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A Computational Analysis of Annuloplasty in Bicuspid Aortic Valve Regurgitation

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01 Introduction

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Background

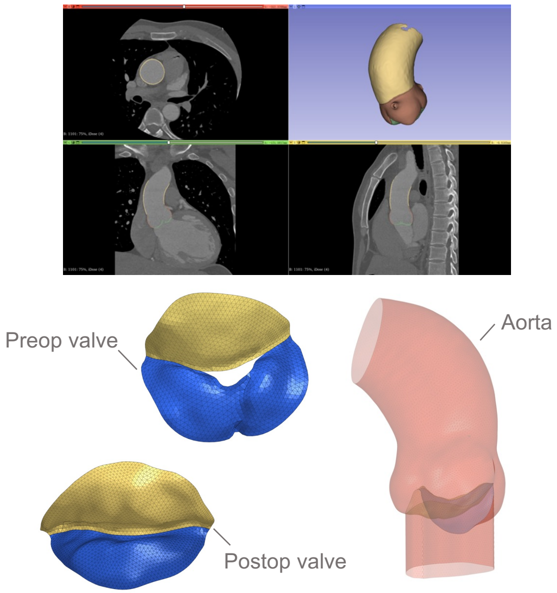
- Bicuspid aortic valve (BAV) is a prevalent cardiac anomaly observed in 0.5%–2% of adults[1].
- 13%-32% of BAV patients experience moderate to severe aortic regurgitation (AR)[2].
- Annuloplasty is crucial for stabilizing the annulus and ensuring the long-term durability of BAV repair[3].
- The optimal size of annuloplasty remains undetermined.

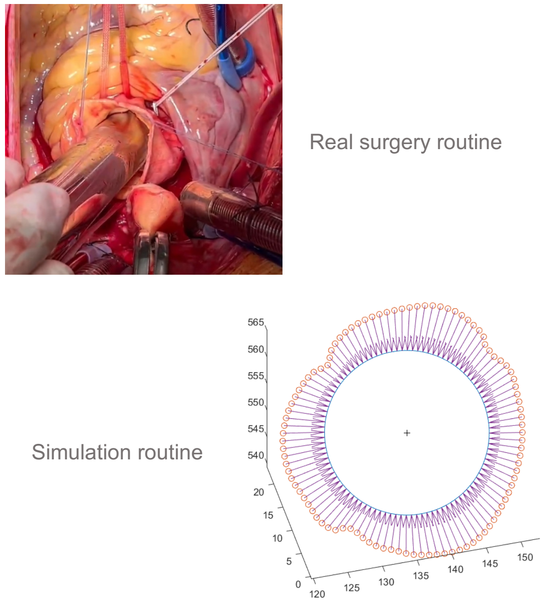
Purpose of this work

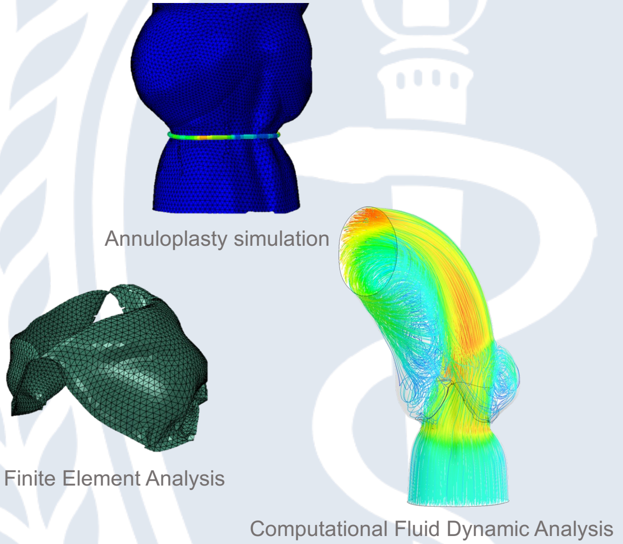
- Create a patient-specific model for BAV
- Use numerical simulation to assess the impact of different annuloplasty sizes on treating BAV regurgitation
- Provide optimal threshold range for annuloplasty size in clinical practice.

Ref
[1] Braverman AC et al. *Curr Probl Cardiol* 2005
[2] Masri A et al. *Heart* 2017
[3] Ehrlich T et al. *Progress in cardiovascular diseases* 2020

02 Methods: Overview







Modeling

Create patient-specific models based on CT image.

»

Routine Planning

Calculate annuloplasty pathways for annular plane.

»

Simulation

Conduct computational analysis to gain mechanical and hemodynamic results.

02 Methods: Modeling

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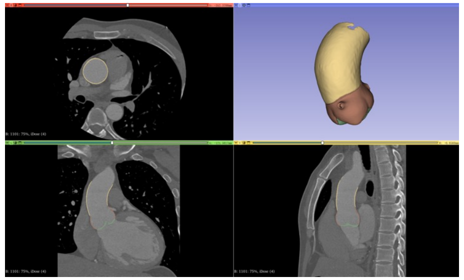
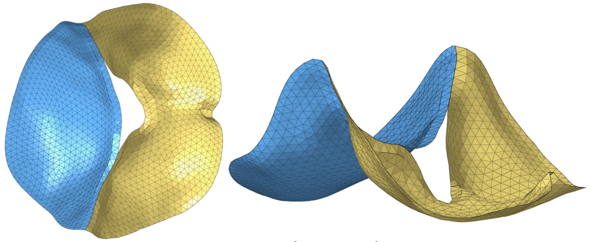
Modeling procedure

- Outline the valve, sinus and ascending aorta at 75% of the cardiac cycle in CT images
- Reconstruct the pre- and post-operative model respectively in the software 3Dslicer
- Smooth and mesh the models for further simulation

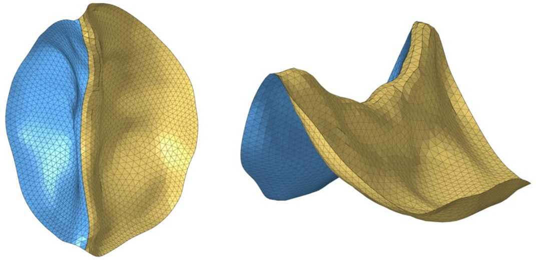
Patient-specific Models



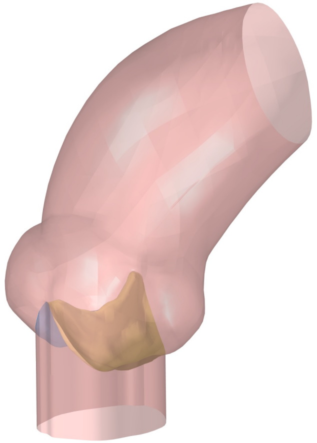
Software 3Dslicer



Pre-operative Valve



Post-operative Valve



Postoperative Aorta

Patient Information

- ✓ 35-year-old male
- ✓ Severe bicuspid aortic valve regurgitation
- ✓ Underwent annuloplasty at the level of basal ring
- ✓ Underwent pre- and post-operative ECG gated MSCT

02 Methods: Routine Planning

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Surgical procedure

Use a **circular steel column** with a diameter of 19-32mm to remold the annular plane.

Routine planning for simulation

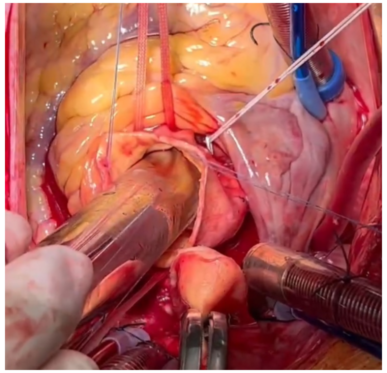
Follow the surgical procedure to plan the annuloplasty simulation routine.

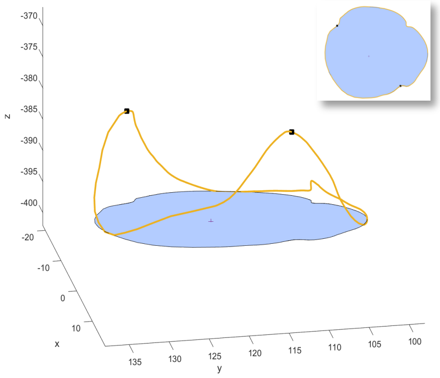
STEP 1	**Project** the annulus curve onto the annular plane.
STEP 2	Create a ring and **register** it with the annular plane.
STEP 3	**Calculate** the pathway based on an optimal algorithm.

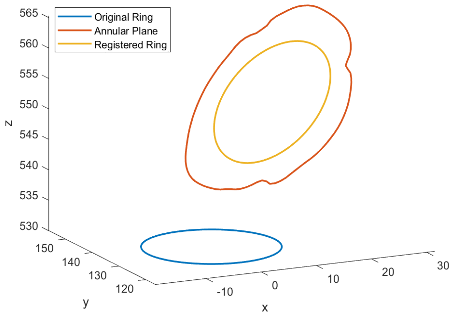
Algorithm:

$$\underset{\varphi\in[0,1)}{\arg\min}\int_0^1 \left\| s_{\text{annulus}}(u)-s_{\text{ring}}(u+\varphi)\right\|_2^2 du$$

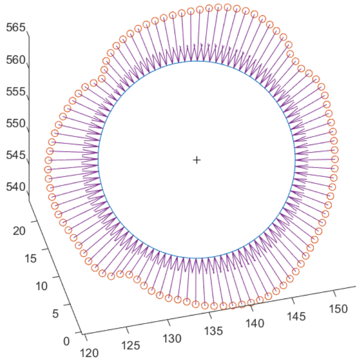
u : Normalized arc length parameter
$\mathbf{s}_{\text{annulus}}(u)$ and $\mathbf{s}_{\text{ring}}(u)$: 3D annular spline curves
φ: A shift in the relative parameterization between curves
$\|\cdot\|_2$: Euclidean norm


Surgical Procedure


STEP 1



STEP 2


STEP 3

02 Methods: Simulation

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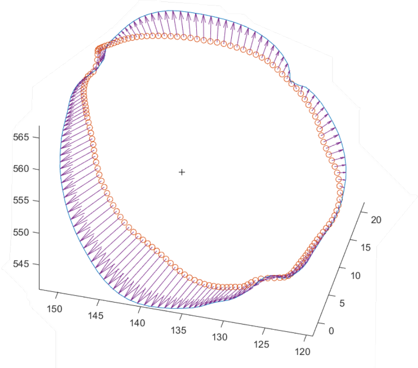
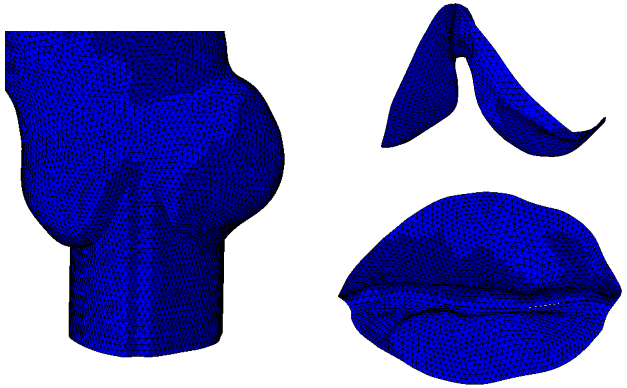
Preprocessing

Expand the annulus of the post-operative model to align with the pre-operative annulus.



Expansion Routine

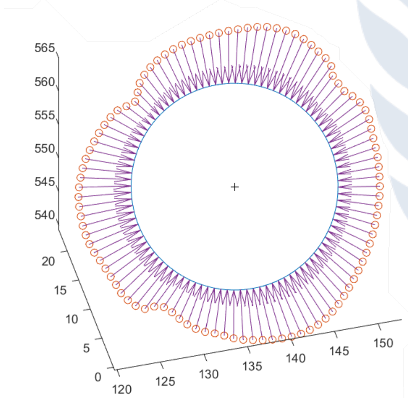


Preprocess Animation *[click]*

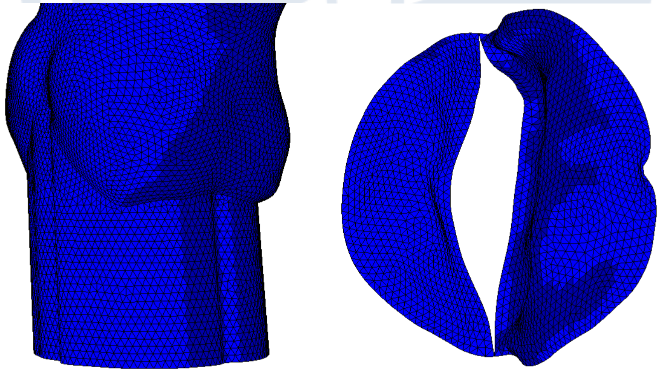
★ **Aim for Preprocessing:**
Obtain a model underwent **raphe relaxation** and **the free margin plication**.

Annuloplasty simulation

- Create **elastic rings** with diameters of 19-27 mm
- Remold the annular plane along the planned routine
- Constrain the annular plane by the elastic rings



Annuloplasty Routine for 23mm Ring



Annuloplasty Animation *[click]*

02 Methods: Simulation

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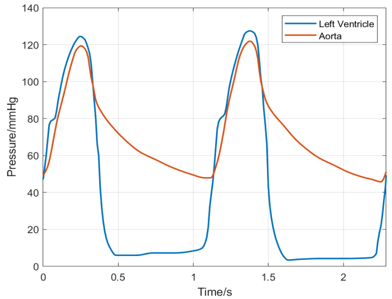
Finite Element (FE) Analysis

Simulate the motion of BAV after annuloplasty within two cardiac cycles

- Material
  - ✓ BAV: Mooney-Rivlin hyperelastic model
  - ✓ Aorta & Ring: linear elastic model
- Boundary condition
  - ✓ Transvalvular pressure drop curve was applied on the leaflets
  - ✓ Inlet and outlet of the aorta were fixed
  - ✓ Rings could move following the aorta

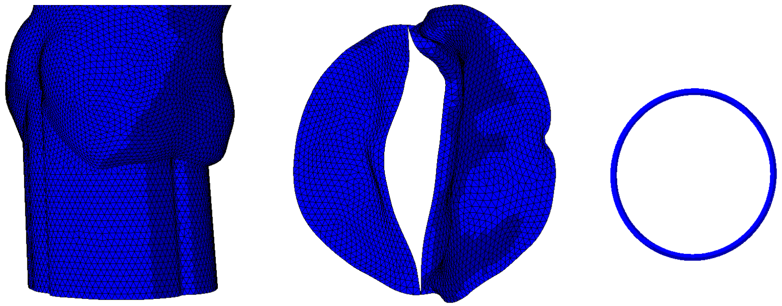


patient-specific pressure curve

Computational Fluid Dynamic (CFD) Analysis

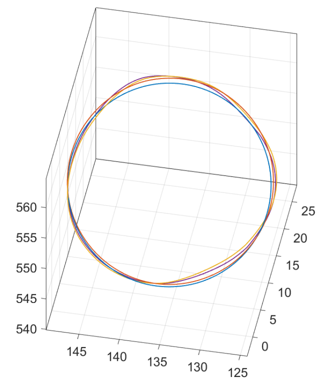
Obtain hemodynamic results at peak systole

- Material
  - ✓ Blood: incompressible Newtonian fluid turbulence model
- Boundary condition
  - ✓ Aortic Inlet: flow-rate
  - ✓ Aortic Outlet: pressure

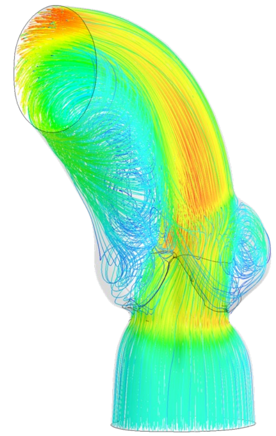


Aorta Valve Ring

Complete FE Analysis Animation *[click]*



Ring Motion



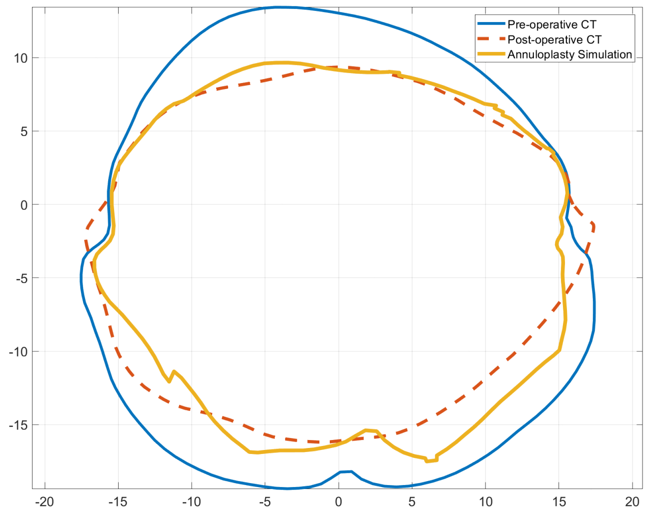
Streamline Result of CFD Analysis

03 Results: Model Validation

The patient underwent annuloplasty surgery using a **23mm-sized steel column**

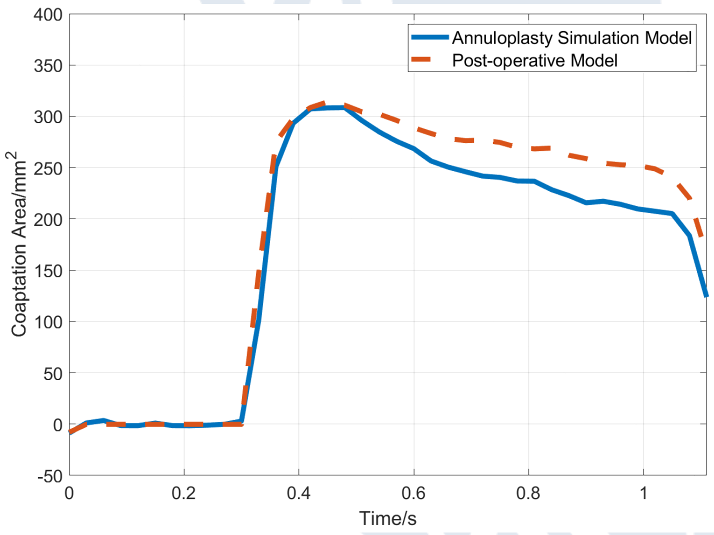
Compare **the 23mm annuloplasty simulation model** with the **post-operative model**

Projection of the annulus on the annular plane



✓The projection shapes were essentially consistent
✓Projected area relative error: 2.84%

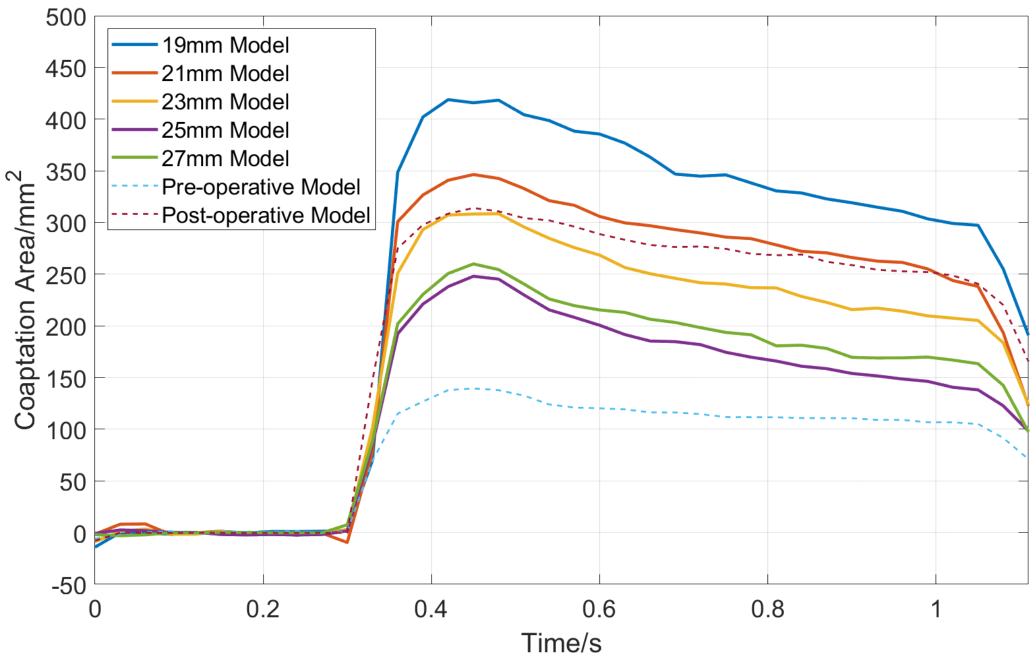
Coaptation area of the leaflets in a cardiac cycle



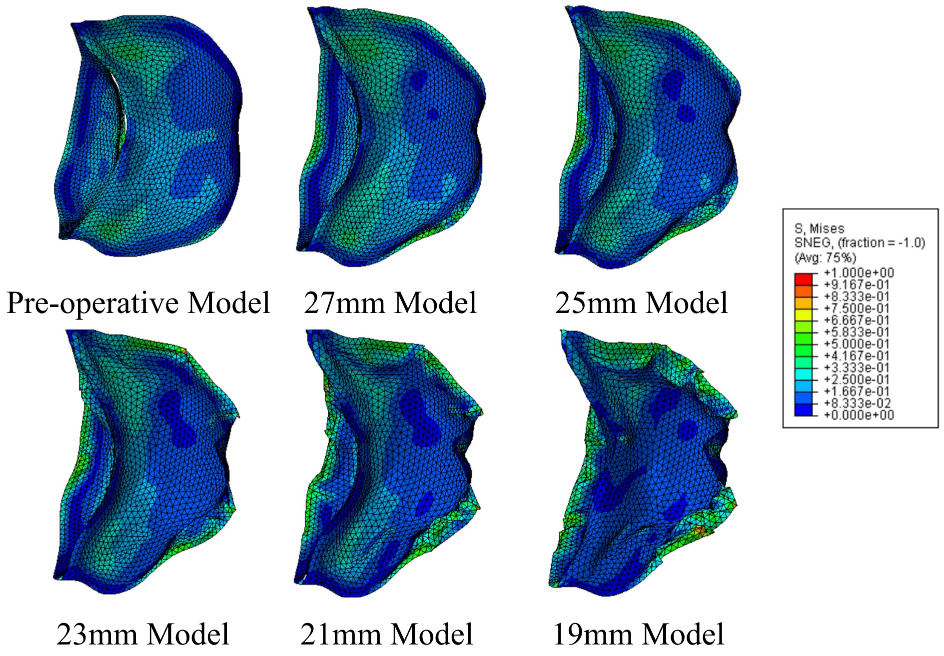
✓Maximum values were close
✓Trends of change were consistent

03 Results: Valve

Coaptation area of the leaflets



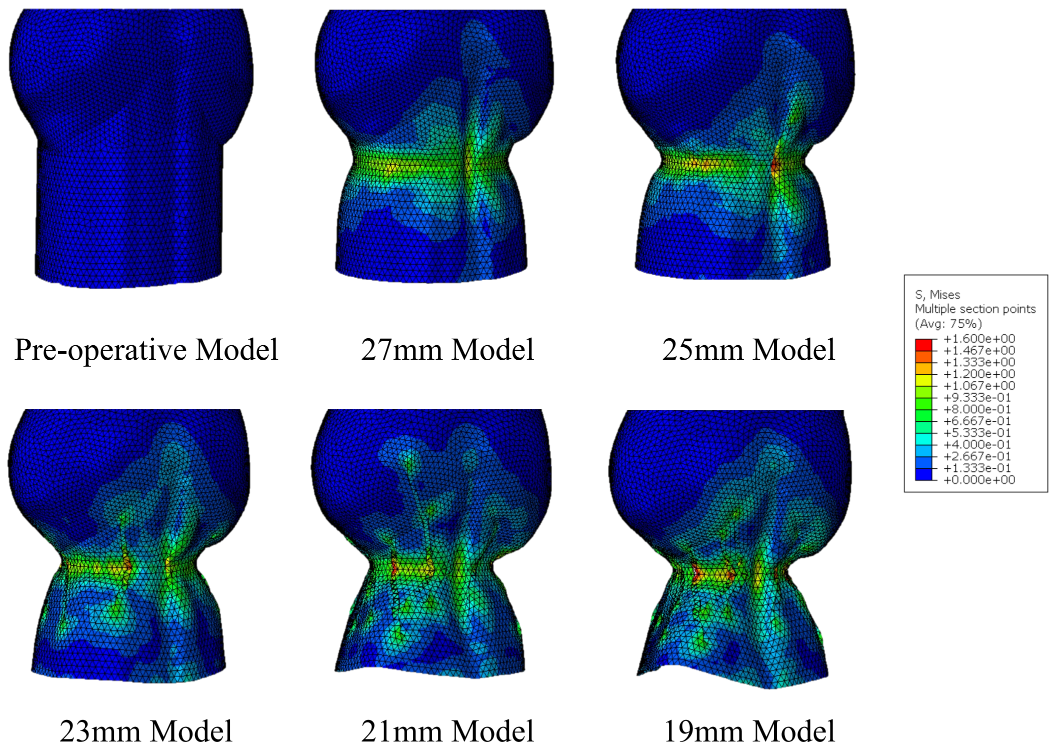
Stress distribution of the valve



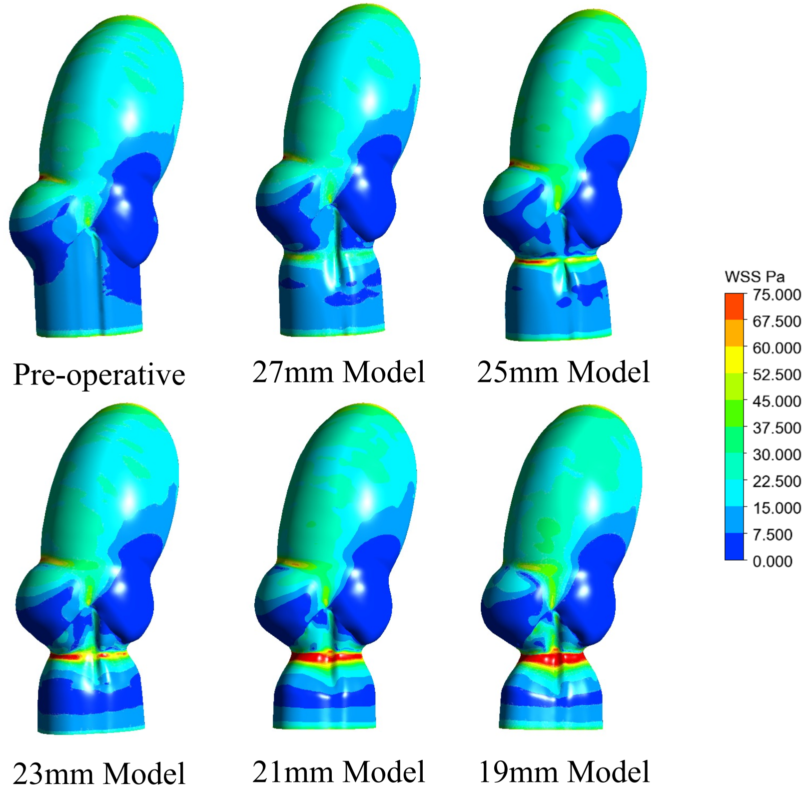
- As the annuloplasty ring shrank, leaflet coaptation area increased, lowering stress there.
- Folds at the leaflet root intensified with ring diameter below 23mm.

03 Results: Aorta

Stress distribution of the aorta root



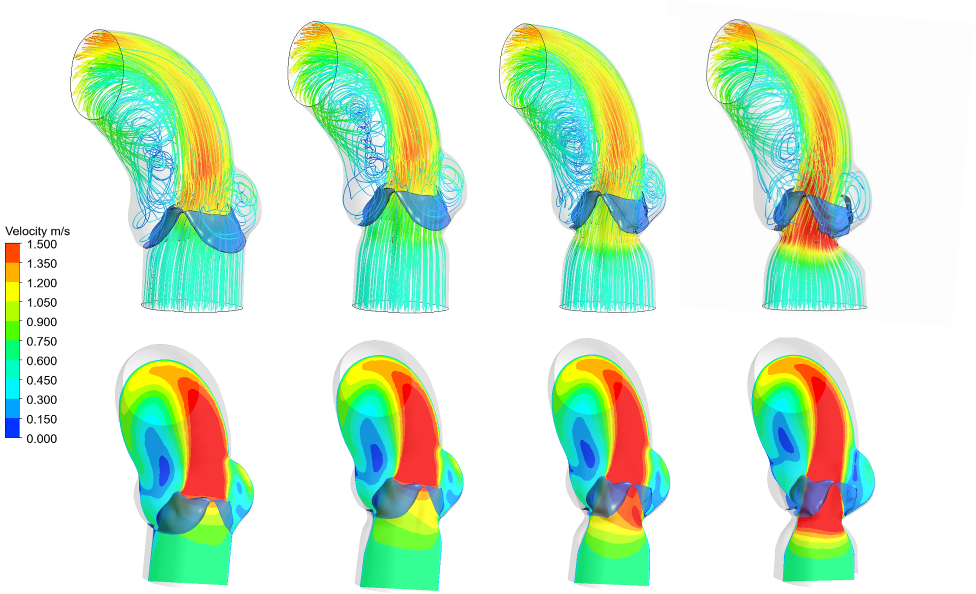
Wall shear stress of the aorta



- With enhanced annular remodeling, the annular plane experienced stress concentration, leading to an increasement in Mises stress and wall shear stress in the adjacent region.

03 Results: Blood Field

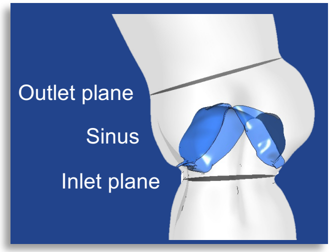
Streamline and velocity profile

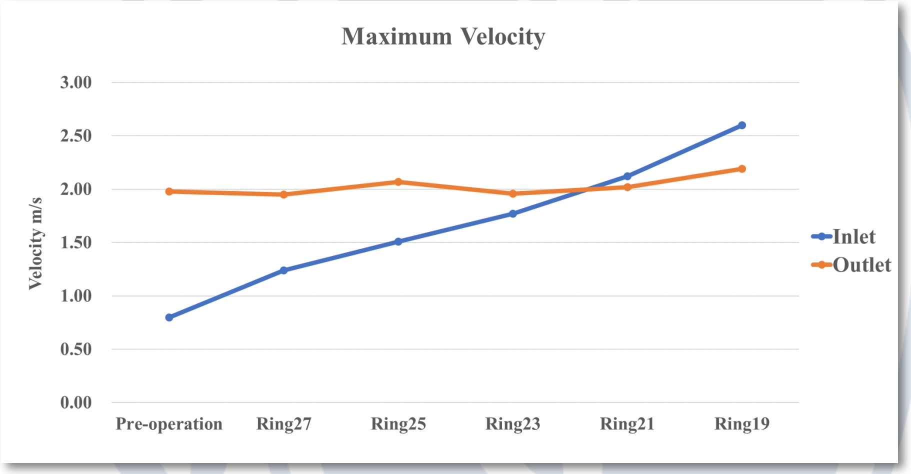


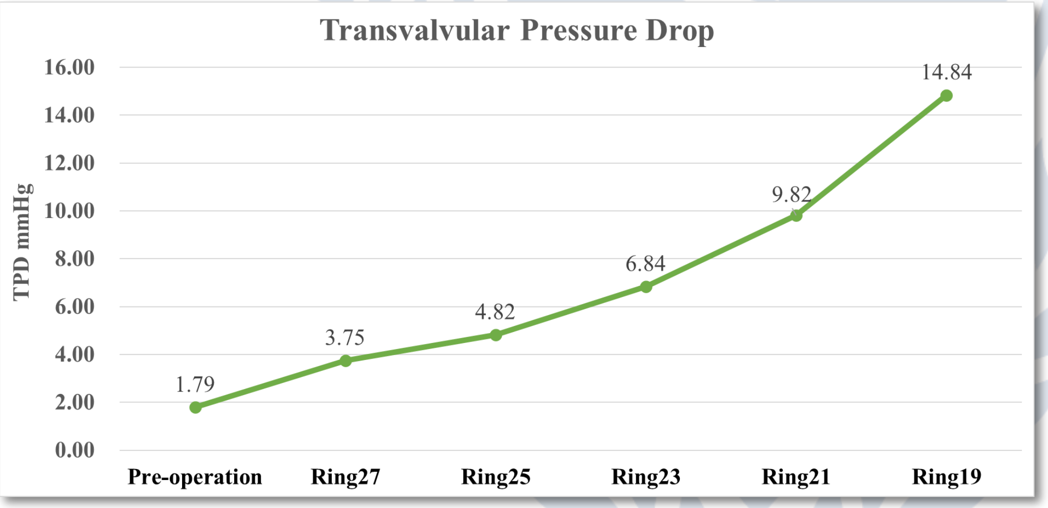
Pre-operative Model 27mm Model 23mm Model 19mm Model

- As the ring size reduced, flow velocity increased in the sinus and remained unchanged in the ascending aorta.
- Transvalvular pressure drop decreased after annuloplasty.

Other Parameters







04 Conclusion

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For the selected patient:

- Smaller-sized ring have benefit on **improving leaflet coaptation area** and **mitigating of leaflet stress and transvalvular pressure gradient**.
- Excessively small ring may result in **leaflet folding at the root** and **wall shear stress increasement at the annular plane region**.

Personalized annuloplasty simulation may be a valuable tool to provide **optimal size threshold** for individual patients before surgery.