Computational Modeling of Patient-Specific Aorta after Aortic Valve Replacement

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Hypothesis and Background :

- The aortic valve (AV) is susceptible to damage leading to failure due to the constant flow and movement of the heart. The failing AV can be replaced with a bioprosthetic valve, but research has portrayed the lack of knowledge of the causes of AV failure, and lack of knowledge on hemodynamic parameter's effect on patient's post-operation.
- Our goal is to observe the hemodynamic parameters in patients with AV replacement using cardiac-resolved CT data, 3D modeling, and computational fluid simulations. Two patients were included to this study : a patient with bicuspid aortic valve (BAV) repaired with a bioprosthetic valve by Edwards Lifesciences, and a patient with tricuspid aortic valve (TAV) repaired with a bioprosthetic valve by St. Jude Medical (Fig. 1).
- In this study, we focused on simulating blood pressure and wall shear stress (WSS), all which were hypothesized to introduce remodeling of the aortic wall.
- Observation of these effects on the patient can lead to further valve research, possible change of designs, and better patient outcomes.

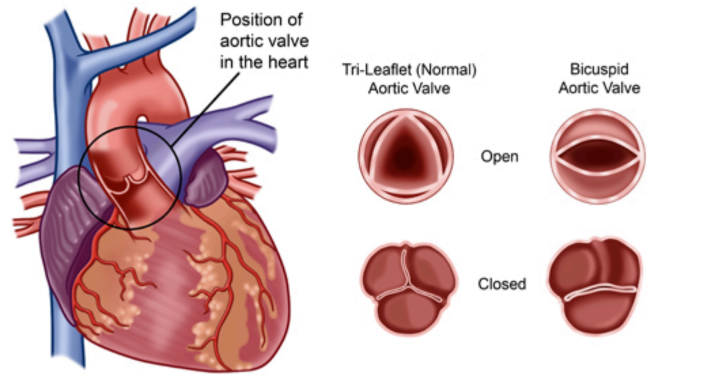
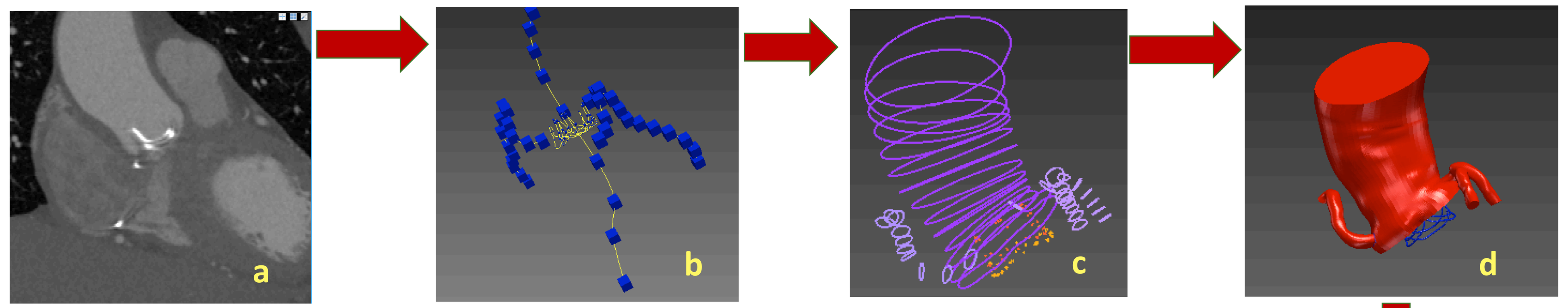
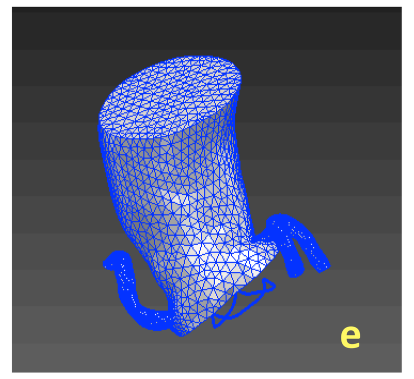


Figure 1. Anatomy of heart, aorta, BAV and TAV

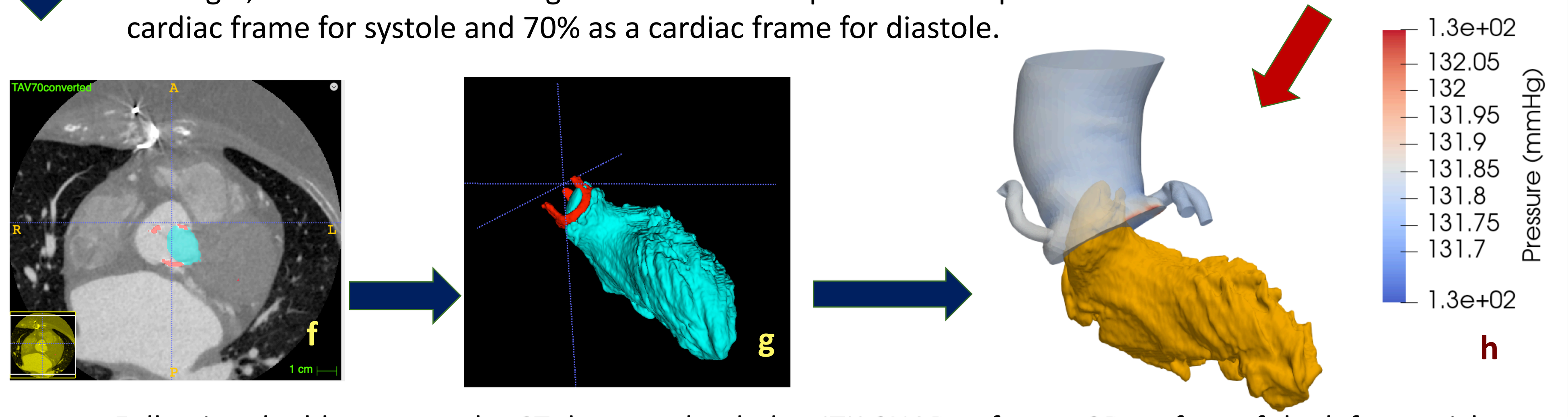
Methods:

Figure 2. Schematics of 3D modeling and computational fluid simulation





- CT data was loaded to SimVascular to form a 3D surface of aorta, coronary arteries, and valve components (a-e): Paths were constructed along the lumen of vessels, valve struts, and valve ring (a-b). Along the paths, bright lumen was segmented orthogonally (c). Segmented contours were lofted to form a 3D surface (d) and discretized into a mesh (e).
- Computational fluid simulation was performed on the mesh (e) with steady volumetric blood flow assigned at the aortic root, and resistance condition assigned at the aortic outlet and coronary arteries. We assumed that the wall was rigid, and blood was homogeneous and incompressible. We picked 30% as a cardiac frame for systole and 70% as a cardiac frame for diastole.



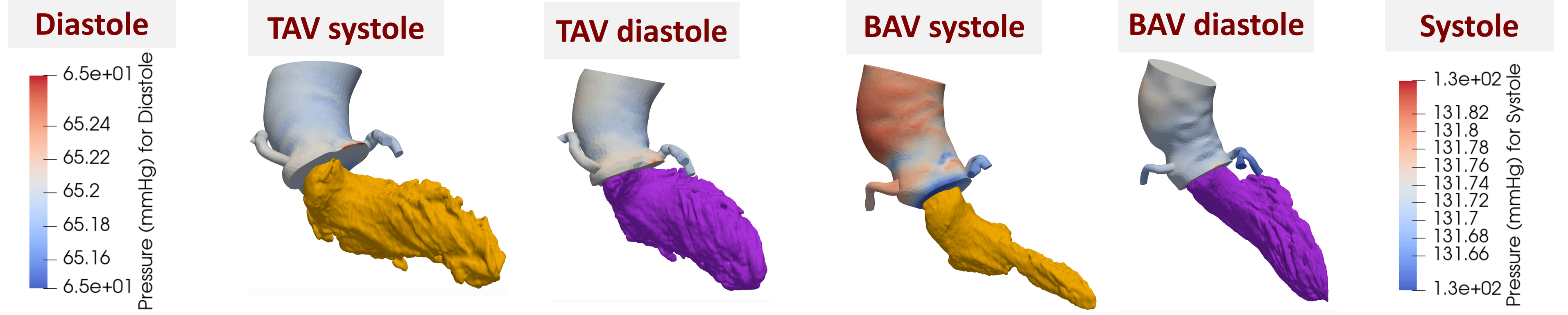
- Following the blue arrow, the CT data was loaded to ITK-SNAP to form a 3D surface of the left ventricle and aortic valve (f-g). A voxel was planted and filled the lumen until it reached the threshold, separately for the bioprosthetic valve struts and the left ventricle (g). These models were co-registered to SimVascular model (h).

With computational modeling we observed high pressure and high wall shear stress in systole for both BAV and TAV patients.

The metallic part of artificial aortic valve was in 3D motion during a cardiac cycle with potential deformation.

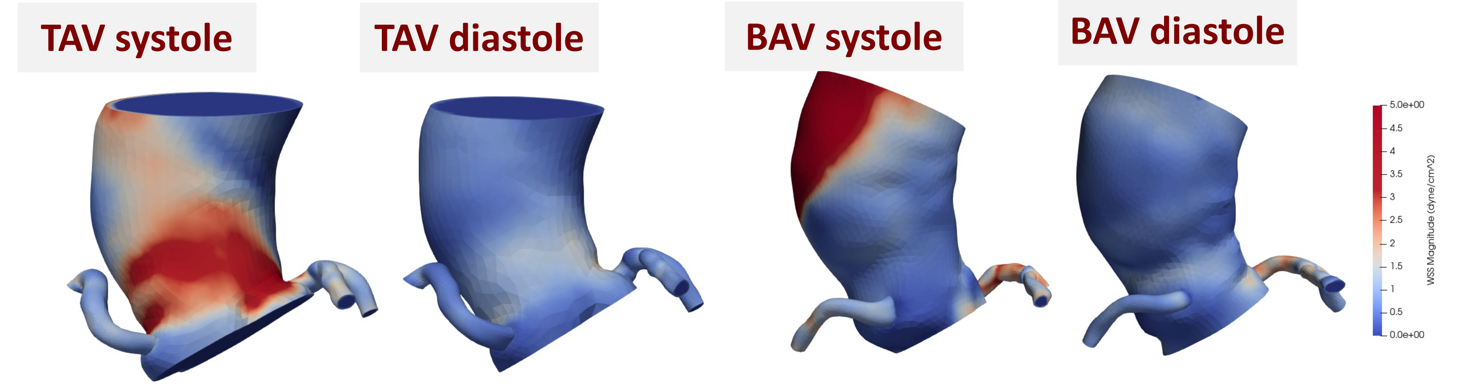
Results and Conclusions:

Figure 3. Simulated result: Blood pressure in the aorta and coronary arteries and left ventricular surface



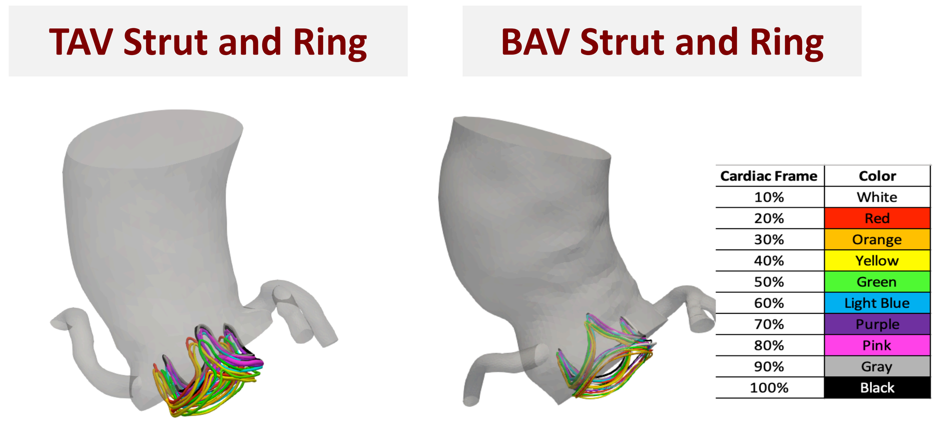
- In the BAV patient, we observed blood pressure in superior curve of the aorta at systole, while the TAV patient exhibited uniformly distributed pressure in the aorta with slight high pressure at the sinotubular junction at systole (Fig. 3). Consistently, high WSS was observed at the region of high blood pressure (Fig. 4).

Figure 4. Simulated result: Wall shear stress in the aorta and coronary arteries



- Guzzardi et al (2015) reported that higher wall shear stress leads to greater elastin degradation, which can lead to aortic wall remodeling to compensate for higher pressure due to cellular redistribution caused by elastin degradation

Figure 5. Models of bioprosthetic valve struts and rings

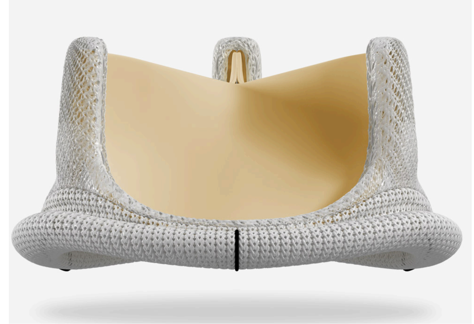


- The BAV and TAV strut and ring portray the deforming movement of the replaced AV during different cardiac cycles (Fig. 5).
- During systole, cardiac cycles 10-40%, deformation is prevalent between the 20% and 40% frame
- During diastole, cardiac cycles 50-100%, deformation is prevalent between 50% and 60% frame.

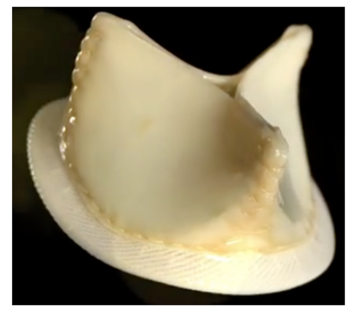
Future Work:

- As a part of our future work, we plan to improve simulation using further sophisticated boundary conditions with pulsatile blood flow, or deforming wall.
  - These simulations more accurately represent a heartbeat when compared to a rigid wall simulation shown above, increasing our knowledge of replaced AV during simulation
- We also plan to create 3D models of the leaflet, or cusps, of the artificially replaced AV seen in the valve designs below and combine with SimVascular models to run more realistic simulations.

Edward Lifesciences Carpentier-Edwards Magna Pericardial Aortic Valve (21 mm)



St. Jude Medical's Trifecta GT Aortic Valve (21 mm)



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