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# Reconstruction, processing and smoothing of surface geometry of a patient specific ascending aortic aneurysm

C Manopoulos<sup>1\*</sup>, A Raptis<sup>1</sup>, W Krishan<sup>2</sup>, C Mavratzas<sup>2</sup>, M Drandakis<sup>2</sup>, S Astraka<sup>2</sup>, I Kouerinis<sup>3</sup>, and N M Vaxevanidis<sup>2</sup>

<sup>1</sup>Biofluid Mechanics and Biomedical Engineering Laboratory, Fluids Section, School of Mechanical Engineering, National Technical University of Athens, Zografos, GR 15780, Greece.

<sup>2</sup>Laboratory of Manufacturing Processes and Machine Tools (LMProMaT), School of Pedagogical and Technological Education (ASPETE), Department of Mechanical Engineering Educators, Amarousion, GR 15122, Greece.

<sup>3</sup>Department of Cardiothoracic Surgery, “Hippocraton” Hospital, Athens, GR 11527, Greece.

\*Corresponding author's e-mail: manopoul@central.ntua.gr

**Abstract.** This work presents the creation of geometric surface models representing the heart chambers and the aorta for two patient specific cases. The first one concerns an acute ascending aortic aneurysm in the anterior Valsalva sinus and the second one a normal aorta for comparison reasons. The surface modelling was implemented in a medical image reconstruction software (Materialise Mimics), based on the computed tomography scans of the patients. For each case, the two atriums and ventricles, the ascending aorta, aortic arch and descending aorta, the pulmonary artery and the superior vena cava were also reconstructed and modelled. Special attention is given to the morphology of the vessels and the heart chambers that are in contact with the ascending aortic aneurysm, due to the acute aneurysmal extension of the Valsalva sinus. A comparison of the non-aneurysmal and the aneurysmal models is necessary to infer whether this disease affects the geometries and/or other vital organs that come in contact with the aortic aneurysm. Special care is given to the surfaces' smoothing process to preserve the morphology of the structures, avoiding any deviations from the actual geometries of the corresponding vessels and heart chambers.

## 1. Introduction

An aneurysm is an expansion or bulge of a blood vessel to more than 1.5 times its normal size. The aorta – the body's largest artery that is responsible for carrying oxygen-rich blood away from the heart – is prone to developing aneurysms. Aortic aneurysms (both abdominal and thoracic) represent the 15th leading cause of death in individuals older than 55 years, and the 19th leading cause of death in individuals of all ages. [1] Mostly, male subjects get affected by the aneurysmal disease. The risk factors include age, family history, arterial pressure, and lifestyle, among other.

If an aneurysm occurs in the ascending aorta, the proximal aortic section after blood leaving the heart through the arterial valve, it is called ascending thoracic aortic aneurysm (aTAA). aTAAs do not always cause symptoms, especially in the early stages and when small. As they increase in size, aTAAs may



begin to cause problems such as: chest pain, back pain, tenderness in the thoracic region, hoarseness, shortness of breath, cough.

Not all patients with an aTAA will experience symptoms, even when the bulge is large. A ruptured aneurysm, on the other hand, is a medical emergency. Symptoms include clamminess, difficulty breathing, difficulty swallowing, dizziness, light-headedness, loss of consciousness, low blood pressure, rapid heart rate, sudden and intense pain in the chest or back, weakness or paralysis on one side of the body.

The heart is a complex organ that pumps blood through the body with an intricate system of muscle layers, chambers, valves, and nodes. It has its own circulation system and receives electric impulses that make it contract and relax, which triggers a sequence of events forming the cardiac cycle. The heart has a middle muscular layer, the myocardium, made up of cardiac muscle cells, and an inner lining called the endocardium. The inside of the heart (heart cavity) is divided into four 4 chambers – two atria and two ventricles – separated by cardiac valves that regulate the passage of blood. The atria receive blood returning to the heart, while the ventricles receive blood from the atria – via the atrioventricular valves – and pumps it into the lungs and the rest of the body. The left atrium and left ventricle are separated from the right atrium and right ventricle by a band of tissue called the septum. The right atrium receives deoxygenated blood from the head and neck and from the rest of the body via the superior and inferior vena cava, respectively. The right ventricle then pumps blood into the lungs (through the pulmonary trunk, which divides into the right and left pulmonary arteries), where it is oxygenated. The oxygenated blood is returned to the left atrium via the pulmonary veins and passes into the left ventricle through the cardiac valves. From the left ventricle, it is delivered to the whole body through the aorta.[2]

Multi-slice computed tomography (CT) image series are a valuable source of information to extract shape and motion parameters of the heart. Indicative 3D reconstruction of the heart chambers from CT images can be found in the literature [3, 4]. Here we present the reconstruction of two cases, one normal and one aneurysmal, including all main chambers of the heart (both ventricles and atria) and the connected vessels (arteries and main vein trunks). The pathological case refers to a patient with an aTAA. A concise 3D reconstruction in a difficult case (like the aTAA) in comparison to a normal case can highlight the extend of the disease and possible effects in surrounding organs, arteries, and veins, that are not clearly visible when examining the 2D CT images. The quality of the reconstruction is crucial for increased understanding of the disease from a clinical point of view but also as a prerequisite for 3D printing applications.

## 2. Materials and methods

### 2.1. Material

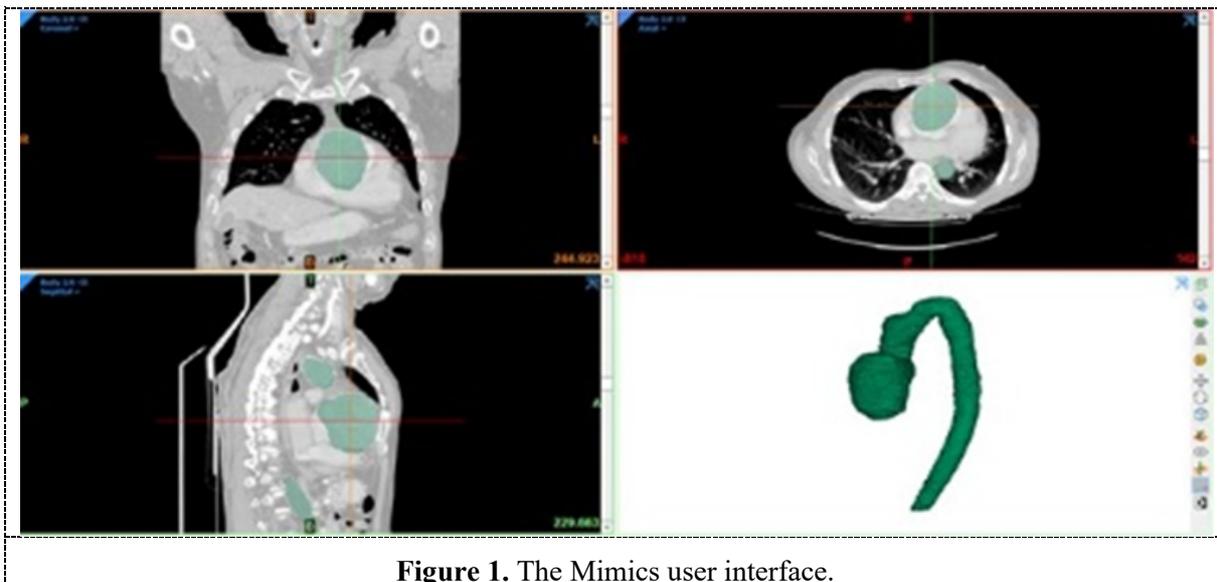
The patient-based analysis relies on the computed tomography (CT) scan of a 70 years old male patient, who suffered from aTAA and underwent aortic repair surgery at “Hippocraton” General Hospital of Athens in 2013. The normal case refers to a 69 years old person who had CT scan at the same hospital for irrelevant reason and was free of cardiovascular diseases. The CT data was made available for further processing, with the informed consent of the patients, by attending physician (cardiac surgeon) at the Cardiac Surgery Department of “Hippocraton” General Hospital of Athens.

### 2.2. CT imaging protocol

The CT scan was performed on a 16-slice multidetector CT (MDCT) scanner (Activion 16, Model TSX-031A, Toshiba). A protocol of 1 mm slice thickness was used with 120 kV, 60 mA tube current, 330 mm field of view for reconstruction and a sharp reconstruction kernel. The CT was performed in the craniocaudal direction, from immediately inferior to the aortic arch to the level of the diaphragm in a single breath-hold. A contrast agent is occasionally injected in the blood flow stream of the patient, to increase the imaging resolution, clearly indicating the lumen. A contrast-enhanced CT scan, known as computed tomography angiography (CTA) was performed in the aTAA case while a typical non-contrast gated CT was performed in the normal case.

### 2.3. Segmentation & Reconstruction

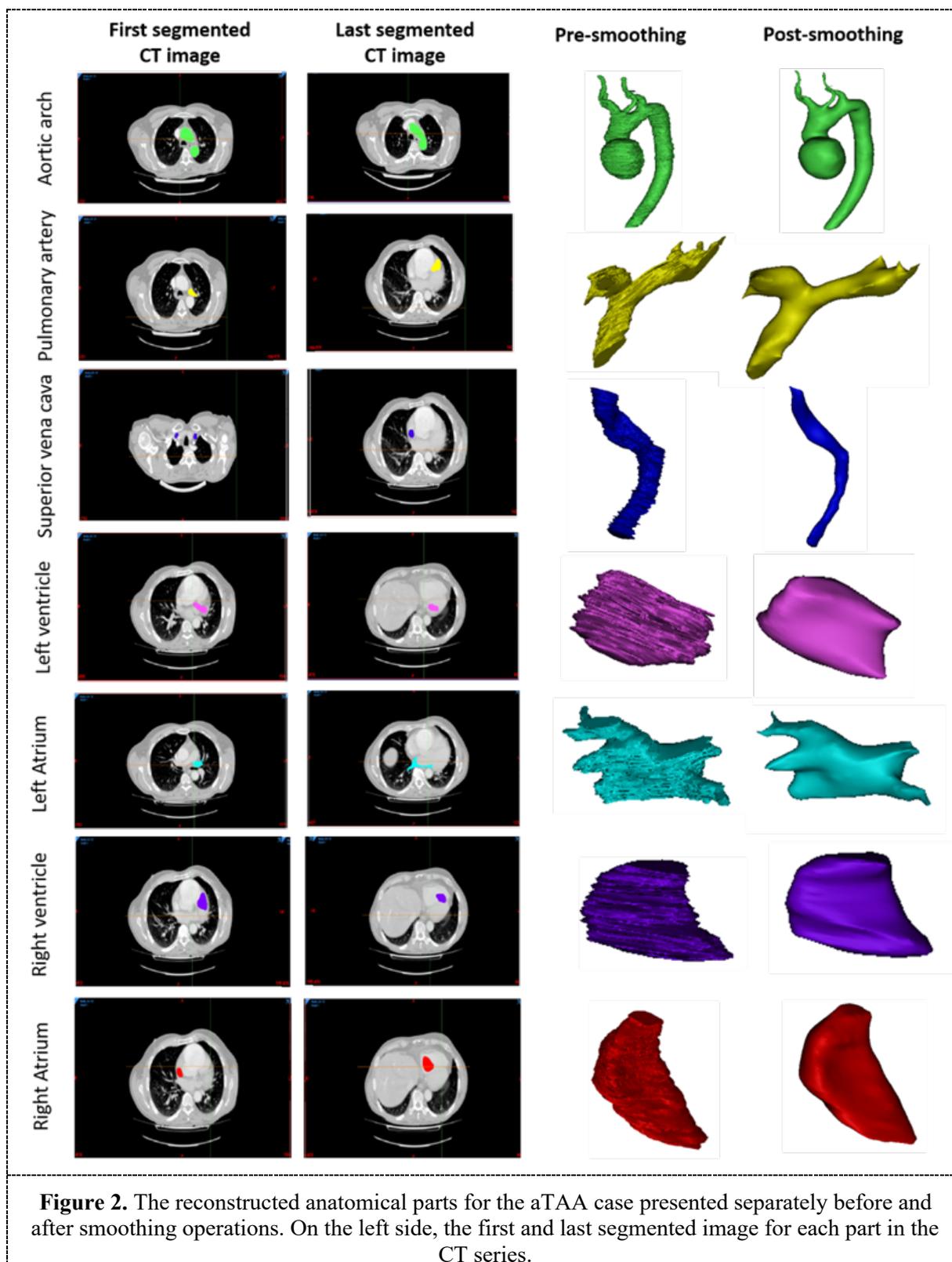
The Mimics software (Materialise inc.) was used for the processing of the CT imaging series, as an advanced medical technology toolbox enabling the segmentation and reconstruction of medical imaging data. Researchers and engineers are using the software to develop state-of-the-art medical device designs, individual implants, and life-saving surgical instruments. The CT scans in Mimics can be examined in four views: 1) the coronal at the upper left window in Fig. 1, 2) the sagittal at the bottom left, 3) the axial at the upper right, and the 4) 3D view at the bottom right window, where the reconstructed anatomic part of interest is accessible. The four views are interrelated, adapting to the selected intersection and the crosshair pinpoint. Moreover, it is possible to adjust the threshold of gray value making the various anatomical parts more distinct, facilitating the segmentation and reconstruction process.



**Figure 1.** The Mimics user interface.

The anatomic parts of interest are the 4 chambers of the heart, the superior vena cava, the pulmonary artery, and the thoracic aorta. All anatomic parts were separately processed, and a different color-coded mask was assigned to each one.

The thoracic aorta, the pulmonary artery, and the superior vena cava were initially isolated from the surrounding bones and organs using the automated “Dynamic region growing” tool in Mimics that is based on gray value connectivity. The initial automated segmentation is rough most of the times and a manual slice-by-slice refinement is certainly required afterwards. Specifically, the anatomic parts were further restricted to the desired limits by batch-removing the out-of-bounds segmented cross-sections and any leftover segmented artifacts. Special focus was given to the aortic wall calcifications not included in the final reconstruction. The thoracic aorta included the aortic root (immediately after the left ventricle), the ascending part and the descending part until the diaphragm level, as well as its main branches, namely the innominate artery, the left common carotid artery and the left subclavian artery. Concerning the pulmonary artery and the superior vena cava, only the proximal (to the heart) parts were taken into consideration while the pulmonary artery was truncated after its bifurcation. The “Dynamic region growing” tool fails in the case of heart chambers and a fully manual segmentation process was instead carried out. All operations were executed by biomedical engineers under the supervision of the cardiac surgeon, to ensure that the reconstruction accurately corresponds to the anatomic parts of interest.



After completing the segmentation process, Mimics provides tools for the transformation of the segmented 2D images into 3D models. The initial reconstructed models feature rough artificial edges on their surfaces due to the resolution of the medical images and the slice thickness. The models need further refinement prior to their use either for computational simulations or 3D-printing.

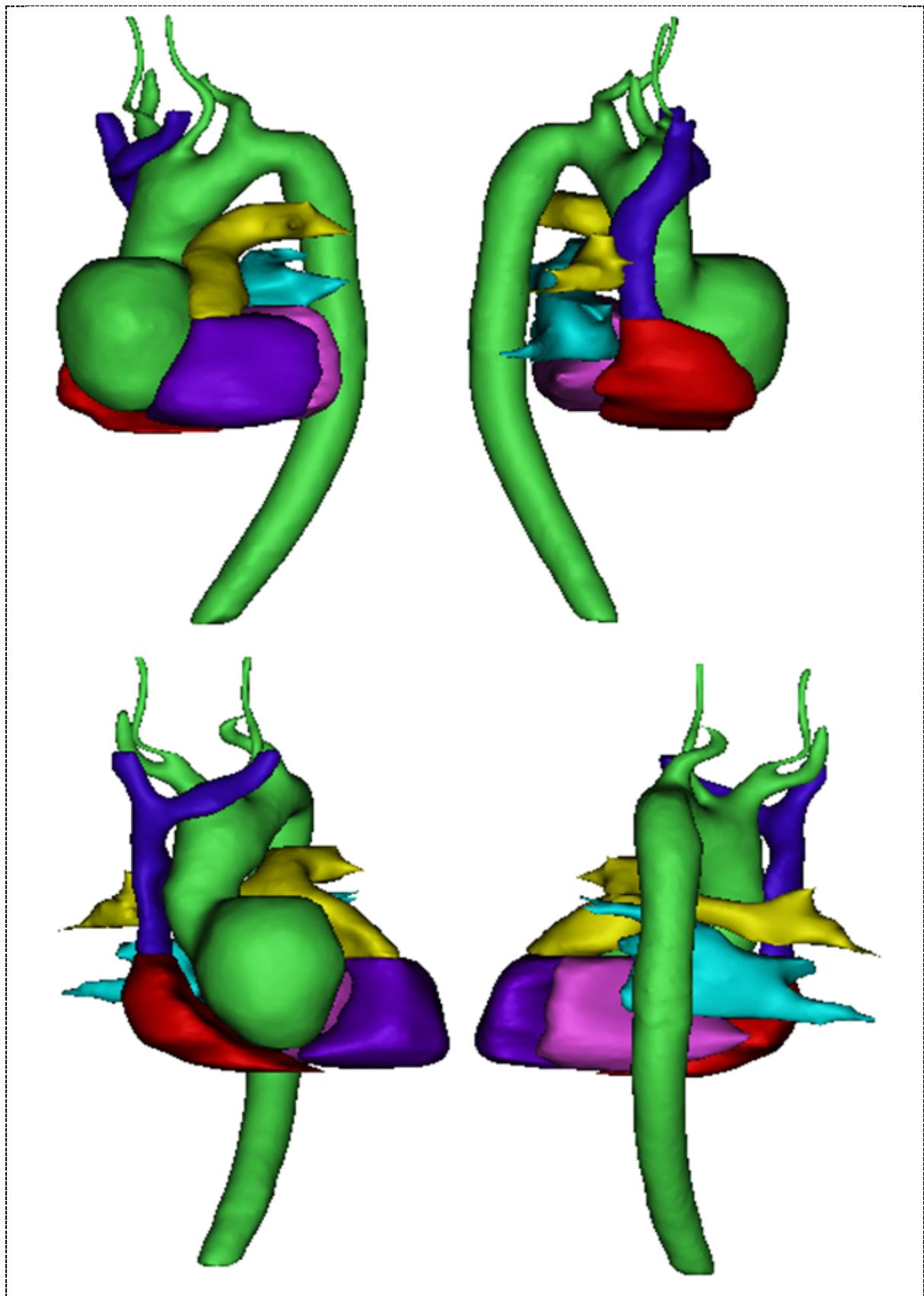
#### *2.4. Smoothing*

Smoothing is an iterative process for the reduction of the surface roughness provided that the least deviation from the original data is ensured. During the smoothing process, it was observed that the cross-sectional area (and the volume of the models in extend) depended on the number of smoothing iterations and the smooth factor. More iterations were leading to a more natural result, while the smooth factor had a heavy impact on the shape of the models. Conclusively, it was decided to perform several iterations (500) and keep the smooth factor to a minimum value (0.1). It is also worth noting that during the segmentation process, we applied a small expansion of the segmentation mask to compensate for the volume shrinkage due to the smoothing, ending up with volume-preserving models with respect to the original data.

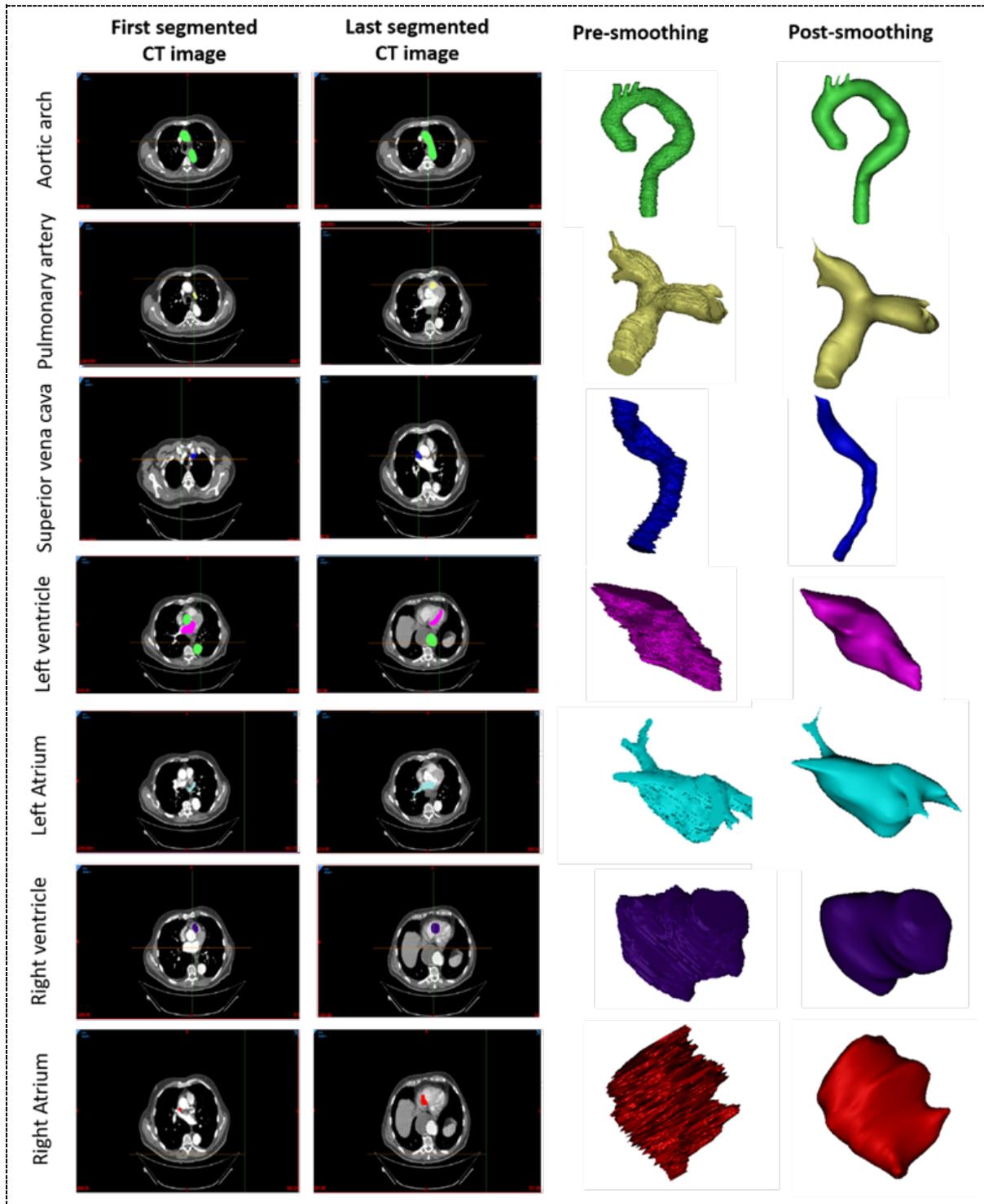
### **3. Results and discussion**

In Fig. 2, the reconstructed models of all anatomic parts of interest for the aTAA case are presented before and after smoothing, along with the first and last segmented images in the CT series for each part. Fig. 3 illustrates the superposition of all reconstructed models providing a detailed view of the heart, its chambers, and the connected vessels from different perspectives. The Figs. 4 and 5 respectively illustrate the anatomic parts separately and in combination for the normal case.

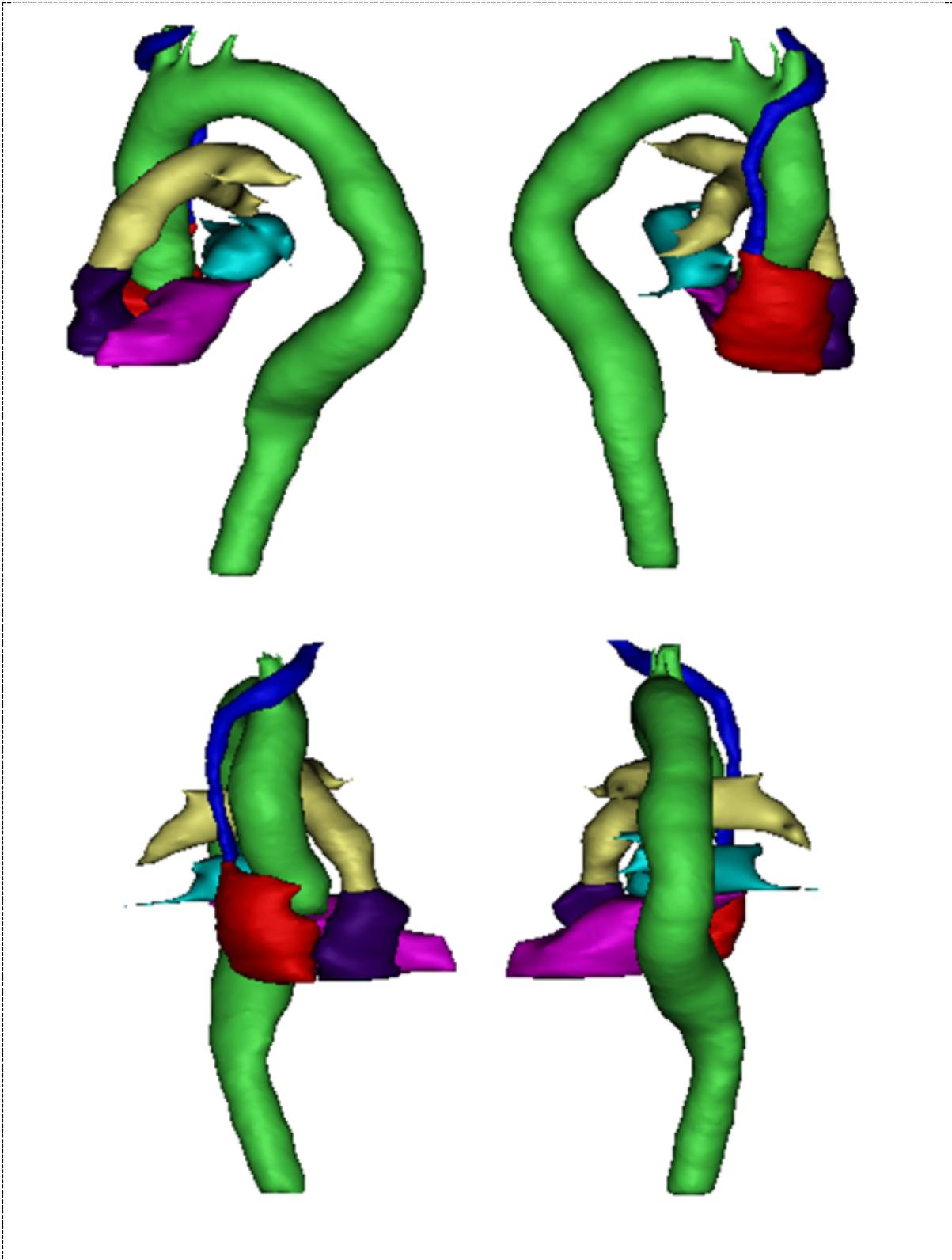
There are characteristic differences in the position of the heart cavities between the two cases. Due to the aTAA bulge, the right ventricle of the aTAA patient has shifted to the left pushing the left ventricle posteriorly. The other two cavities have also slightly shifted. As the aTAA developed in the posterior direction, the right atrium has been compressed detaching to an extend from the right ventricle. The pulmonary artery has also been compressed due to the aneurysm. From the patient follow-up, it is known that a rupture occurred in the non-coronary Valsalva sinus almost anti-diametrically from the right-coronary sinus where the aneurysmal bulge was primarily concentrated. The aTAA case is rare as rupture did not occur at the distended part of aTAA wall but on the opposite direction. A patient-based biomechanical analysis could further enlighten the special features of the aTAA case, highlighting the stress condition and the critical areas of the aTAA wall.



**Figure 3.** Superposition of the geometrical surfaces corresponding to the chambers of the heart and the connected vessels of the aTAA case.



**Figure 4.** The reconstructed anatomical parts for the normal case, presented separately before and after smoothing operations. On the left side, the first and last segmented image for each part in the CT series.



**Figure 5.** Superposition of the geometrical surfaces corresponding to the chambers of the heart and the connected vessels of the normal case.

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