Computational Modeling of Patient-Specific Aorta after Aortic Valve Replacement

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Abstract:
Aortic valve replacement is surgery for patients with a malfunctioning native aortic valve, located between the left ventricle and aorta. Advances in replacement surgery have led to various techniques, and one common technique is open-heart aortic valve replacement using a bioprosthetic valve. Despite the 55-57% chance of survival for patients ten years post-operation, the main contributor for valve failure is yet unclear. As the aortic valve is located at the most active and pulsatile location, it is possible that blood flow through the bioprosthetic valves play an important role, and even affects the downstream vasculature. Understanding key parameters of hemodynamics, such as wall shear stress or kinetic energy is essential since they introduce cellular re-distribution on the aortic wall, or facilitate leaflet tearing and leakage of bioprosthetic valves. Such comprehension will help us to project the potential effect of aortic valve replacement in the long term.
Our aim is to model patient-specific aorta, valve, and heart, and perform computational simulation to estimate the key hemodynamic parameters. With this information, we seek to answer the effects of altered hemodynamics on the downstream vessel. We hypothesize that wall shear stress and kinetic energy distribution distal to the bioprosthetic valve will depend on the angle of jet flow during ejection, and shape of aorta and valve.
Computational modeling and simulation were performed using custom software SimVascular, itK-SNAP, and ParaView. 3D models of aortic valve, aorta, coronary arteries, and left ventricle were constructed based on cardiac-resolved computed tomography (CT) angiography. CTs were acquired from two different patient types, bicuspid aortic valve (BAV) and tricuspid aortic valve (TAV); each had ten frames of CT to resolve a cardiac cycle. Next, boundary conditions were chosen to mimic physiologic blood flow inside the 3D model for analysis. We started with steady flow and rigid wall conditions, then will advance to pulsatile flow and deformable wall conditions.
We successfully constructed 20 models and visualized their active geometries during a cardiac cycle. We observed a dilated aorta in both BAV and TAV cases which may indicate aortic wall remodeling, as well as the dynamic motion of coronary arteries. Preliminary flow simulation was performed to seek boundary conditions for vessel outlets which mimic physiologic hemodynamics. These preliminary results will lead our study to perform simulation using realistic boundary conditions, and replicate

hemodynamics in the aorta and left ventricle. These results will help analyze blood flow post operation, and even find the possible relationship with valve failure such as valve degeneration and leaflet tearing. Our patient-specific analysis may benefit clinicians and device manufacturers by providing the key hemodynamic parameters for design improvement.