Lars Walczak*, Leonid Goubergrits, Markus Hüllebrand, Joachim Georgii, Volkmar Falk and Anja Hennemuth

Using position-based dynamics to simulate deformation in aortic valve replacement procedure

https://doi.org/10.1515/cdbme-2020-0042

Abstract: We present a novel approach to simulate deformation in aortic valve replacement scenarios with applications in operation planning and batch domain creation for large computational fluid dynamics studies of the aortic arch.

Keywords: aortic valve replacement; computational fluid dynamics; position-based dynamics.

Introduction

Aortic valve replacement (AVR) aims to restore normal function of the diseased aortic valve. However, post-treatment analysis frequently found abnormal flow profile after surgical AVR [1]. Model-based therapy planning is able to optimize treatment and thus improve patient outcome. During AVR, the aortic valve annulus is deformed by and fitted to a rigid ring of the biological or mechanical aortic valve prosthesis. The device implant replaces the function of the biological aortic valve. Finding the right size of an implant, a good placement, and a good angulation of the device is not an easy task even for experienced surgeons. To analyze possible outcomes before the physical implantation, computer simulations have to be conducted and the resulting deformation as well as blood flow have to be predicted approximately. This requires a huge number of simulations in individually deformed aorta representations. For each simulation setup, a volumetric mesh triangulation based on a deformed representation of the aorta and the device implant has to be created.

To achieve the goal, we present a novel method that allows to create deformed surface representations of soft bodies such as the aorta. Resulting deformations conform to the shape of a rigid object such as a replacement aortic valve. The execution time of our approach is relatively low and, therefore, deformations can be calculated quickly. The method is tailored towards usage in computational fluid dynamics (CFD) domain creation where special constraints on the mesh topology and quality exist. The method is not limited to this specific application, but can be used in any application where rigid objects need to be placed inside deformable objects. Here, the artificial valve can be placed in different angulation to analyze the impact in blood flow simulations with respect to flow velocities and derived values such as wall shear stress. The CFD simulations themselves are presented elsewhere [2].

Methods

We split this section into the descriptions of the two main aspects. One section describes the generation as well as the geometric alignment process of aorta and valve model. The other section describes the simulation approach used for the deformation of the model created in the prior step. The simulation approach has not been used before in this context.

Model setup

We use semi-automatic 3D reconstruction based on patient-specific CT or MRI data for generating computational models for the aorta. The aorta model is represented as a surface mesh and consists of a set of vertices, edges, and triangles. The aorta model does not include the model of the diseased aortic valve.

The triangular surface mesh for the Magna Ease replacement valve (Edwards Lifesciences, USA) in its open state was reverse-engineered using micro computed tomography, cf. Figure 1A. A sample with 21 mm diameter was scanned for reference. Since the valves are available in different sizes from the manufacturer, we scale

***Corresponding author: Lars Walczak,** Charite - Universitätsmedizin Berlin, Berlin, Germany; and Fraunhofer Institute for Digital Medicine MEVIS, Bremen, Germany, E-mail: lars.walczak@charite.de
Leonid Goubergrits, Charite - Universitätsmedizin Berlin, Berlin, Germany
Markus Hüllebrand and Anja Hennemuth, Charite - Universitätsmedizin Berlin, Berlin, Germany; Fraunhofer Institute for Digital Medicine MEVIS, Bremen, Germany
Joachim Georgii, Fraunhofer Institute for Digital Medicine MEVIS, Bremen, Germany
Volkmar Falk, Charite - Universitätsmedizin Berlin, Berlin, Germany; German Heart Institute, Berlin, Germany

(a) Valve model (b) Valve model and center-line (c) Valve model placement

Figure 1: (a) Detail view of Magna Ease valve model. Both edge loops in the annulus region are depicted. The two spheres indicate the size of the bounding box in which the deformation will be calculated. **(b)** View of center-line $\mathbf{f}(s)$ and aligned valve. **(c)** Placement of the valve along the center-line inside aorta model.

the model uniformly to the desired size. The usage of other models of replacement valves is possible as well.

To prepare the implantation process, the replacement valve can be placed (manually or automatically) along the path of the aorta center-line, cf. Figure 1B and C. For a manual placement, the center-line is interpreted as a parameterized curve $\mathbf{f}: \mathbf{R} \mapsto \mathbf{R}^3$. The interpolation parameter $s \in [0, 1]$ is used for positioning the valve at position $\mathbf{f}(s) \in \mathbf{R}^3$, the tangent, normal and bi-normal are referred to as $\mathbf{t}(s)$, $\mathbf{n}(s)$ and $\mathbf{b}(s) = \mathbf{t}(s) \times \mathbf{n}(s)$ (TNB frame). Automatic positioning is possible using a local minimum of the center-line radius. Using the local coordinate system induced by the TNB frame of the center-line and the local coordinate system of the valve (its main axis is oriented according to the opening, i.e. the main flow direction through the valve, its origin is located in the center of gravity), we use basis transformation to align the model to the curve and translate it to position $\mathbf{f}(s)$. In addition, we allow changes to the orientation of the valve. In particular, the valve can be rotated around the center-line tangent $\mathbf{t}(s)$ and can be tilted relative to $\mathbf{t}(s)$. Translation of the valve's origin in the plane defined by $\mathbf{n}(s)$ and $\mathbf{b}(s)$ at position $\mathbf{f}(s)$ is possible as well. The whole process can be automated by choosing the angles and offset in a random fashion. After this, the geometry is setup for simulation of deformation due to valve placement.

Valve replacement simulation

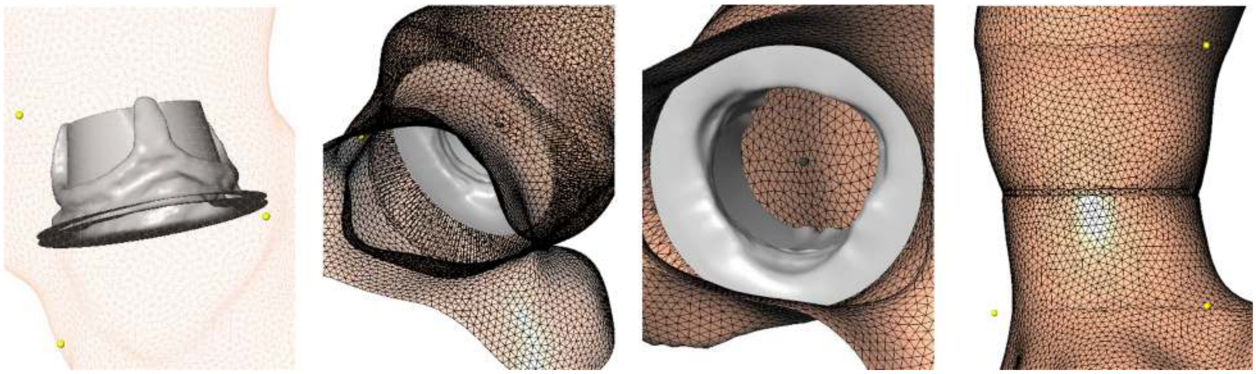
Since the general simulation approach follows the one presented in [3] in the context of mitral valves, we briefly summarize the changes for applying the method to simulate deformation for AVR. In general, depending on the mesh size, the method can be executed at interactive frame rates on current PC hardware which enables us to reduce the time spent for creating the deformed meshes for CFD. This allows for a larger set of models with varying valve angulation to be analyzed. Processing and simulation are implemented using the MeVisLab platform [4].

Using the approach in [3], the aorta shape is approximated by the triangular mesh created in section 2.1 and can be deformed. The valve model created in section 2.1 acts as a rigid body. The initial state is referred to as $t = 0$ and the simulation creates a deformed result at $t > 0$.

The reconstructed mesh of the aorta is augmented with a set of constraints modeling a simplified material for the aortic wall. These constraints relate multiple vertices to each other. The vertices are assigned mass, position and velocity. The extended position-based dynamics (XPBD, [5]) approach taken in [3] uses linearly elastic distance constraints, bending constraints as well as area conservation constraints to model the mitral valve material. The same modeling is used here for the vessel wall, cf. distance constraints shown as edges in Figure 2A–D. Contact between wall and valve is modeled using collision constraints. External forces can be defined for deformation, e.g. a pressure force can drive the aorta model to narrow or widen its diameter.

To allow for building a surface mesh that serves as a basis for CFD volume mesh generation, the surface mesh of the valve does not form a closed surface, instead it features two free edge loops where the connections to the aorta are placed. This is referred to as the annulus side. The surface is not connected at the annulus side to create the right topology for domain creation, cf. Figure 1A. The two free edge loops in this area can be connected to the outer aortic wall. Here, we use distance constraints with zero rest length between the vertices of the non-manifold boundary edges of the valve mesh and the aorta to simulate sewing. The distance constraints are created by casting rays radially outward from each of the boundary vertices, cf. Figure 2B. The direction is found by forming the cross product of $t(s)$ (TNB frame of the curve and valve are aligned) and the direction of the adjacent edge. The total number of rays is equal to the number of vertices in both edge loops. There are two alternatives for the further processing of the mesh. Either we apply nearest neighbor search for the definition of the distance constraints (remember these connect two vertices), or we subdivide the triangles, create new vertices, and perform mesh post-processing to ensure consistent topology.

In the first case, the closest vertex of the aorta mesh to the hit position of the ray is connected with the boundary vertex and forms a new distance constraint. This implies that multiple boundary vertices can be connected to the same vertex of the aorta mesh, depending on the ratio of boundary vertices to vertices next to the projection of the boundary onto the aorta mesh. For the deformation this is not an important factor, but for domain creation. Since we want to achieve the correct topology for CFD domain creation, this will not result in the



(a) Valve Placement (b) Ray casting connections (c) Deformation (inside) (d) Deformation (outside)

Figure 2: **(a)** Detail view of Magna Ease valve placed inside of aorta model. **(b)** View of ray connections inside aorta model. The connections reach from the vertices of the non-manifold edges radially outward towards the wall. **(c)** Deformation of aorta model (inside view). The gap between wall and valve has been closed, the connections are not visible anymore. Both structures meet at the diameter of the replacement valve. **(d)** Deformation of aorta model (outside view). Compared to the initial state, the aortic wall now meets with the outside diameter of the replacement valve.

correct topology. By applying constructive solid geometry operations, in particular a Boolean union operation, on both meshes afterwards, we can ensure correct topology.

The second alternative uses triangle subdivision to create new vertices. In this case, we have to refine the triangle hit by the ray and subdivide the hit triangle into three new triangles. The fourth new vertex is positioned inside the hit triangle at the hit position. To clean up the mesh topology after refinement, we apply series of post-processing operations such as edge contraction or edge flipping to ensure correct topology, cf. Figure 2D.

In cases where the diameter of the valve implant is larger than that of the aorta at the chosen center-line position and orientation, or the shape of the aortic wall is not convex and, therefore, no placement of the valve that lies fully inside of the aorta mesh can be found, the size of the implant can be scaled to the final size, beginning at a diameter that is known to fit into the aorta. By expanding the rigid body, the collision constraints ensure a simultaneous expansion of the aorta mesh. To limit the computational effort further, a bounding box with an appropriate size can be placed around $\mathbf{f}(s)$, cf. spheres shown in Figure 1A. The bounding box vertices are shown as yellow spheres, e.g., in Figure 2A.

Results

We initially applied the method to a set of ten patient-specific aorta models and assessed the resulting meshes by visual inspection. The deformation in the chosen parameterization seemed plausible, cf. Figure 2C, D. We achieved a smooth transition between fixed and deformed parts of the aorta mesh. The gap between valve and aorta was closed. There were no intersections between the rigid body valve mesh and the soft body aorta mesh. The time needed to create one simulation domain from alignment to convergence was below 30 s.

Both alternatives for sewing are suitable for domain creation. Using the refinement method in combination with some of the test meshes and some valve orientations, the correct topology could not be ensured by the implemented limited set of mesh post-processing methods and required manual mesh repair for one or two faces.

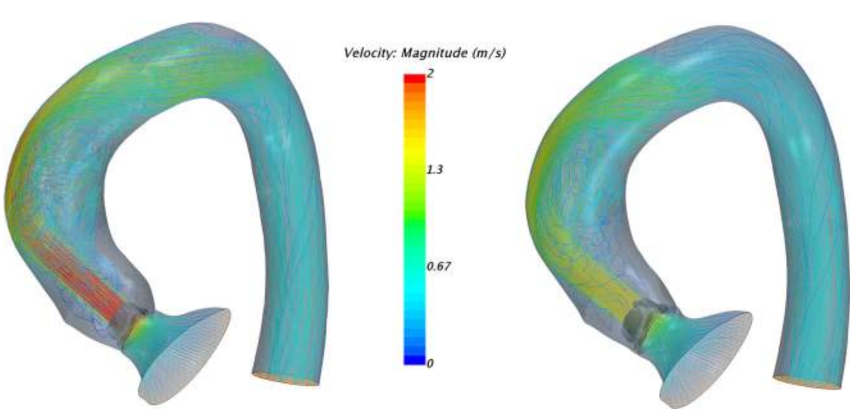


Figure 3: Streamline view of the CFD results using two different valve sizes (18 mm on the left and 20 mm on the right). Velocity magnitudes are much higher using the valve with the smaller diameter which is directly associated with a higher transvalvular pressure gradient (17 vs. 9 mmHg).

Figure 3 shows CFD results with two different valve sizes (18 and 20 mm) in a second aorta model and at the same location. The 2 mm size difference in valve diameter is responsible for reducing the pressure drop across the valve from 17 to 9 mmHg which is almost a factor of two.

Conclusion

We presented a novel method for the deformation of mesh representations of the aorta with applications in AVR CFD modeling and beyond. The resulting deformations are plausible and are suitable for CFD domain creation. To avoid manual mesh repair using the second alternative, further post-processing options are necessary to ensure the correct topology in all cases and orientations. We will address this aspect in the future. Compared to a manual domain setup using a 3D software, the amount of work for creating hundreds of simulation domains is significantly reduced using our approach and enables conducting larger CFD studies in the future.

Research funding: This work is part of the BMBF VIP+ projects DSS Mitral and TRANSNAV (partially funded by the German Federal Ministry of Education and Research).
Author contributions: All authors have accepted responsibility for the entire content of this manuscript and approved its submission.
Conflict of interest: The authors declare that they have no conflict of interest.
Informed consent: Informed consent was obtained from all individual participants included in the study.
Ethical approval: All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

References

1. Nordmeyer S, Hellmeier F, Yevtushenko P, Kelm M, Lee CB, Lehmann D, et al. Abnormal aortic flow profiles persist after aortic valve replacement in the majority of patients with aortic valve disease: how model-based personalized therapy planning could improve results. a pilot study approach. Eur J Cardio Thorac Surg 2020;57:133–41.
2. Yevtushenko P, Hellmeier F, Bruening J, Nordmeyer S, Falk V, Knosalla C, et al. Surgical aortic valve replacement: are we able to improve hemodynamic outcome?. Biophys J 2019;117: 2324–36.
3. Walczak L, Georgii J, Tautz L, Neugebauer M, Wamala I, Sündermann S, et al. Using position-based dynamics for simulating the mitral valve in a decision support system. In: Eurographics workshop on visual computing for biology and medicine. The Eurographics Association; 2019.
4. Ritter F, Boskamp T, Homeyer A, Laue H, Schwier M, Link F, et al. Medical image analysis. IEEE Pulse 2011;2:60–70.
5. Macklin M, Müller M, Chentanez N. XPBD: position-based simulation of compliant constrained dynamics. In: Proceedings of the 9th international conference on motion in games; 2016, pp. 49–54.