs, such as blood flow diseases, which extend the total harm towards nutritional and oxygen deficiencies over time. Insufficient flow can cause brain and nerve damage that further decreases the patient's quality of life.

B. Congenital Heart Diseases

Congenital heart diseases are those that come with birth. Such diseases are thought to occur in approximately one out of every hundred births [2]. Such diseases refer to any structural and/or major vascular abnormalities that would be present from birth. An estimated 75% of infants born with such CHD live to one year due to abnormalities that cause impairments to the function of the heart [3].

C. Diagnosis & Treatments in Imaging

Imaging modalities have had a net positive impact on the diagnosis and treatment of congenital heart diseases. However, the risk estimation of aneurysm rupture, for example, is still difficult and rather an inaccurate measurement since the size of the actual aneurysm does not provide enough information. Conventional catheter angiography is considered the golden standard for congenital diseases as it allows for both diagnosis and treatment. However, it still requires a certain level of invasiveness with a radiation burden.

On the other hand, the usage of echocardiography is still considered a safer option however, due to its operator dependency, limited spatial resolution, and real-time nature, the use of MRI and CT is becoming more impactful since they are less invasive and allow for more information to be extracted [4]. Once a proper diagnosis is achieved, an appropriate surgical or treatment plan will be created based on the findings of these different imaging modalities.

D. Computer-Aided Design tools (CAD)

Tools that aid in the process of analysis, design, and optimization of any item by computers are considered computer-aided design tools. Within the realm of medicine, the research and development process of implantable devices makes use of such tools. The advent of these tools makes it possible to simulate the flow of blood within a patient from a three-dimensional reconstruction of the patient's anatomy. Such models are crucial in surgical planning for visualization, growth modeling, and many more applications that are only increasing [5]. However, to obtain a 3D model of a patient's anatomy, a process known as medical image segmentation is to be done utilizing various software such as 3D slicer. Segmentation is the process of partitioning different regions from a stack of images generally obtained from radiology departments. A 3D model would be obtained that can be further processed to remove artifacts via CAD tools such as Fusion360, Ansys, or GeoMagic [6].

III. METHOD

The work package of this project started with obtaining the approval of the ethics committee, and accordingly, the data procurement process was initiated. The completed steps are described under the following headings:

A. Patient Files

The patient files of newborns diagnosed with DORV (Double Outlet Right Ventricle) who underwent surgical treatment between July 2017 and February 2023 were examined. Furthermore, patient reports were re-evaluated in the presence of cardiologists and radiologists, and diagnoses such as ASD, VSD, PDA, and coarctation were also used in labeling. Thus, in addition to preparing a comprehensive and detailed database, a congenital heart defect database was created that allows for classifications that can be used in possible future studies. At least Forty neonatal patient files with multidetector imaging were planned to be identified with the aid of clinicians. However, the image quality and problems arising from segmentation are also considered. The patient files were collected with clinical data and imaging results.

B. CT Screening Protocol

One of the imaging modalities that were used to obtain the patients' data was the CT scan, which must have clear contrast and must be aligned. In addition, the patient should be in the supine position for the CT scan, and the inspection must cover all the specified areas and be in high resolution. More CT scanning requirements include the high section count, which improves the quality of reconstruction, the patient's heart being below 65, and the standard ECG-triggered diastolic protocol being suitable for cardiac structural information. Additionally, the thickness of the sections should be approximately 0.625mm with an increased section distance of P=1 to determine the degree of section overlap to improve the image quality [7].

C. MRI Scanning Requirements

The second imaging modality that was used to obtain the patients' data was MRI. Pediatric thoracic angiography MR scans were performed per the congenital vascular anomaly screening, which are vascular ring, pulmonary sling, pulmonary vein anomalies, systemic-pulmonary collateral vasculature or bronchopulmonary sequestration, and all congenital anomalies. They were also evaluated to obtain appropriate scan requirements for segmentation of the pediatric heart and vessels following 'Pediatric Thorax MR Standards.' More MR scanning requirements include a high number of sections that improve the quality of the reconstruction and increase sections or equal sections. Additionally, a 1.5 Tesla MRI scan is recommended to avoid losing the ECG triggering effect, breath holding is required (if not possible, sedation should be applied). Same as for the CT scan, the patient should be placed in the supine position.

D. Anonymization and Database Import

Within the framework of the study plan, image data (CT and MRI scans) were regularly labeled and placed in the database under ethical clearance. Extensive labeling was performed to contribute to subsequent similar studies, classification, and statistical analyses. Thus, a unique sub-database of congenital heart diseases was created in the hospital Picture Archiving and Communication System (PACS) environment, providing an encrypted and secure interdisciplinary working platform suitable for a wide range of database queries. Patients' medical images were anonymized and recorded by assigning special codes instead of names. The selected patients' names were anonymized, and they were tagged and listed in a password-protected Apache database.

The patient's data was segmented by using a software known as 3D slicer, which allows the data to be imported and to view the CT or MRI scan from the software. This will allow the user to segment and make a 3D model of the heart. In this project, the focus is on creating three different models per patient, which are the aorta, pulmonary arteries (PA), and ventricles.

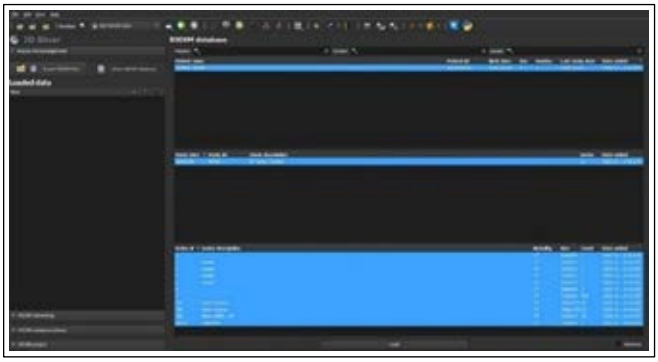

Fig 1. *The data of the patient is obtained from the raw image file.*

As seen from the figure above, the CT scan database of one of the patients was imported into 3D slicer software, which can give us an idea of the patient's age, date of birth, and date of the scan. As was mentioned, these patients are listed as numbers in the database and not as their names.

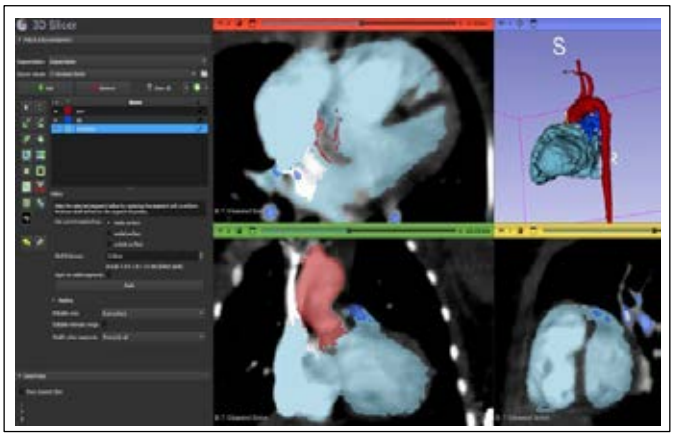

Fig 2. *The 3D model reconstruction of the heart*

As seen from the figure above, the 3D model of the heart was divided into three different sections where: the aorta is the red color, the pulmonary arteries are the dark blue color, and the ventricles are the light blue color. The same process will be applied for each patient, where there will be three models per patient. Lastly, these models will be converted into STL files.

E. 3D Surface Processing

After creating the models of the heart, they must be cleaned to ensure a better understanding of the model for each patient. This process can be done by using computer-aided design tools (CAD), such as Geomagic software, to give more in-depth information on the patient's case.

IV. Results

A. Patients' 3D Models

As was mentioned in the methods section, the 3D models of the patients' hearts were segmented using 3D slicer software. The whole heart model for each patient was segmented successfully for about 40-50 patients while having three separate models per patient that include the aorta, pulmonary arteries, and ventricles.

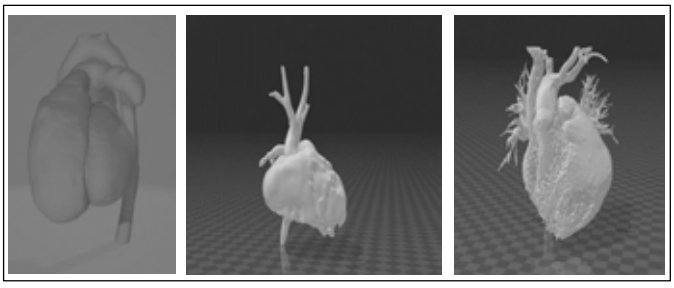

Fig 3. *Sample whole-heart 3D models.*

B. Cleaned Models

In this section, the separated models were cleaned using CAD tools in which the aortic branches and pulmonary artery branches were trimmed. In addition, the whole model was smoothed to make a better representation and to understand the morphological structure of the models. As can be seen from the final aortic model, the aorta is now cleaned and in a better shape than before, and this aids in understanding the morphology, anatomy, and the case of each patient.

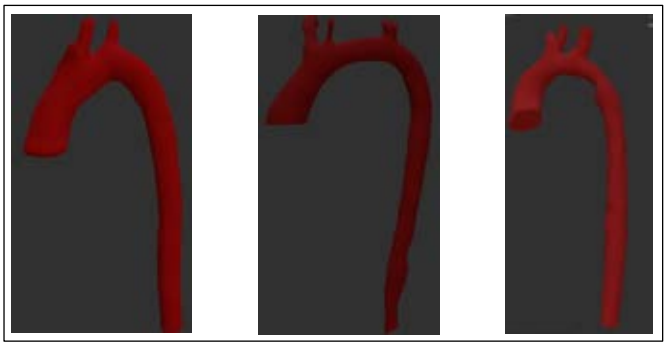

Fig 4. *More aortic-cleaned models*

The same process can be applied to different parts of the heart, such as the pulmonary arteries and the ventricles.

Fig 5. *Surface Optimizing steps: (a) Region-specific model cleaning and smoothing. (b) Cuts and Trim for unwanted regions. (c) final smoothing and remeshing of the entire model.*

These cleaned PA models can aid in understanding the anatomy and morphology of the pulmonary arteries for each patient.

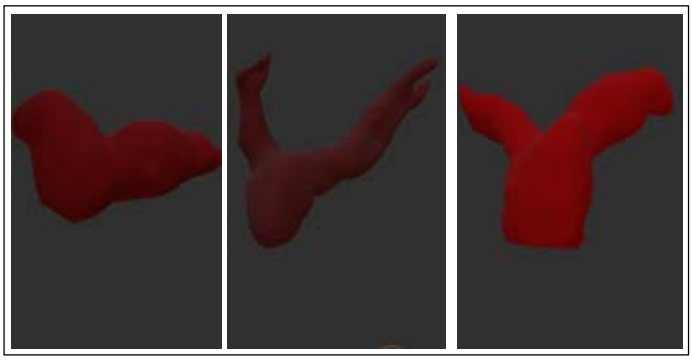

Fig 6. *Finalized Pulmonary models.*

C. Organizing the Database

A database was created for each patient where the date of birth, surgical operation dates, diagnosis dates, age of the patient at scan, and other clinical data were entered into the database, specifying the patients as numbers. Furthermore, each patient would also have the main anatomical structures measured through the 2D scan. Additionally, the information obtained from the database itself will act as a data bank along with all the segmented files. Moreover, this database would then be utilized for various applications under the project's main scope.

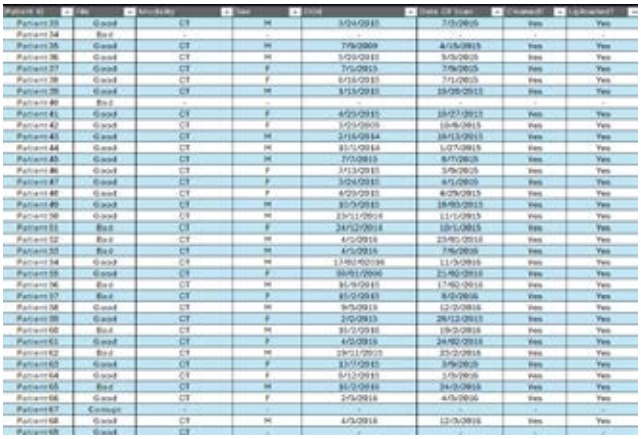

Fig 7. *The generated database*

V. Discussion and Conclusion

The main aim of this study is to enhance the understanding of congenital heart diseases in terms of a proper standardized channel of virtual twin reconstruction through the utilization of various computational-based methodologies. The methods of this study entail the usage of various computational algorithms such as medical image segmentation, computer-aided design tools, and others to extract the maximum amount of information from the data. Data obtained would then be utilized to create a standard approach when dealing with increasingly complicated pediatric cardiac cases. Speaking of which, this study entails the use of anonymized pediatric patient reports obtained from hospitals coupled with three-dimensional models that have already been created through the initial period of the study. Moreover, patient-specific anatomical measurements have been obtained for a section of the data set to be utilized for testing the set protocols that carry out this study. Each patient would have three models created that show a 1:1 replication of the Aorta, Pulmonary Arteries, and the entire heart.

Moreover, this study would make use of DICOM scans, clinical information, multiple 3D reconstructions per patient, and statistical information. A database containing all the previously mentioned information on each patient would then be created. Considering the scale of this study, which has a designated period of thirty-six months, twelve of which have already been concluded. The first year of the study involved gathering the datasets and creating an appropriate database.

Currently, due to the ongoing nature of the study, multiple sections of the study are advancing at the same time. Radiological measurements are taken to allow for an even more detailed approach when creating standard processes for complicated cases. To conclude, this study has the potential to add true value to the diagnosis and detection process of anomalies in pediatric cardiovascular patients. To further elevate the understanding of congenital disease development and treatment plans. A hoped-for achievement is to confidently suggest the best method for standardizing patient virtual reconstructions that would make it possible to implement a system for early-stage pediatric cardiology anomaly detection.

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VII. Affiliations

This research is Affiliated with Istinye University, Istanbul Medipol University, and The Anadolu Medical Center.

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