Title:
**CAD Construction of an Aortic Valve Model for Surgical Training**

Authors:
Hamad M. Bubshait, bubshahm@mcmaster.ca, McMaster University
Allan D. Spence, aspence@niagaracollege.ca, Niagara College Canada
Dominic Parry, Dominic.Parry@southerndhb.govt.nz, Mercy Hospital
Zahra K. Motamed, motamedz@mcmaster.ca, McMaster University
Gregory R. Wohl, wohlg@mcmaster.ca, McMaster University

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Introduction:
Many aspects of surgical skills training, such as procuring suitable testing materials and the lack of suitable training models, can be challenging. In cardiac surgery, the surgeons typically use animal hearts for Hands-On Simulation Training (HOST). This is because on-patient hands-on training can be very risky. Animal hearts are not ideal because they do not have the same pathologies found in human hearts. Also, having different anatomies can make the training less realistic. For those reasons, there is a need for high fidelity artificial training models. Also, adequate training models can contribute to increasing the technical proficiency of the surgeons. It has been demonstrated that there is a correlation between the mortality and morbidity after congenital heart surgery and the cardiac surgeon's technical proficiency [9]. The number and complexity of congenital heart surgeries performed by the cardiac surgeon and the institution are also strongly correlated [9]. As well, operative confidence can be an important influencing factor regarding the need for simulation training. It has been demonstrated that simulation training can improve surgical skills and surgeon confidence [1,3].

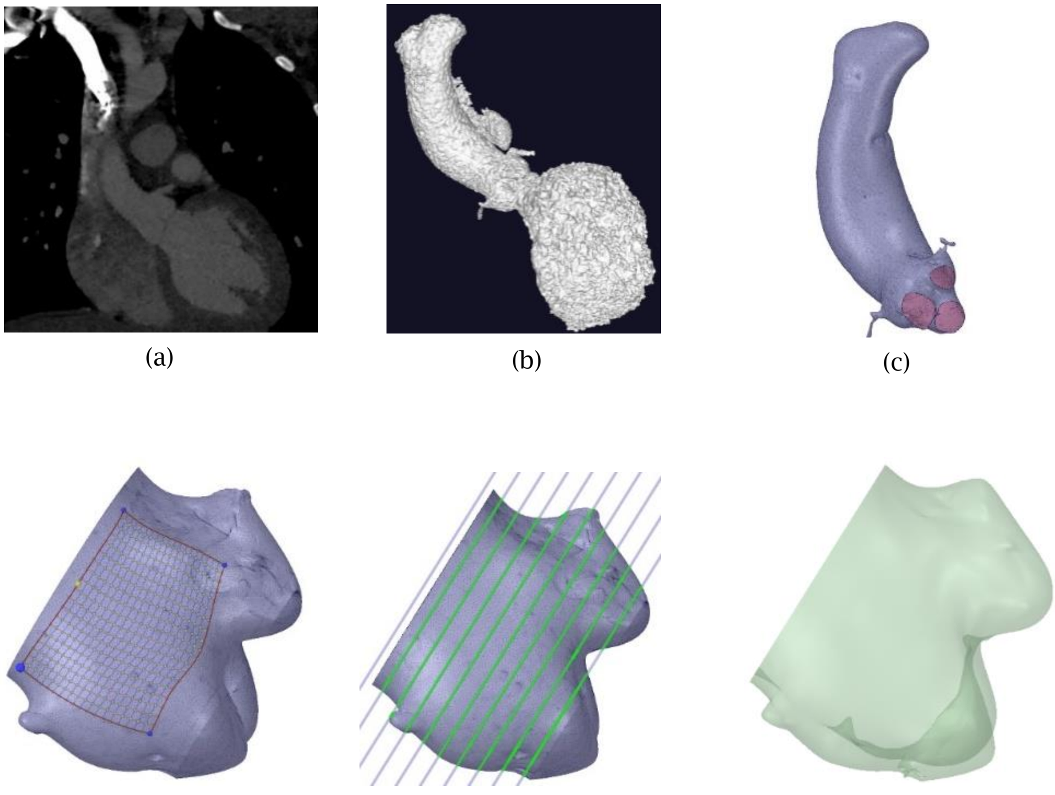
The objective of this research is to create aortic valve educational tools of high fidelity. A survey of residents and faculty members indicated that most deemed high fidelity models to be extremely useful [3]. In addition, for a study of laboratory-based vascular anastomosis training, there was a correlation between skills acquisition and the fidelity level of the model. The results were that training using high fidelity models could increase skills acquisition better than low fidelity models [6].

Main Idea:
Two aortic valve modelling approaches were investigated. The first approach was based on patient-specific computed tomography (CT) scan data. The second approach was based on creating a simplified CAD model using feedback and information from cardiac surgeons.

*Patient-Specific Model*
Major challenges in capturing the geometry of delicate structures such as the aortic valve include the lack of available CAD models and adequate measurement methods. It is possible to get meaningful geometric information about the aortic valve using medical imaging such as CT (e.g., Fig. 1(a)) and magnetic resonance imaging (MRI) scans. Medical imaging segmentation is the process of extracting geometric information from a Digital Imaging and Communications in Medicine (DICOM) file. The segmentation process involves using different computational approaches to analyze the variations in the contrast levels in the DICOM file slices. The software used to process these data was VMTK lab (v1.54, Orbix). The segmentation process starts by importing the DICOM slices into the VMTK lab software. Then the user must manipulate the slice planes to identify possible starting points for the source seed, which

is the starting position of the segmentation process. In order to improve the accuracy of the process, suitable thresholds for the contrast have to be selected. For soft tissues, the threshold can be between 50 to 500 or slightly higher depending on the scan quality. Other segmentation parameters were chosen according to the developers' tutorials and trial and error approach.

Next, the segmentation results were exported as STL file to be smoothed by GeoMagic Studio (v.12, 3D Systems). This process started by importing the STL file and running the mesh doctor option to automatically clean the mesh and remove any isolated small facets around the model. Then using GeoMagic smooth functions, the model was processed further to make it suitable for CAD reconstruction. For example, noise and spikes reductions were used to make the surface of model smoother relative to the original prismatic nature. These extra refinements made the model more adequate for the reverse engineering process as extracting geometric information became relatively simpler. The geometry reconstruction process used the segmentation results as a baseline model for curves extractions. The reverse engineering principles used in this step were focused on utilizing the curves obtained from the STL facets to create blended geometries. This method uses parallel planes that intersect the scanned surface in different locations. Other approaches involved using NURBS reverse engineering functions in SpaceClaim (v.19) to extract surfaces from the segmentation results.



(a) (b) (c)

(d) (e) (f)

Fig. 1: (a) CT scan, (b) Segmentation results, (c) Smooth segmented model post-refinement, (d) Skin surface using NURBS method, (e) Extracting curves using planes method, (f) Reverse engineered model of the leaflets area of the aortic valve.

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*General Training Model*:
Creating a CAD model from the segmented results can be challenging especially since the geometric information obtained for cardiovascular tissue is based on the blood volume (i.e. the internal lumen of the vessel) rather than the tissues of the vessel. This is similar to creating the shape of a cup by using only the contents after freezing it into ice – the internal shape is well defined, but the thickness and variations of the vessel must be artificially generated. Moreover, the timing of the CT scan and the image quality can impact the amount of the geometric information extracted. This is particularly true for analyzing the geometries of the leaflets of the aortic valve. Identifying the leaflets boundaries and the regions of valve coaptation was not possible using images from blood contrast CT scans. Therefore, we proposed that a relatively simple CAD model constructed from published geometric data of the human aorta and aortic valves could serve as the standard model for the surgical training setup. In future iterations, the basic model will be modified to create geometric abnormalities to represent pathologies that require surgical intervention.

The standard model schematic resembled a cylinder (Fig. 2(a)). This representation followed simplified anatomy of the key sections of the aortic root from Kerchove and El Khoury [2]. This design was further modified based on consultation with a cardiovascular surgeon. The geometry of the model was also inspired by data from Swanson and Clark [8] and Schäfers and colleagues [5].

Fig. 2 shows the initial aortic valve design taking into account all the necessary information that is relevant to a cardiac surgeon. Guided by Dr. Parry, the major dimensions of the model were simplified as much as possible. That is, the sinotubular junction (STJ) and ventriculo-aortic junction (VAJ) had the same dimensions at 25 mm. In addition, the middle section of the model had a diameter of 35 mm. The thicknesses of the major sections of the model were 0.5 mm for the leaflets, 2 mm for the walls of the sinuses and 3 mm for the walls of the aorta. Those dimensions were very close to values from Sauren and colleagues [4]. The initial design gained praises from the cardiac surgeons, and their feedback led to the development of the second CAD model. This model included a more realistic sinuses of Valsalva as well as a non-coronary sinus aneurysm. In addition, many aspects of the model were updated to allow for a parametric manipulation of the model dimensions.

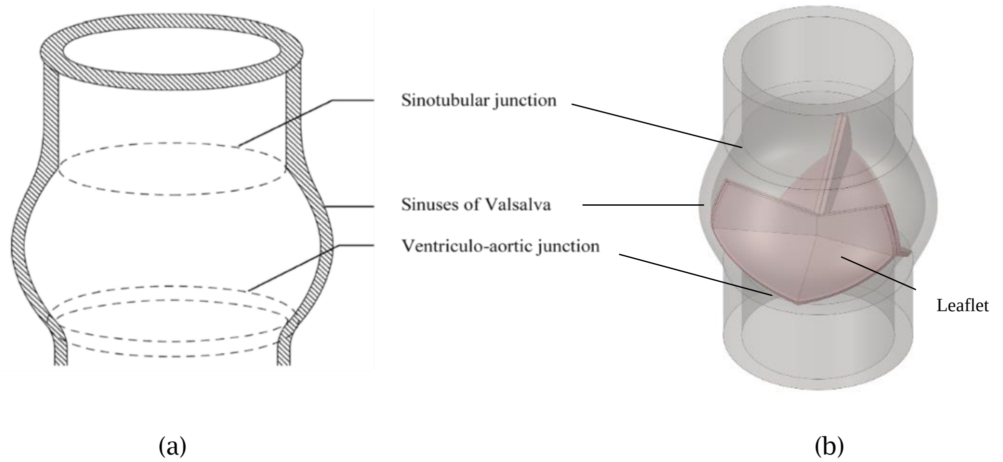


Fig. 2: (a). Simplified aortic root diagram [2], (b). Aortic valve CAD model.

*Training Setup Design*
The objective of this project was to create suitable training tools for cardiac surgeons. A visualization of the model can be seen in Fig. 3. The setup consisted of an extended aortic portion (including more of the ascending aorta to the aortic arch) and coronary arteries as well as a solid fixture that holds the aortic valve model in place. A prototype of the model was created by additive manufacturing with a compliant polymer material (Tango Plus, Stratasys [7]) with a shore-A hardness value of 27. The rigid training fixture

was 3D printed with polylactic acid (PLA). With the relatively rigid training fixture secured to a bench surface, the surgical trainees can cut and suture the compliant synthetic aortic tissue to practice and develop surgical procedures on a model that is relatively inexpensive and carries no risk to a patient.

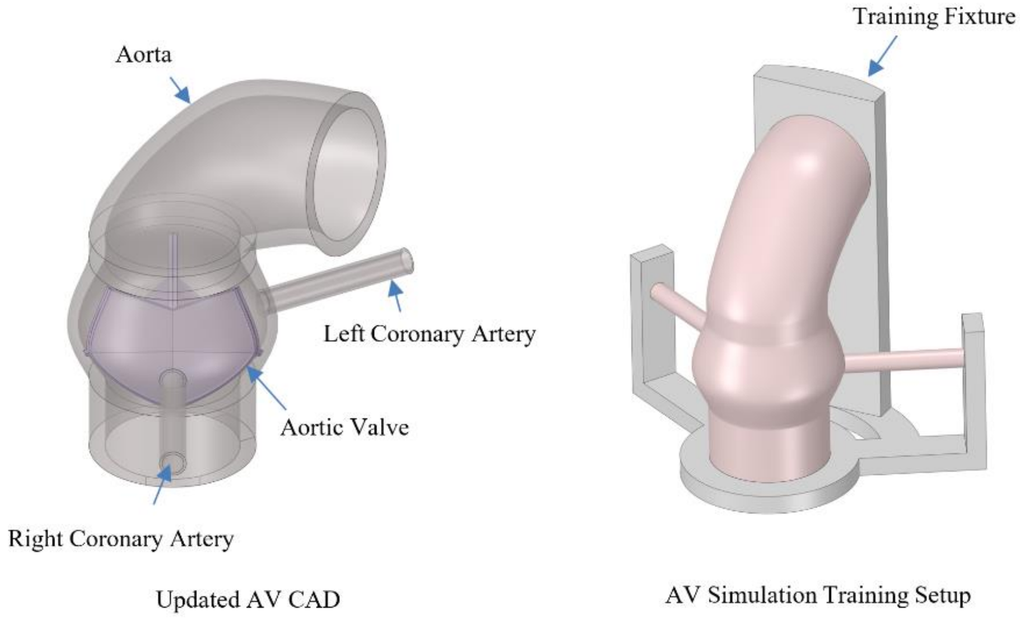


Fig. 3: Training setup design.

Conclusions:
The first step toward creating the educational cardiac tools was successfully realized. Several CAD models of the aortic valve were developed using different approaches. The patient-specific approach was able to produce results from medical imaging data, but the technological limitations can make this approach very challenging to use. On the other hand, a general training model can offer more flexibility for surgeons by mimicking different pathologies by modifying the CAD model of the aortic valve. The second approach produced promising results that can be further enhanced as part of our future work. Enhancing the CAD model of the aortic valve includes creating a library of different pathologies for the aortic valve surgery. Also, improving the model by adding realistic design features can increase the fidelity of the CAD model. The next step after preparing the CAD model is to create physical models using rapid prototyping techniques such as additive manufacturing.

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