*3D Reconstruction and 3D Printing of Sections of the Aortic Arch

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Abstract

The application of digital technologies such as 3D modeling, 3D printing, and virtual surgery implemented in the medical field makes it possible to improve the representation of the patient's anatomy and to analyze the clinical case in more detail than the two-dimensional visualization of images from CT, MRI, and ultrasound. In particular, the use of technologies such as 3D printing in cardiac surgery is useful for studying patient-specific cardiac anatomy and manipulating the object of study preoperatively. The integration of a preoperative planning methodology integrated with the new advanced tools facilitates the cardiac surgeon in developing a more informed and precise surgical strategy. Indeed, new technologies allow surgery to be designed and planned in a virtual environment before it is performed in the operating room.

This study reports the application of advanced technologies for aortic arch reconstruction in a virtual and physical environment as a tool for the analysis of cardiac pathologies, e.g., aortic dissection. The process involves the use of software that can convert the patient's medical information into a three-dimensional digital model that can be imported into a virtual environment and then 3D printed.

Keywords
3D Modelling, 3D Printing, Virtual Surgical Simulation, Cardiovascular Surgery, Aortic arch.

1. Introduction
The reconstruction and study of realistic 3D printed models is a key point to better understand patient specific pathologies. The use of new technologies such as 3D modeling, 3D printing, and virtual surgery in the medical field aims to improve knowledge of specific pathologies by combining visual and haptic feedback.
3D technologies make the planning phase easier, clearer, and more scalable than conventional diagnostic tools, such as MRI, tomography and ultrasound. Detailed planning would not be possible without 3D simulation, as the representation of the organ would be reduced solely to the interpretation of 2D images.
In the presented study, three-dimensional anatomical models were reconstructed from CT scans. Possible operative actions were evaluated through a preoperative study using virtual simulation and rapid prototyping techniques.

1.1 Objectives
The main objective of the study is to provide a methodology to study in detail the anatomy of the aorta in the case of an aortic dissection through 3D printing. In this type of cardiac disease, the inner layer of the aortic wall separates from the middle layer of the wall itself, creating new and false aortic canals. Therefore, it is important to identify and

isolate the connectors between the true lumen and false lumen that characterize the malformation. Three-dimensional digital visualization of cardiac anatomy can provide support for this type of analysis.

2. Literature Review

New technologies are increasingly used in medical applications, as they allow for a more detailed focus of the procedure than traditional ones. Preoperative planning, on the other hand, allows patient-specific strategies to be implemented.

In cardiac surgery, preoperative planning is important to provide as much information as possible to the surgical team in order to better understand the complexities of the patient's clinical picture, intervene more efficiently, and create a patient-specific template for surgery. Preoperative planning based on two-dimensional radiographic images often cannot provide a complete understanding of the clinical case, especially when complex as in the case of aortic disease. Aortic diseases include a wide spectrum of entities: aortic aneurysms, acute aortic syndromes (AAS), pseudoaneurysms, aortic ruptures, atherosclerotic and inflammatory conditions, genetic diseases, and congenital abnormalities. Treatment can be surgical or endovascular, the planning of which depends heavily on radiological imaging, such as AngioCT or AngioMRI examinations, from which the surgeon can decide the extent of surgery, surgical access, and the type and size of prostheses.

Studies have shown how the integration of 3D printing, for example, provides tangibility of patients' anatomical models, enabling a better understanding of intracardiac anatomy (Hopfner et al. 2021; Segaran et al. 2021). The reconstruction of 3D cardiac models ensure a better evaluation of the clinical case under investigation, a tool for training medical specialists, and support in dealing with patients. Hoashi et al. (2018) performed printing of patient-specific hearts using a stereolithography method that allowed the model to be flexible to improve preoperative study. Other research has evaluated the importance of accurate reproduction and 3D printing for proper assessment and preparation for surgery in cases of complex congenital heart disease (Borracci et al. 2020; Valverde et al. 2017; Yang et al. 2021). Finally, some studies have exploited virtual simulation as a guide and method for evaluating the final surgical configuration (Gallo et al. 2020; Kim et al. 2021; Sadeghi et al. 2022; Szugye et al. 2021). Currently, new technologies are mainly used to support preoperative surgical planning to improve its accuracy. What more can be provided is a better level of detail regarding complex cardiac pathology such as aortic dissection by going to a patient-specific physical model of the aortic arch that can be dissected and analyzed in an overall.

3. Methods

The methodology used consists in a series of defined processes (Frizziero et al. 2021; Napolitano et al. 2021; Osti et al. 2019; Papaleo et al. 2021) and requires the interaction of a diversified team consisting of doctors and engineers. Communication within the team must be transparent, and the exchange of data and information must occur on both sides. The methodology is shown in Figure 1.

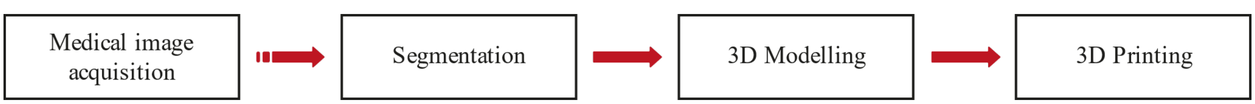


Figure 1. Workflow

The workflow starts with the collection of medical images such as AngioCT, AngioMRI, or ultrasound regarding cases of aneurysm or aortic dissection. The engineering team will perform a 3D reconstruction of the medical images using segmentation software (3D Slicer v4.11) (Fedorov et al. 2012) followed by digital manipulation and 3D printing of the object. This approach allows the patient's specific problem to be explored three-dimensionally. By manipulating the patient-specific 3D model through design software (Blender v3.1.0) it will be possible to hypothesize different solutions and study different surgical scenarios. The three-dimensional representation allows the type of surgery and the final procedural strategy to be chosen with more accuracy and detail. Simultaneously, a 3D printed model is built to capture the tactile sensation that cannot be reproduced in a virtual representation. This printed model of the organ is important for assessing the physical dimensions of the area being analyzed, predicting the best access, and possibly trying out a demo of the surgery itself.

Segmentation

The segmentation step consists of identifying through selection masks the interesting regions to be analyzed. In cardiac surgery, the reprocessing of a medical image such as AngioCT or AngioMRI is preferred because these are exams that take advantage of contrast medium and allow visualization of the blood flow and vascular system of the human body. Through image segmentation it is indeed possible to select the blood volume rather than the blood vessel wall, which is difficult to identify. What is obtained from this process therefore is the three-dimensional reconstruction of blood flow (Figure 2). Also, in the case of aortic dissection, it is important to go and identify the true blood lumen and the false blood lumen. Equally important is to identify the connection points between the two blood lumens. Determining these points is critical to the surgeon in specifying the mode of access and surgical approach.

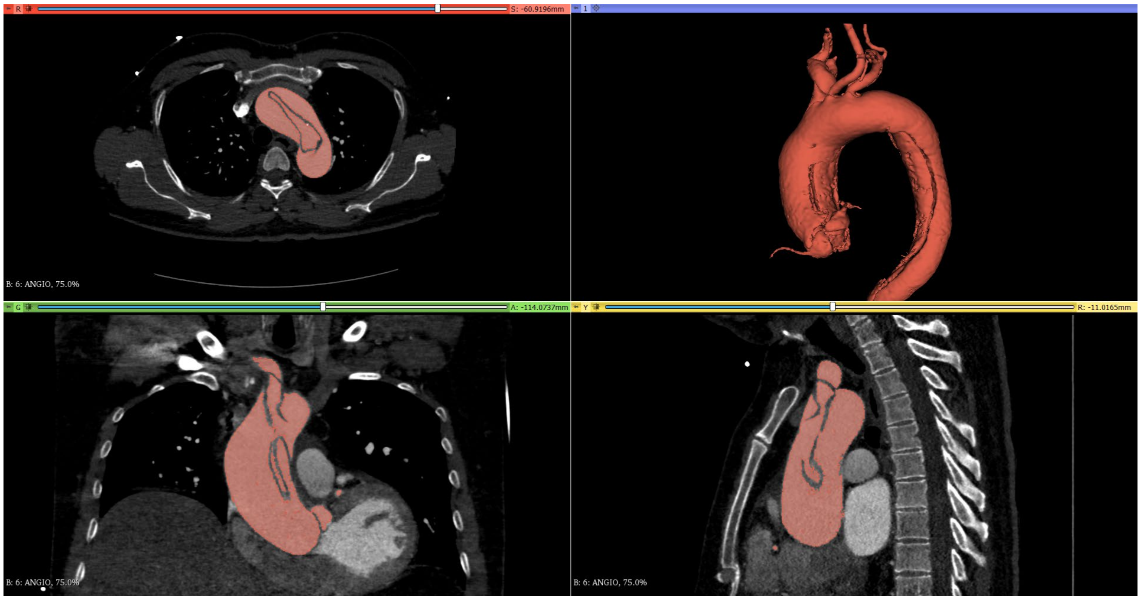
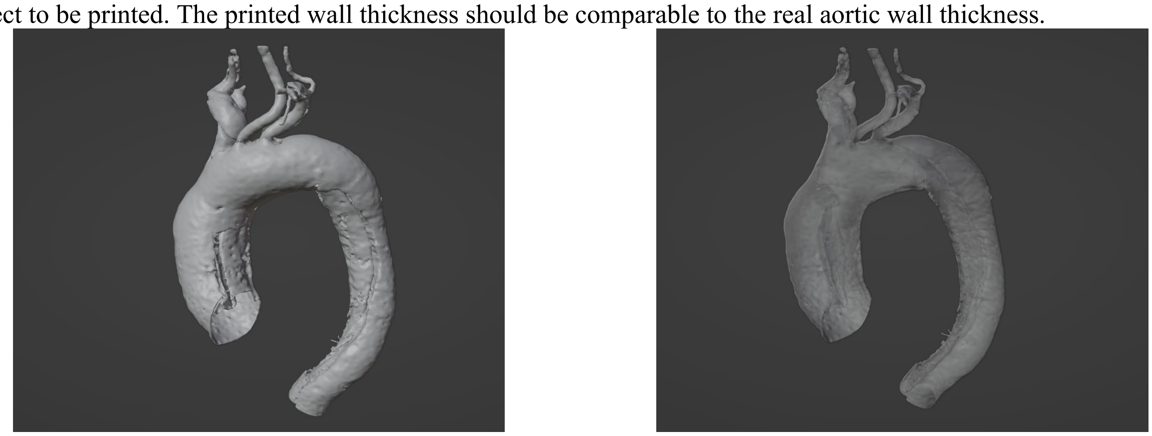


Figure 2. Segmentation of a case of aortic dissection

3d modelling

Created the selection masks from the segmentation stage, it is possible to export the circumscribed areas in .stl format. This format represents a three-dimensional model characterized by a mesh that is manageable in any digital modeling software. For this study, Blender was used to visualize and manipulate the model exported in the previous step. In this environment it is possible to apply commands called "Modifiers" that allow to act on the mesh. The modifier exploited in this case is the "Solidify" to go and set a thickness to the outside of the blood volume and simulate the containing wall (Figure 3). The wall thickness is set according to the printing parameters, particularly that of the “Walls” of the object to be printed. The printed wall thickness should be comparable to the real aortic wall thickness.



a) b)

Figure 3. 3D digital model in solid shading (a) and in translucent shading (b)

3d printing
Once the digital model is prepared, the parameters and the printing material are set. The case presented in this study was printed in PLA material loaded on a Delta AnyCubic Predator printer. The challenge of this process is to obtain a print without infill or supports, but only of the outline of the blood vessel in which of see the internal sections and especially the cardiac malformation to be studied. The standard ways of creating 3D printed object is to use surfaces as body skin while the inner part is filled with standard infill. Moreover, when the geometry has cantilevered pars, the slicer software tend to apply supports to complete the printing. This is not the case of the aortic tube. In this specific case the main problem was to get the thickness of the tube printed properly in order to find the right dissection points over the geometry. The .stl produced by the segmentation software represents just the inner skin of the blood path and it cannot be filled using an infill value. Because of that, the use of Blender was necessaire to set up a thickness of the tube respect to the outside normal and several sections where needed to avoid supports. The slicer used is Ultimaker Cura version 4.13. Thanks to Vase Mode, aesthetic and seamless 3D objects can be printed while saving time and material. With Vase Mode, it is possible to print almost any shape with the thickness of a single wall, which means that less time and filament is needed per object. With Vase Mode, the print is moved upward in the form of a spiral, so there are no layers as there are in traditional 3D printing. This results in a low-cost physical prototype printed in three different sections (Figure 4).

Figure 4. 3D printed models in three distinct sections

5. Results and Discussion
The result of this process is a low-cost 3D printed physical prototype representing different cross sections of an aortic arch affected by internal dissections. Printing the different sections using the idea of avoiding supports and infill through the wall thickness and studied section is useful for the surgeon to better analyze different points of the aortic tract that are difficult to visualize from simple two-dimensional medical images. In addition, dividing into sections has facilitated the successful three-dimensional printing itself by decreasing the complexity due to the arch shape of the piece. 3D printing reconstruction provides an accurate and physical preview of the surgical field, including consideration of the dimensions of anatomical structures. In fact, a 3D printing model helps predict the best access for insertion of endoprostheses, for example. This is of great importance for both the success of the procedure and subsequent endovascular planning. Moreover, the methodology proved to be efficient in reconstructing soft tissue with a thin thickness starting from the inner surface. It worth remembering that the segmentation of the AngioCT scan is not the tube itself, but the blood passing inside the tube. While in a bone reconstruction, the modeled surfaces are already the boundary of the geometry, in this specific case, the surfaces reconstructed are the inner part of a tube that is impossible to reconstruct from the outside. The thickness is imposed later and suffer from the problem of the minimum printable width. This parameter is defined by the nozzle dimension and can be reduced increasing on the opposite the total printing time.

5.3 Proposed Improvements
The integration of virtual 3D models, virtual simulation, virtual surgery and 3D printed physical models can bring several advantages in cardiology. The proposed methodology can also be applied to other areas of cardiac surgery,

such as in studies of complex implants for heart failure. A 3D virtual model and virtual simulation can help better position devices for implantation, providing information that cannot be obtained with conventional procedures.
Virtual surgery technology has the potential to improve procedure planning and to compare the actual result with that obtained in the virtual environment. The process can be leveraged by the surgeon who will be able to examine the pros and cons of simulated procedures and then choose the best treatment to perform in each specific case.
For optimal evaluation of the physical prototype, it is interesting to test different materials suitable for additive manufacturing with the aim of reproducing anatomically similar features. In this specific case, the testing of flexible material can be a great improvement in the twin process between physical, digital and 3D printed object. For this purpose, it is important that the physical prototype be as faithful as possible to its real counterpart, promoting a better understanding and tangibility that lacks

6. Conclusion

The study provides a methodology for three-dimensional reconstruction from AngioCT and 3D printing of a case of aortic disease. In fact, the methodology allows a 3D model to be obtained first digitally and then physically through the use of advanced technologies such as CAD modeling and 3D printing. These technologies are accessible as they are open source, leading to a low-cost but quality result. The presented methodology resulted to be flexible respect to many medical applications from orthopedy to the presented cardiological case. This is very important since there is no need for different tools applied in different medical field. The most important fact remains the interaction between doctors and engineers that can accomplish great results.

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Biography

Gian Maria Santi is a Researcher of the Department of Industrial Engineering at Alma Mater Studiorum University of Bologna. Gian Maria is involved in Augmented Reality and 3D Printing applications and studies. He is also a tutor at the aforementioned university.

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Leonardo Frizziero is a Senior Assistant Professor of the Department of Industrial Engineering at Alma Mater Studiorum University of Bologna. He promotes the scientific issues related to the Mechanical Design and Industrial Design Methods (CAD 2D, 3D, Advanced Design, QFD, TRIZ, DFSS, DFD, DFA, ecc.). In 2005, he was recruited by Ferrari Spa, as project manager of new Ferrari cars projects. In 2009 he came back to University, obtained the Ph.D. degree and started collaborating with the Design and Methods Research Group of Industrial Engineering becoming Junior Assistant Professor in February 2013 at DIN of AMS University of Bologna. He teaches and follows researches in the design fields, participating at various competitive regional, national and international research projects. Since 2018 he has been a Senior Assistant Professor. Since 2017 he is qualified Associate Professor of Design and Methods of Industrial Engineering (ING-IND/15). Prior to the role of university professor, he held relevant positions for some industrial companies.

Antonio Loforte is a specialist in cardiac surgery. He is mainly involved in heart failure surgery, heart transplantation, artificial heart, minimally invasive cardiac surgery, thoracic aorta surgery, and valve surgery. In 2000, he graduated in Medicine and Surgery from the University of Catania and completed his residency in Cardiac Surgery at the University of Bologna in 2005. Subsequently, between 2009 and 2013, he performs a PhD in "Organ Transplantation" with international relevance. Currently, Dr. Loforte holds the position of Medical Director Cardiac Surgeon at the Operative Unit of Cardiac Surgery and Transplantation of Policlinico S. Orsola-Malpighi in Bologna, as well as teaching numerous courses in the field of Cardiac Surgery. Finally, a member of prestigious scientific associations in the field of Cardiosurgery, he is the author of more than 300 scientific publications in national and international journals. He is the author and Editor in Chief of book chapters, manuals and monographs of international profile and a member of the Editorial Board of numerous national and international scientific journals.

Gianluca Folesani is a heart surgeon at S. Orsola-Malpighi Hospital in Bologna. In 2008, he graduated in Medicine and Surgery from the University of Bologna and completed his residency in Cardiac Surgery at the University of Bologna in 2014. He's member of SICCH (Società Italiana di Chirurgia Cardiaca), EACTS (European Society for Cardio-Thoracic Surgery) and QUIP (Quality Improvement Programme).

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