12th European LS-DYNA Conference 2019
14-16 May 2019
Koblenz (Germany)

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The effect of element formulation on FSI heart valve simulations

Giulia Luraghi
Francesco Migliavacca, José Félix Rodriguez Matas

Contents of the speech

Study on the Accuracy of FSI Heart Valves Simulations

Transcatheter Aortic Valve Implantation: an FSI study

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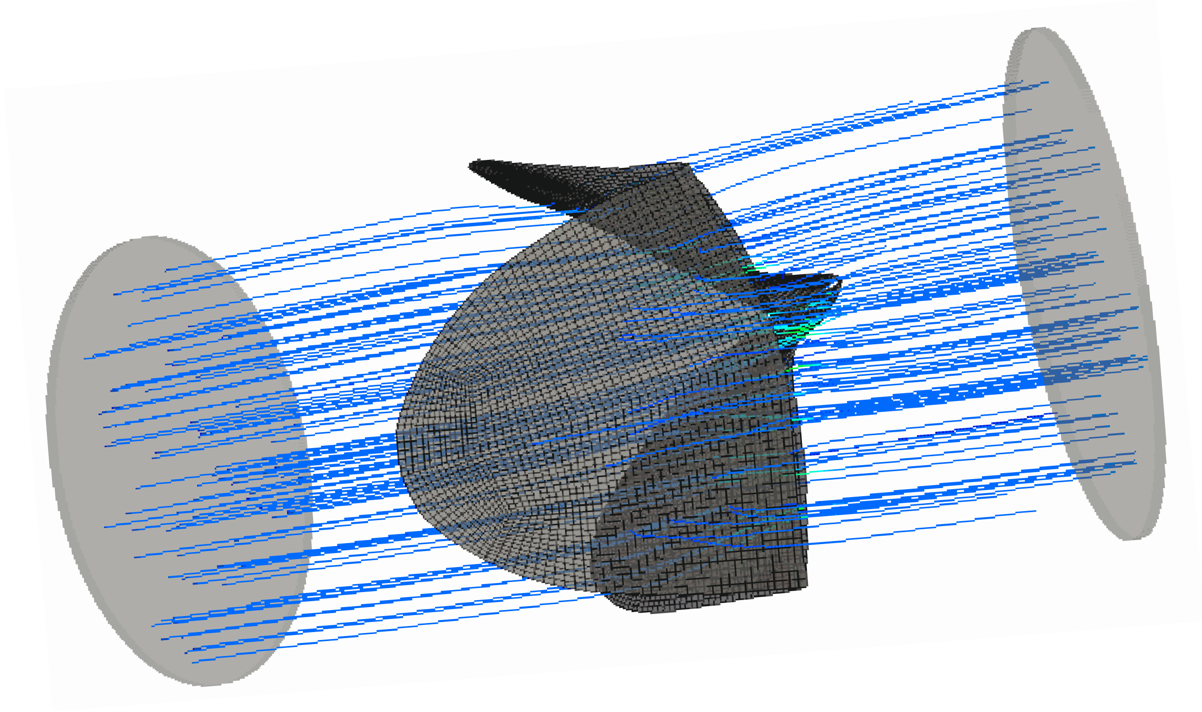
Transcatheter Aortic Valve Implantation: an FSI study



giulia.luraghi@polimi.it

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Study on the Accuracy of FSI Heart Valves Simulations

Transcatheter Aortic Valve Implantation: an FSI study

Aim: to verify and compare different technical details of heart valve simulations

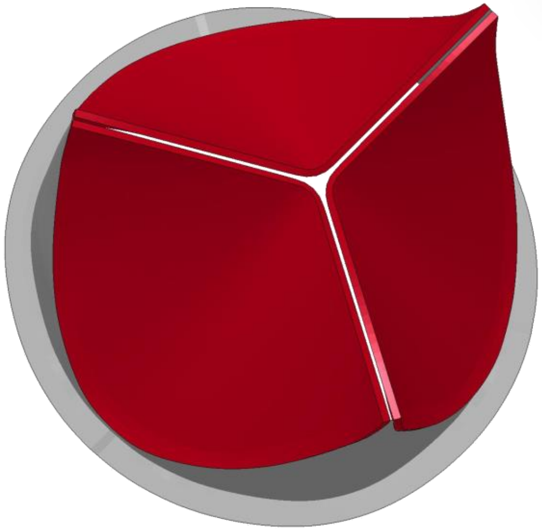
- Convergence of the mesh
- Finite element typology and formulation
- Damping factor

Set-up of the simulations

Structure: three leaflets biological valve

$$\rho = 1100\ {}^{kg}/_{m^3}$$
$$\mathrm{E} = 3\ MPa$$
$$\nu = 0.49$$
$$\text{Thickness} = 0.4\ mm$$

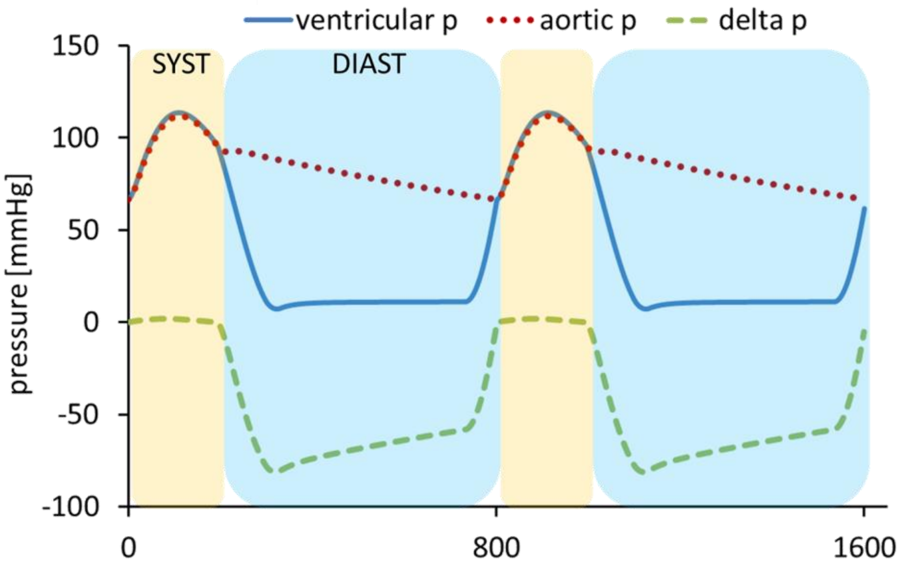
BC: fixed commissural edges



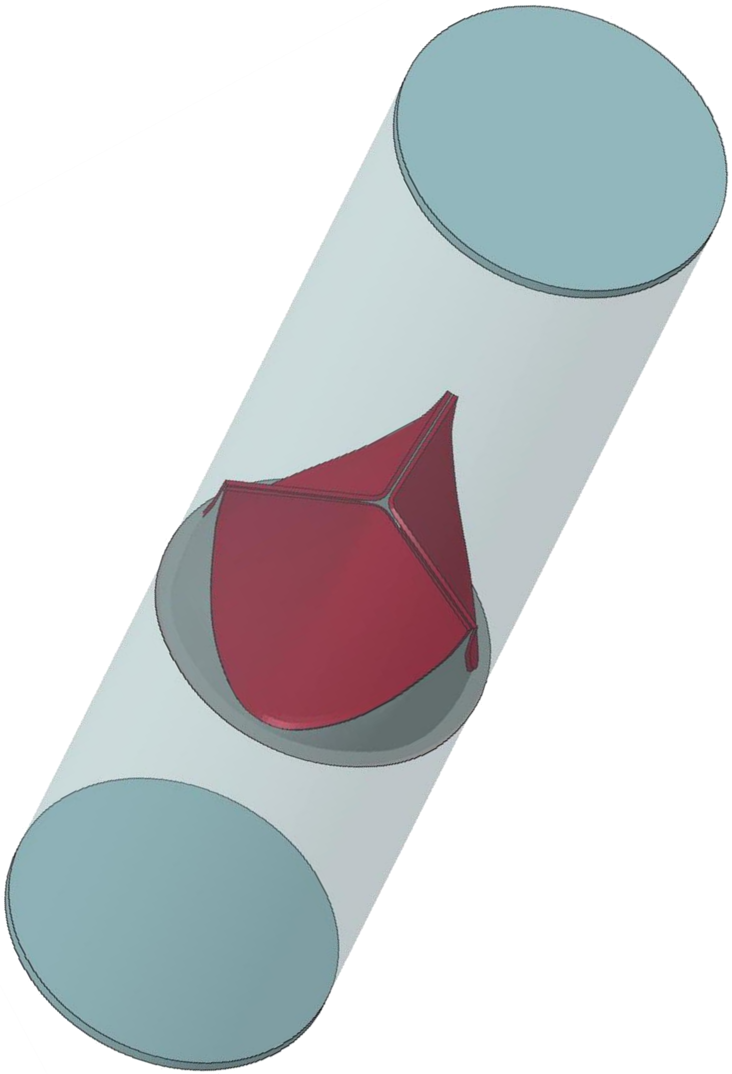
Fluid: blood in a rigid tube

$$\rho = 1060\ {}^{kg}/_{m^3}$$
$$\mu = 3.5\ cP$$

BC: physiological pressure gradient



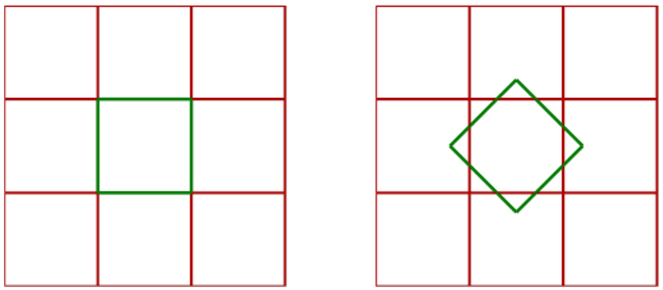
Set-up of the simulations



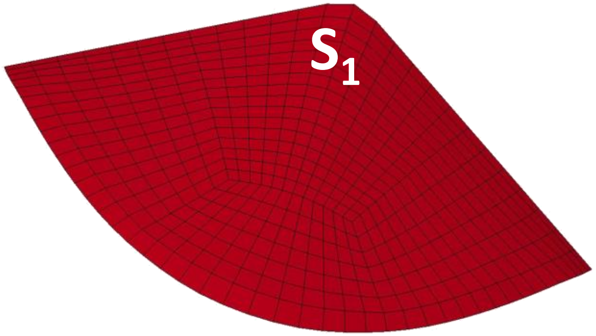
Fluid-Structure Interaction (FSI)
*COSTRAINED_LAGRANGE_IN_SOLID

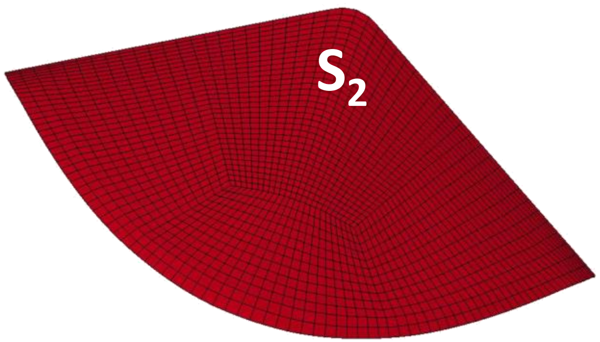
Non-boundary fitted method
Operator Split algorithm

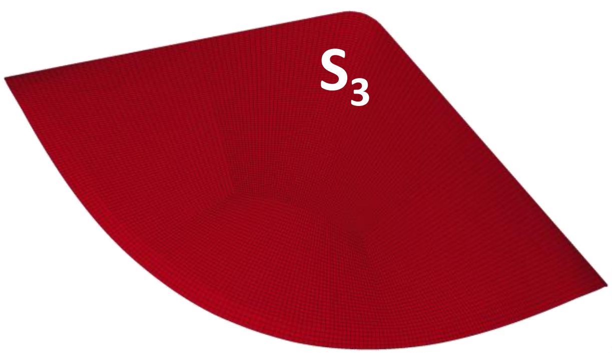
Fluid domain: control volume + inlet and outlet parts



Accuracy of FSI Heart Valves Simulations







SHELL

S_1

S_2

S_3

BRICK

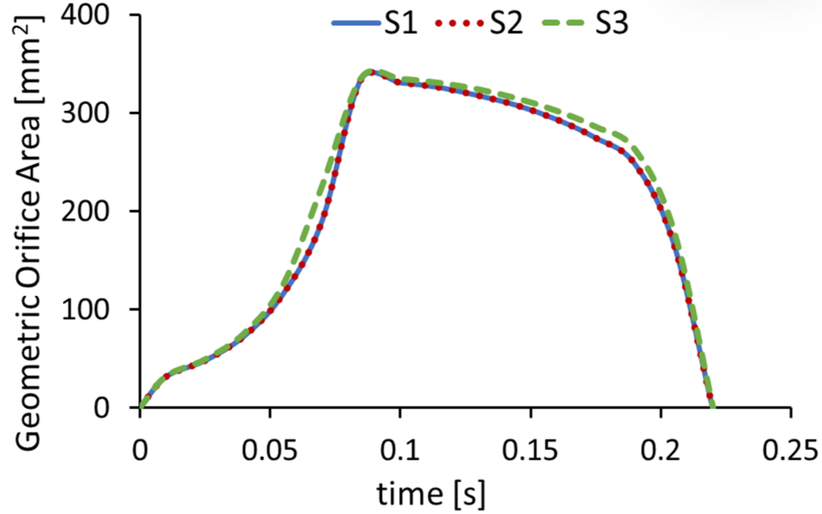
B_1

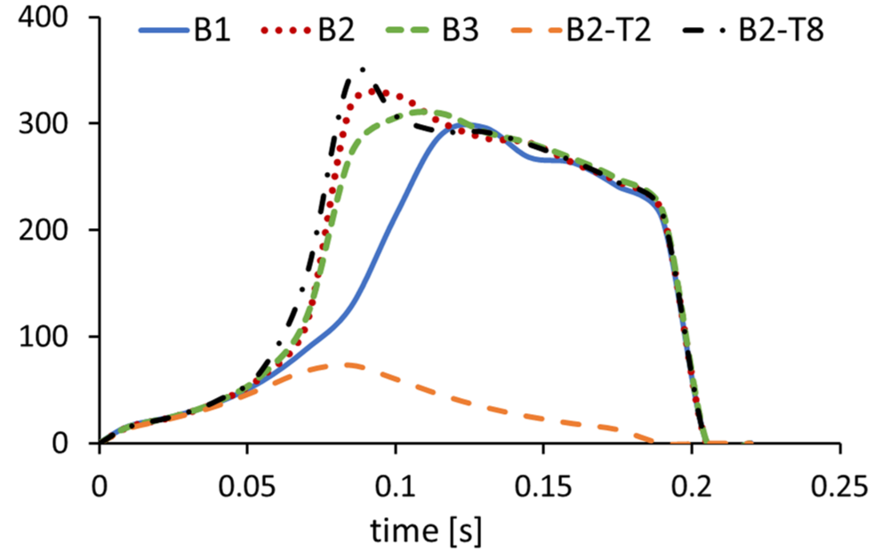
B_2

B_3

$B_2 - T_2$

$B_2 - T_8$





giulia.luraghi@polimi.it

Accuracy of FSI Heart Valves Simulations

S_2: Belytschko-Lin-Tsay reduced-int, Hg Viscosity, Damp 1-5 — *ELFORM=2 *IHQ=2

S_2-BL: Belytschko-Leviathan, Damp 1-5 — *ELFORM=8

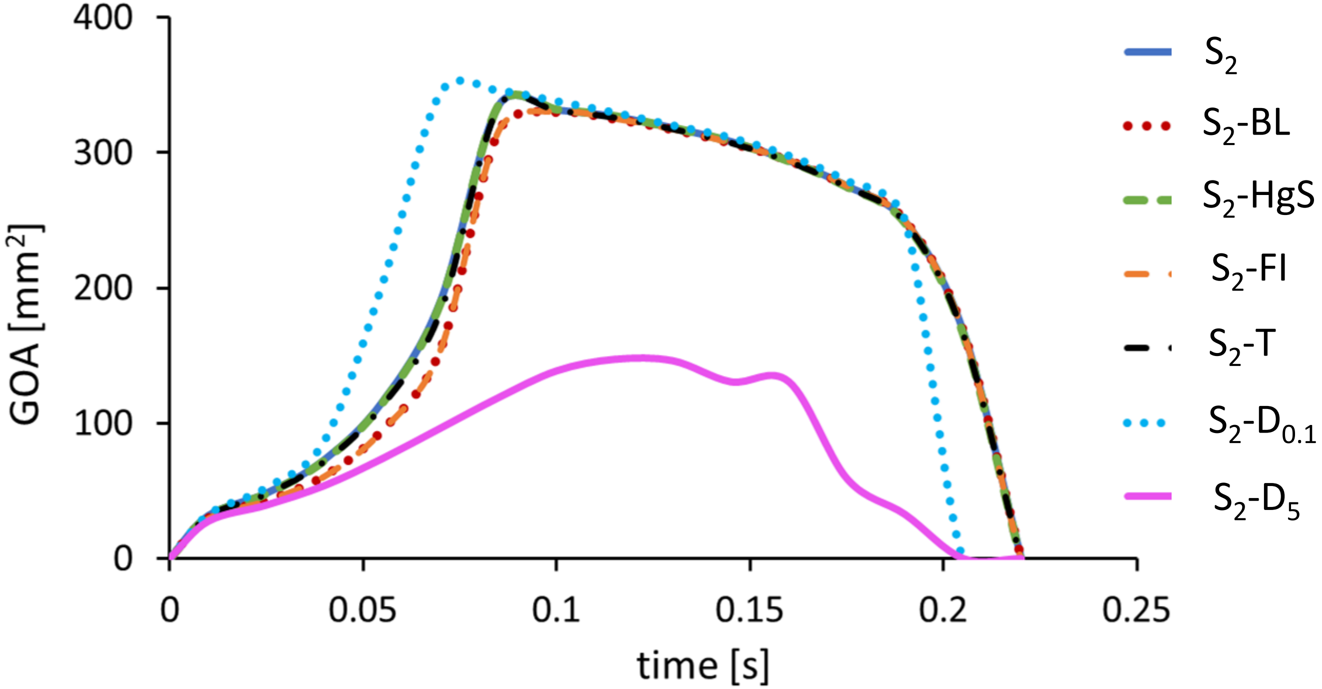
S_2-HgS: Belytschko-Lin-Tsay reduced-int, Hg Stiffness, Damp 1-5 — *IHQ=4

S_2-FI: full-int, Damp 1-5 — *ELFORM=16

S_2-T: thickness enhanced reduced-int, Damp 1-5 — *ELFORM=25

S_2-$D_{0.1}$: S_2 model, Damp 0.1-0.1

S_2-D_5: S_2 model, Damp 5-5



Accuracy of FSI Heart Valves Simulations

B_2: quadratic full-int, Damp 0.1-1 *ELFORM=3

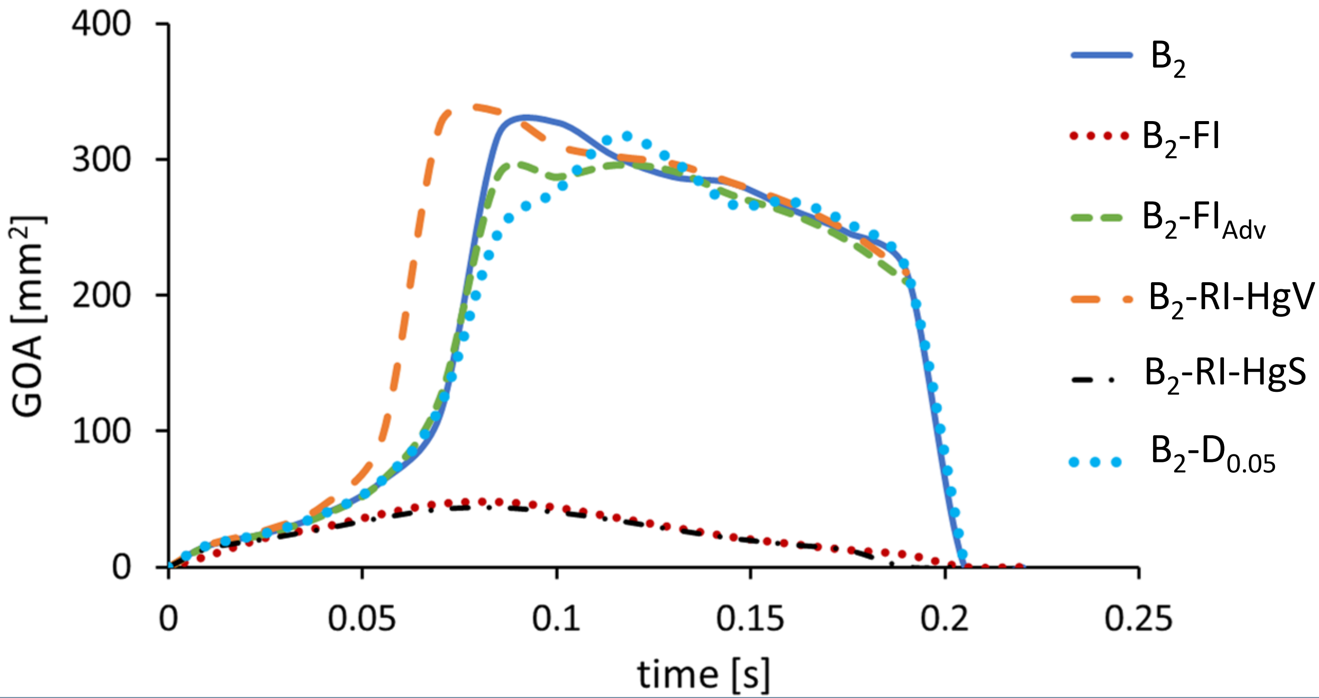
B_2 -FI: linear full-int, Damp 0.1-1 *ELFORM=2

B_2 -FI$_{Adv}$: linear advance full-int, Damp 0.1-1 *ELFORM=-2

B_2 –RI-HgV : reduced-int Viscous, Hg Viscosity ,Damp 0.1-1 *ELFORM=1 *IHQ=2

B_2 –RI-HgS : reduced-int Stiffness, , Hg Stiffness ,Damp 0.1-1 *ELFORM=1 *IHQ=4

B_2 -D$_{0.05}$: B_2 model, Damp 0.05-0.05



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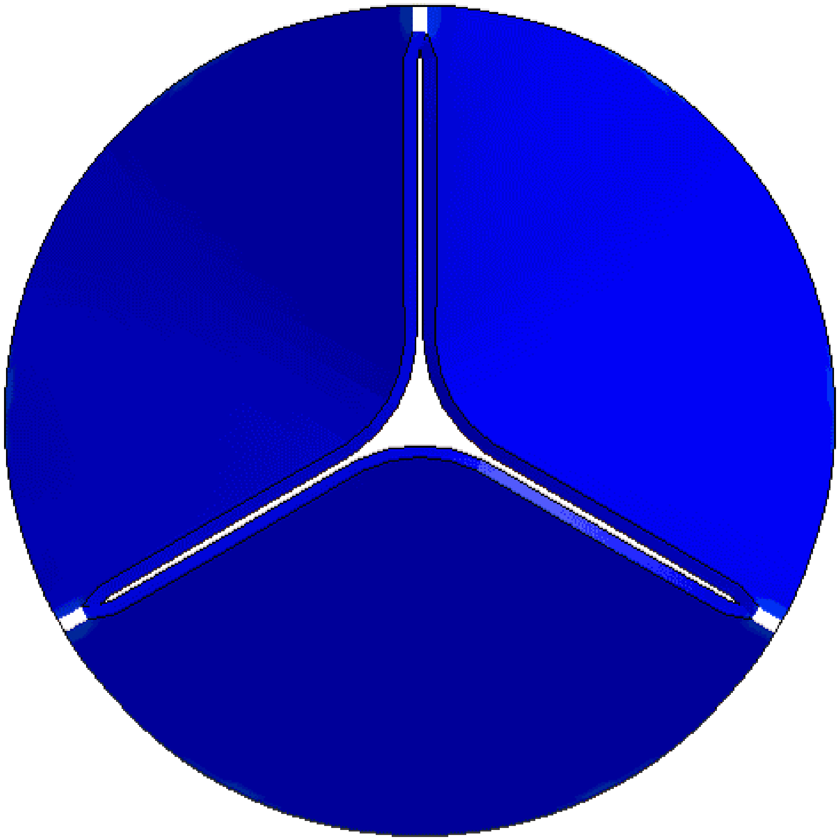
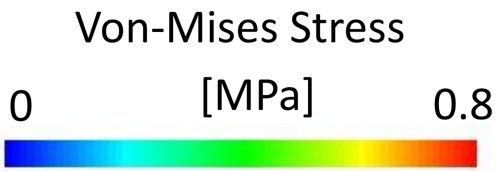
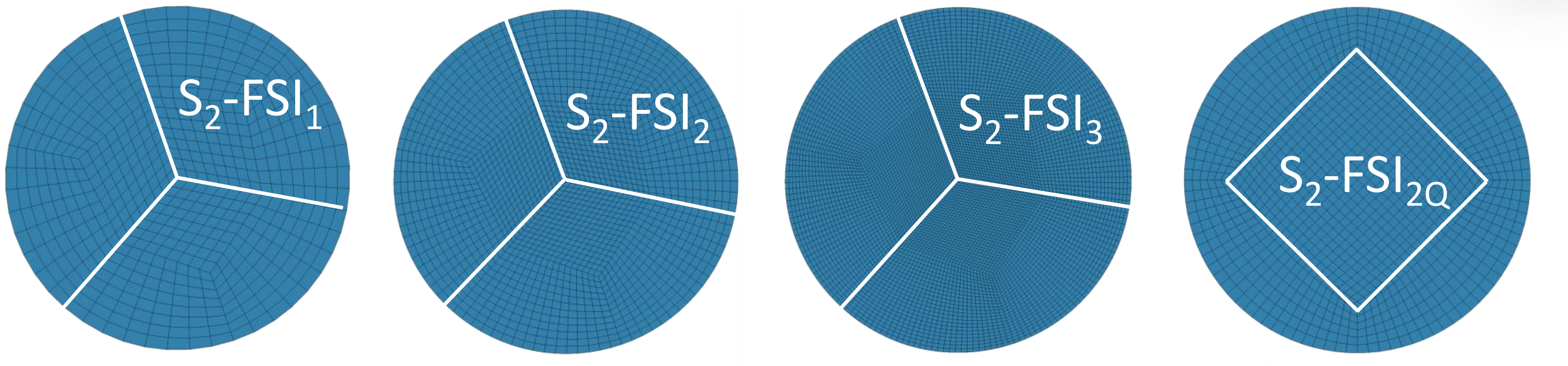
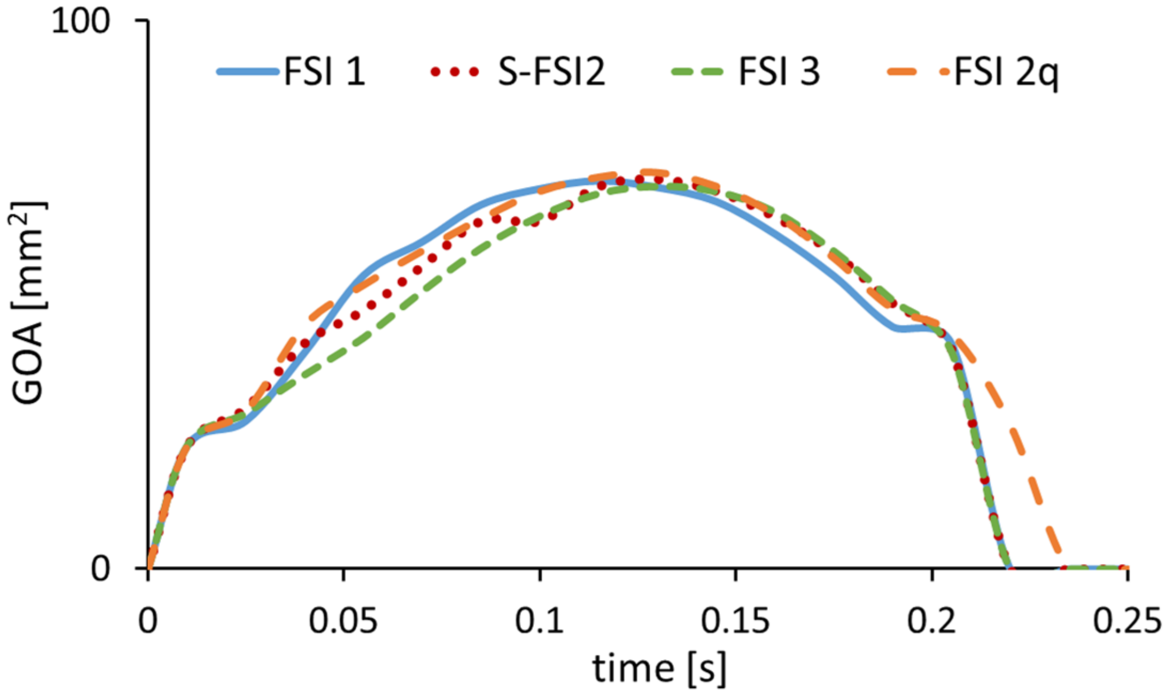
Accuracy of FSI Heart Valves Simulations





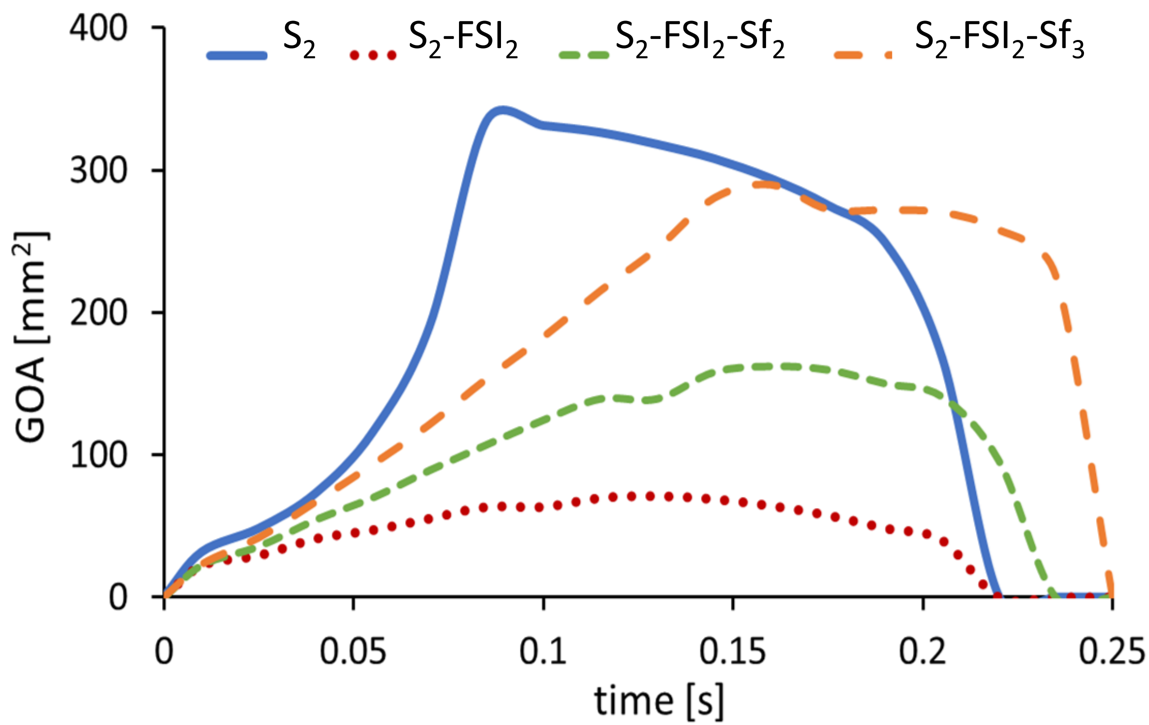
Accuracy of FSI Heart Valves Simulations

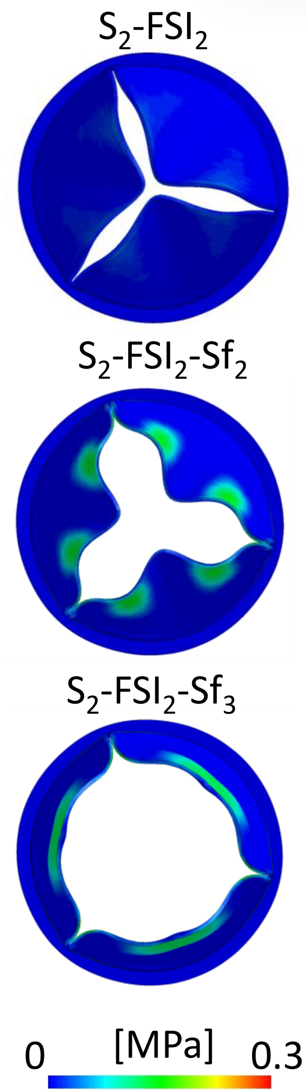




Accuracy of FSI Heart Valves Simulations

S_2: Belytschko-Lin-Tsay reduced-int Viscosity Hg Damp 1-5
S_2 –FSI_2: 1 scale factor BC
S_2 –FSI_2 -Sf_2 : 2 scale factor BC
S_2 –FSI_2 -Sf_2 : 3 scale factor BC





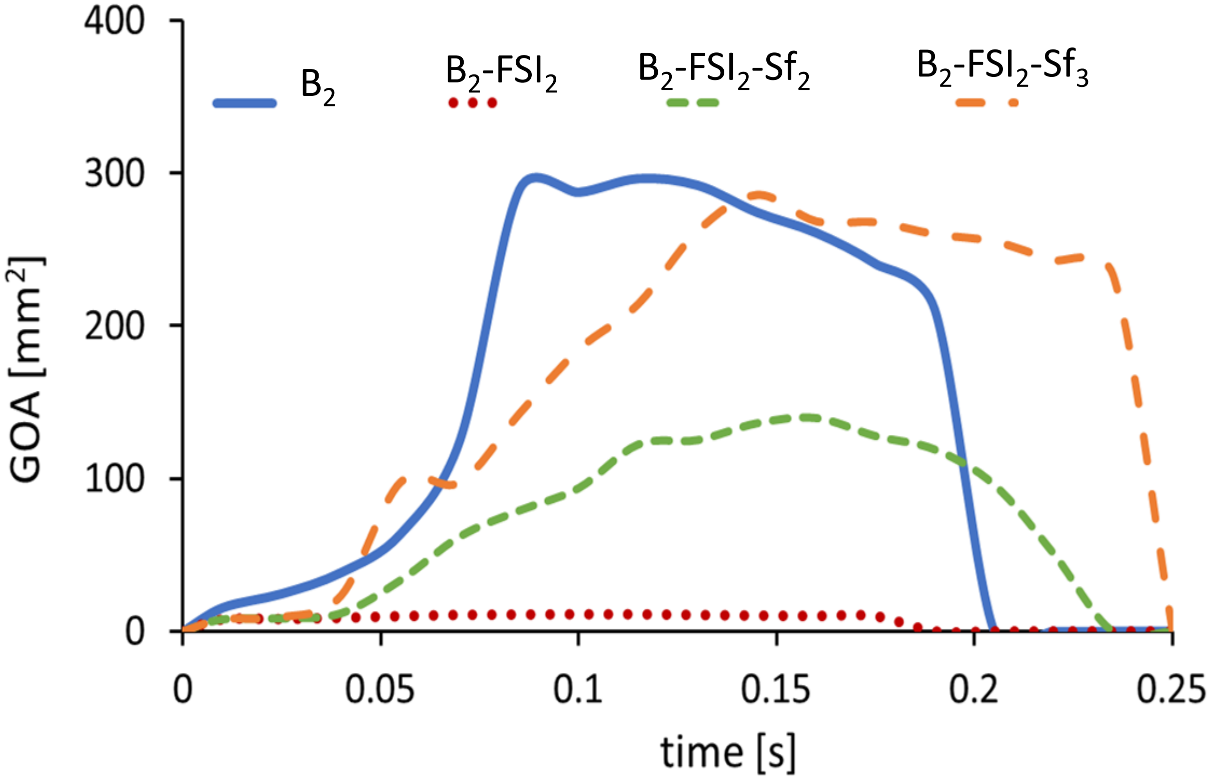
Accuracy of FSI Heart Valves Simulations

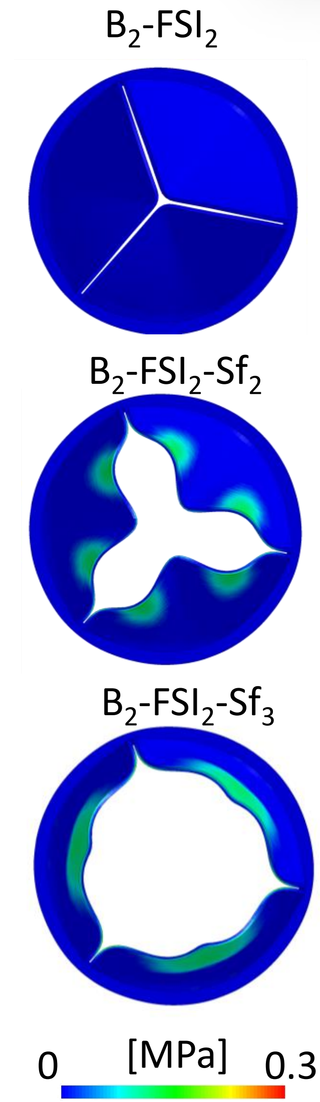
B_2: quadratic full-int Damp 0.1-1

B_2 –FSI_2: 1 scale factor BCs

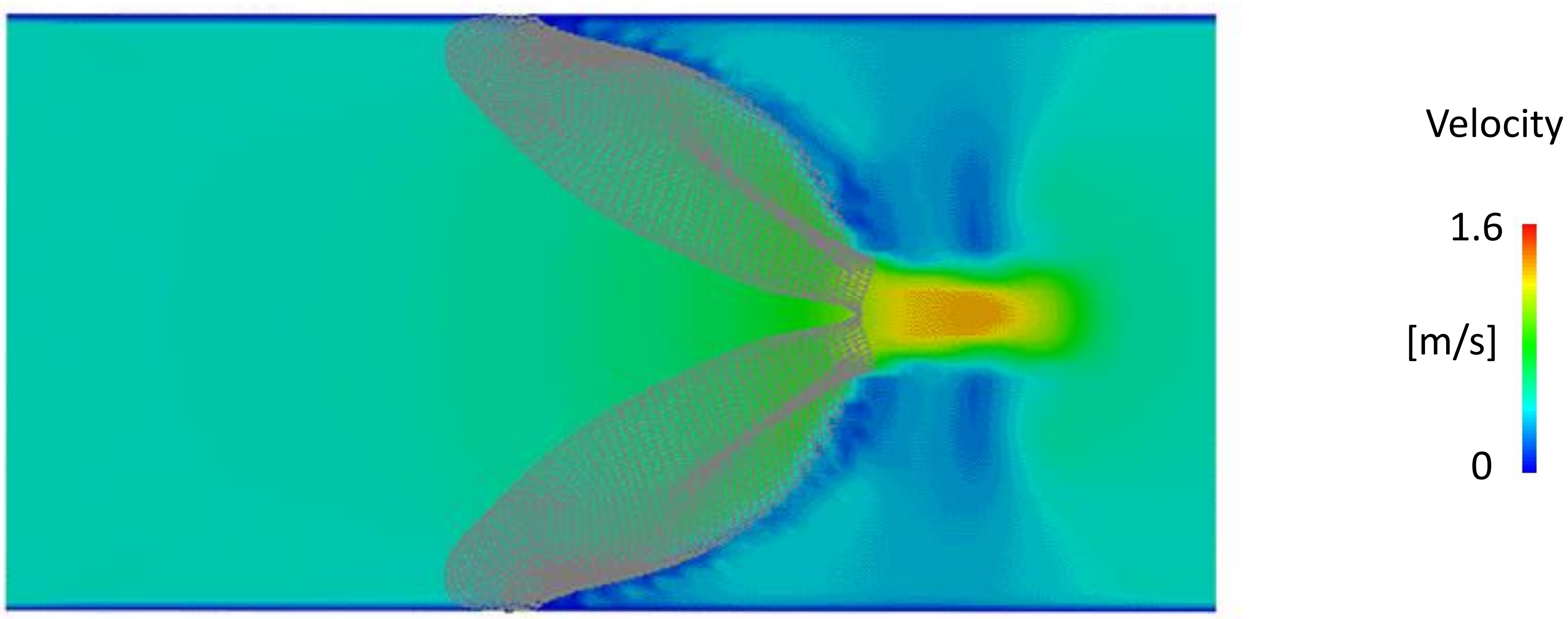
B_2 –FSI_2 -Sf_2 : 2 scale factor BCs

B_2 –FSI_2 -Sf_2 : 3 scale factor BCs





Accuracy of FSI Heart Valves Simulations

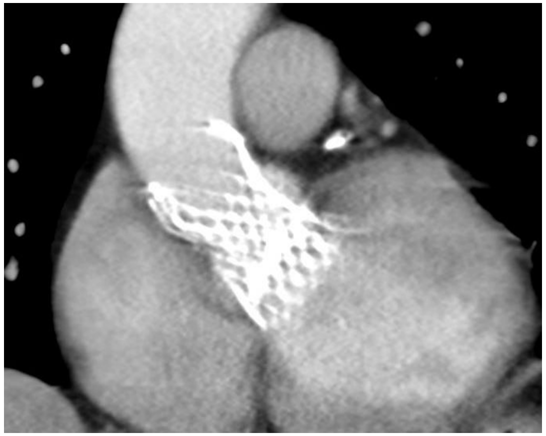


Study on the Accuracy of FSI Heart Valves Simulations

Transcatheter Aortic Valve Implantation: an FSI study

<u>Aim</u>: Efficient methodological approach to perform FSI simulations of TAVI procedure

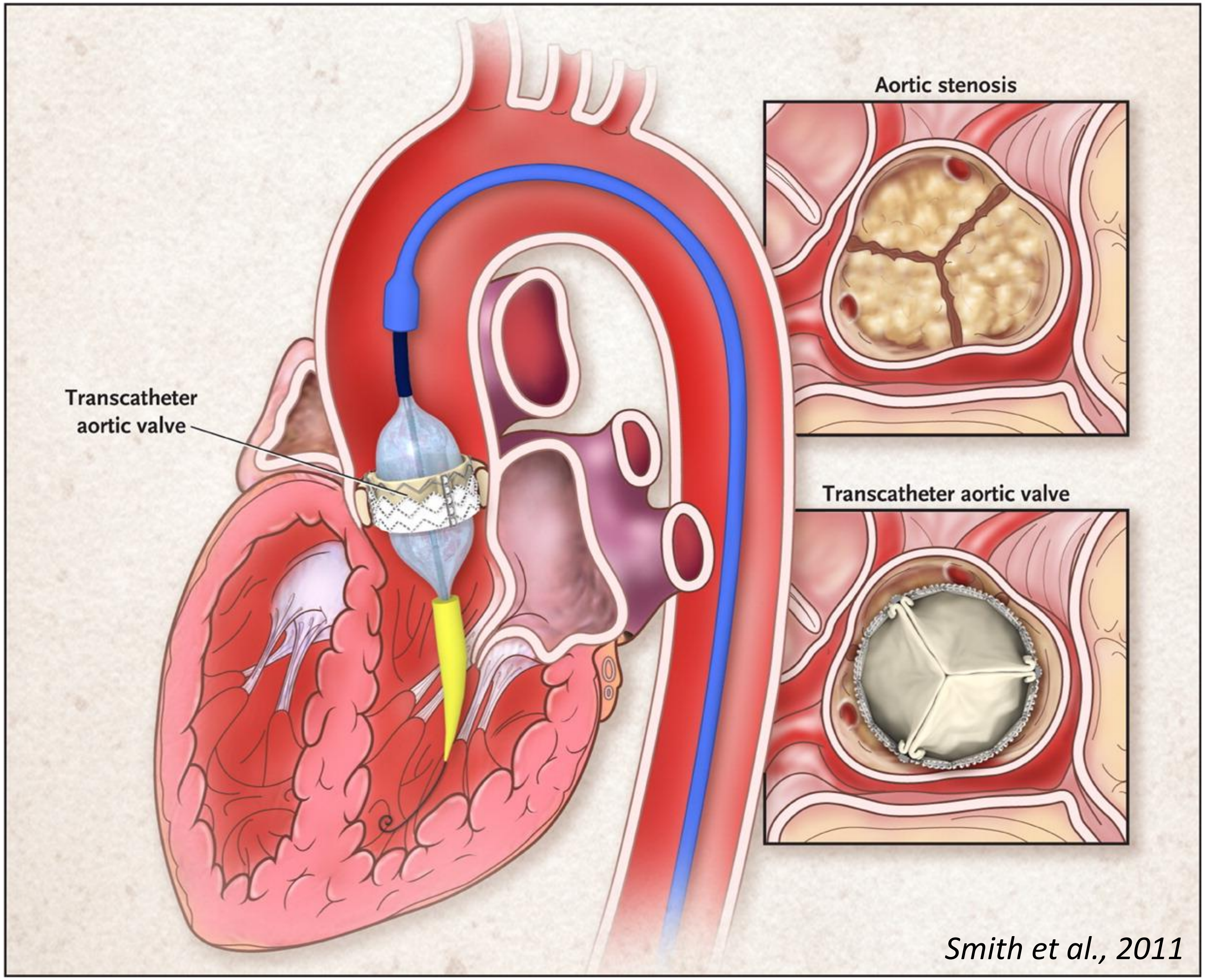
- **Patient-specific domain**
- **Patient-specific BCs**



Clinical data provided by Humanitas University (prof. Giulio Stefanini)

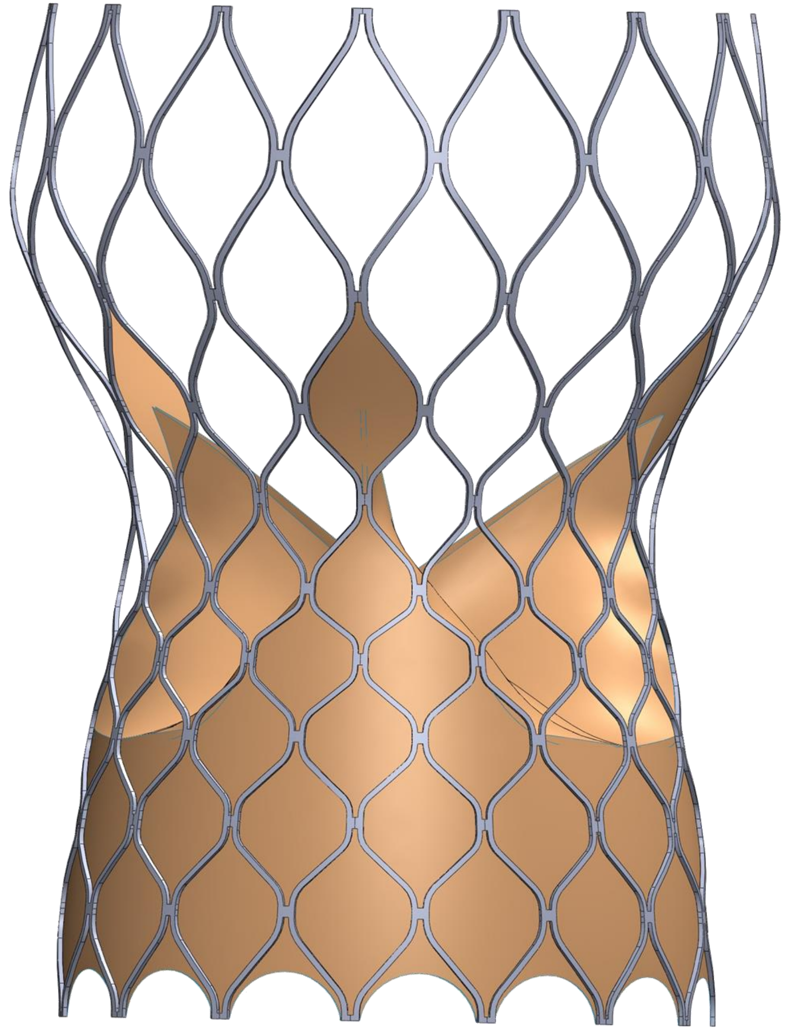
TAVI: an FSI study

- ✓ Mini-invasive procedure
- ✓ Intermediate- and high-risk patients

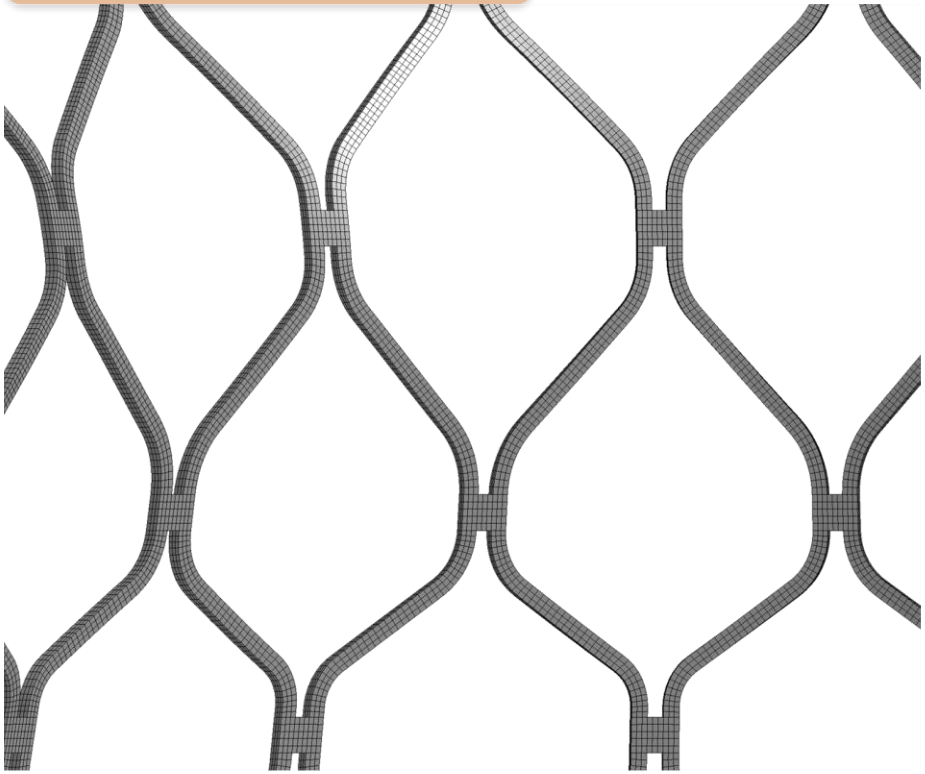


Smith et al., 2011

TAVI: an FSI study

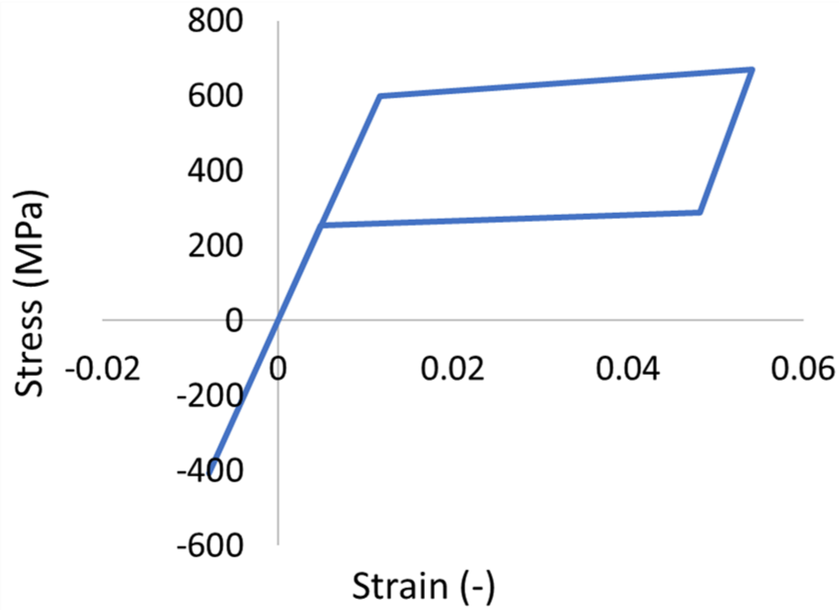


DEVICE: FRAME



Pseudo-elastic material

*MAT_SHAPE_MEMORY



159,435 **hexahedral reduce integrated** elements

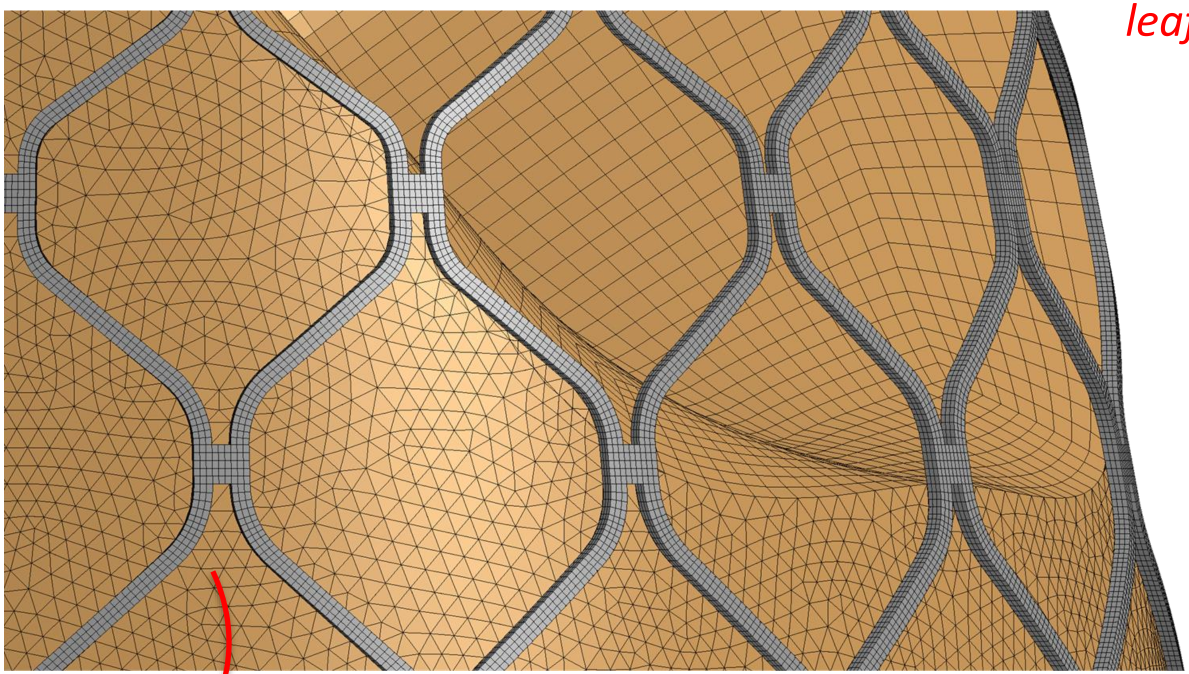
*ELFORM=1

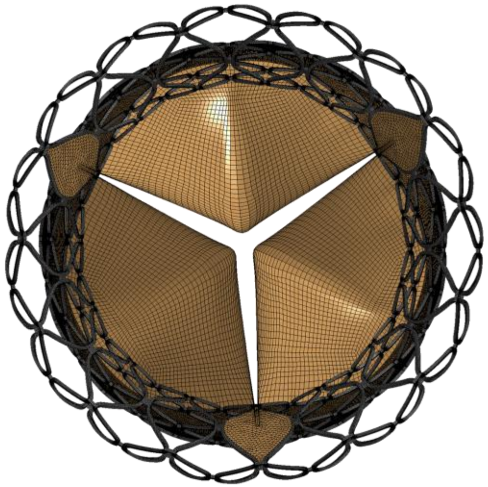
TAVI: an FSI study

DEVICE: PERICARDIUM TISSUE

5,706 **quadrilateral shell elements**
*ELFORM=2

leaflets





skirt

32,388 **triangular membrane elements**
*ELFORM=5

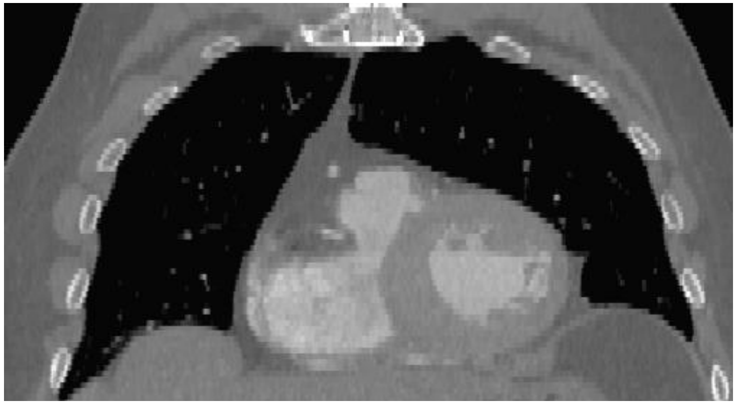
Linear elastic
*MAT_ELASTIC

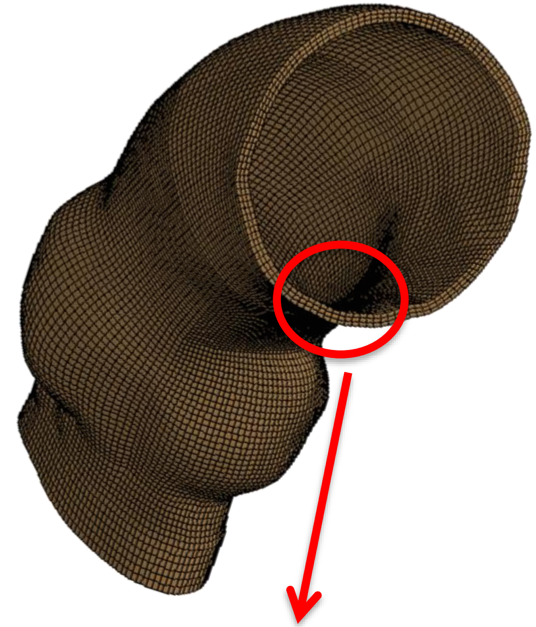
$$E = 1\ MPa$$
$$\nu = 0.45$$
$$\rho = 1100\ kg/m^3$$

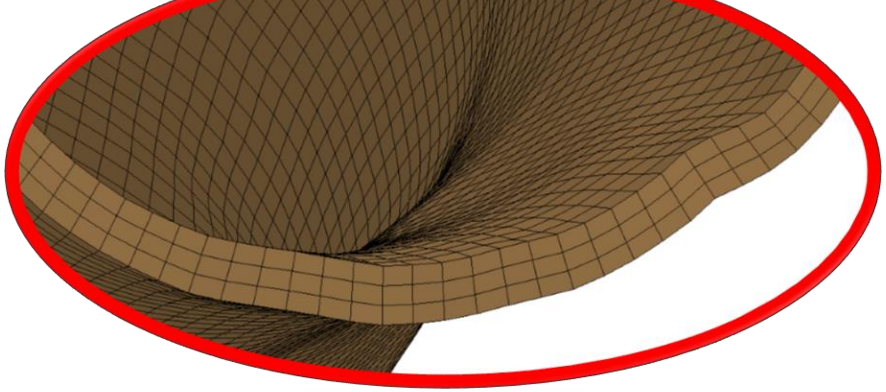
Element formulation details:
Luraghi et al., 2018. Study on the Accuracy of Structural and FSI Heart Valves Simulations. *Cardiovasc. Eng. Technol.*

PATIENT-SPECIFIC DOMAIN: AORTA

CT images segmentation







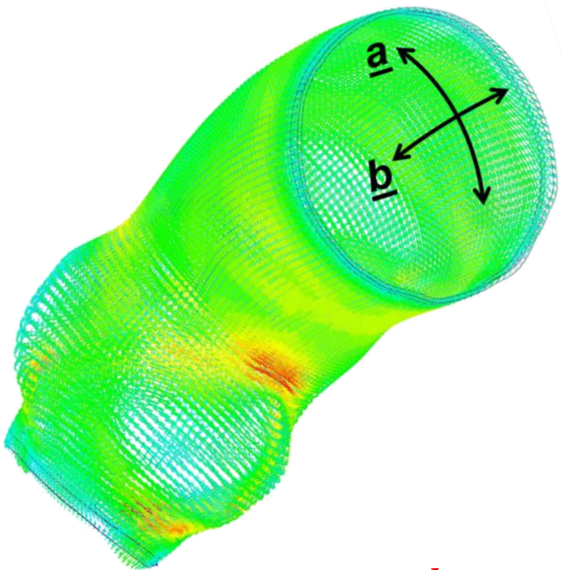
35,640 **hexahedral fully integrated** elements

*ELFORM=2

PATIENT-SPECIFIC DOMAIN: AORTA

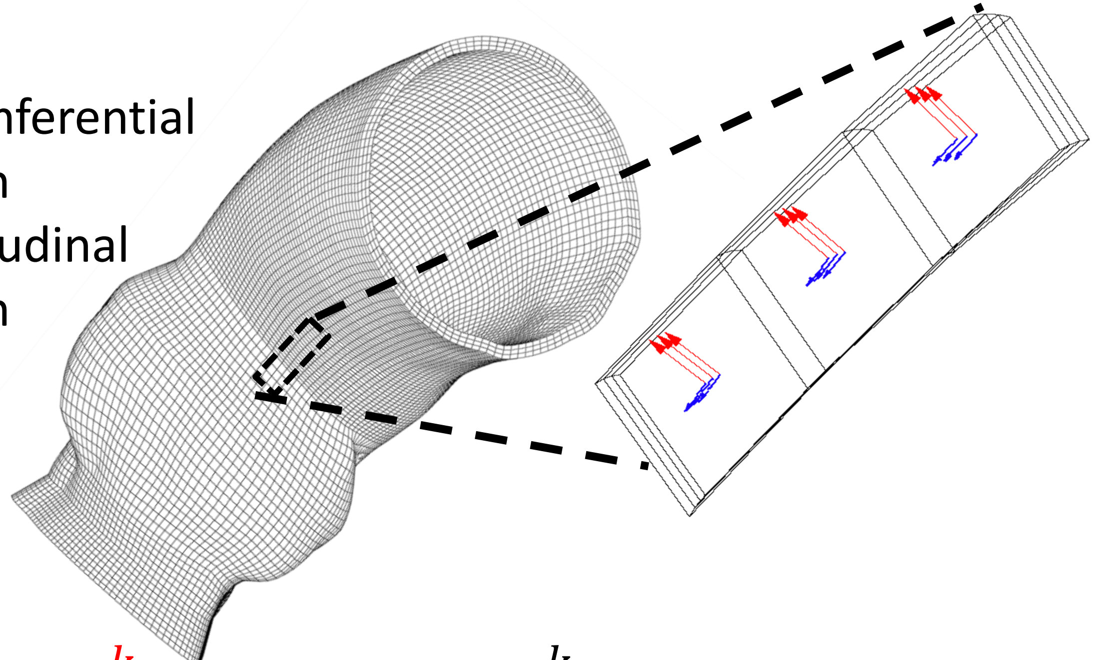
<u>Hyperelastic matrix with embedded fibres</u>

*MAT_USER_DEFINED_MATERIAL



<u>a</u>: circumferential direction

<u>b</u>: longitudinal direction



$$W = C_{10}(\bar{I}_1 - 3) + \frac{k_1}{2k_2}\left[e^{k_2(I_4-3)^2} - 1\right] + \frac{k_3}{2k_4}\left[e^{k_4(I_6-3)^2} - 1\right] + \frac{k}{2}(J-1)^2$$

Holzapfel-Gasser-Odgen model

$C_{10} = 5\ kPa \quad \upsilon = 0.49 \quad \rho = 1100\ kg/m^3$

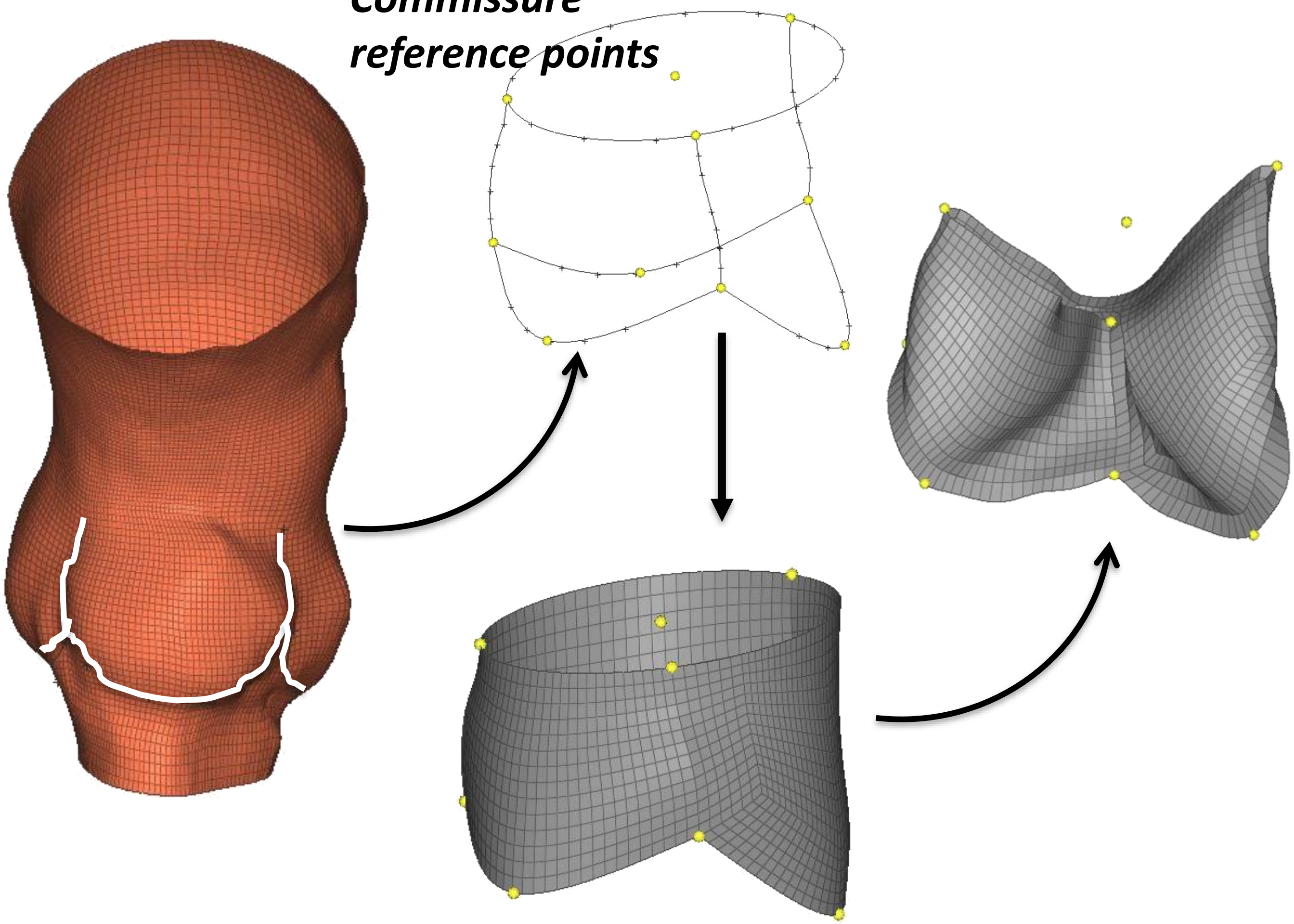
$k_1 = 50.31\ kPa \quad k_2 = 0.56$

$k_3 = 82.51\ kPa \quad k_4 = 57.53$

Vande Geest et al., 2006

giulia.luraghi@polimi.it

PATIENT-SPECIFIC DOMAIN: NATIVE VALVE

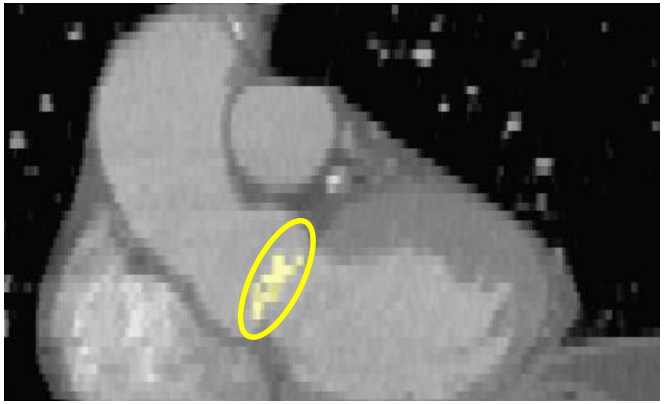


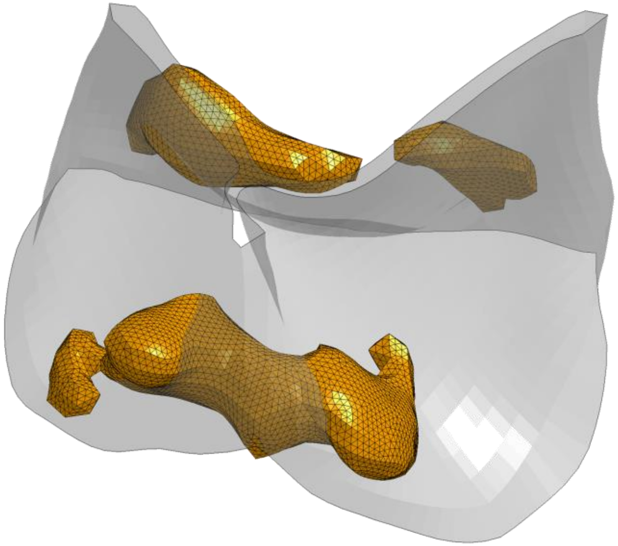
Linear elastic

*MAT_ELASTIC

$$E = 4\ MPa$$
$$\nu = 0.45$$
$$\rho = 1100\ kg/m^3$$

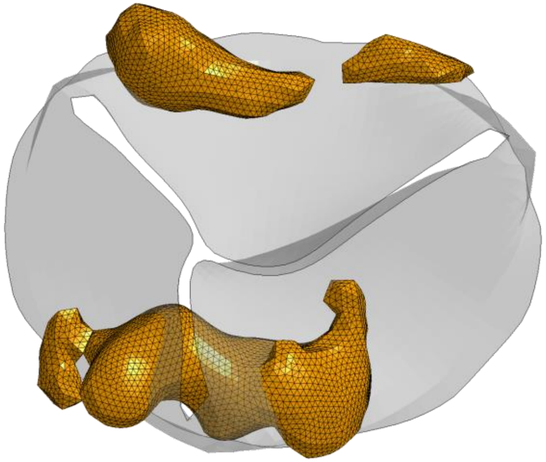
PATIENT-SPECIFIC DOMAIN: CALCIFICATIONS





38,429 **tetrahedral elements**

*ELFORM=10



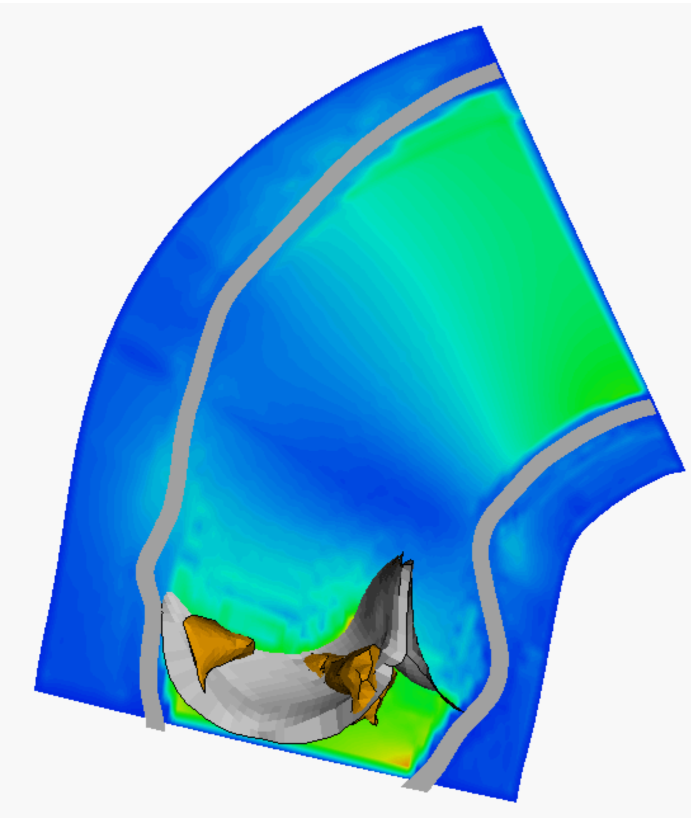
Linear elastic

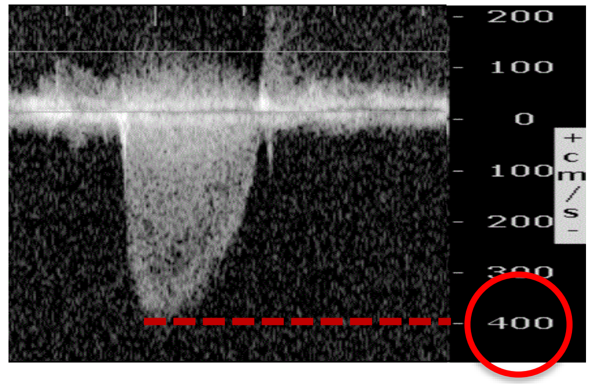
*MAT_ELASTIC

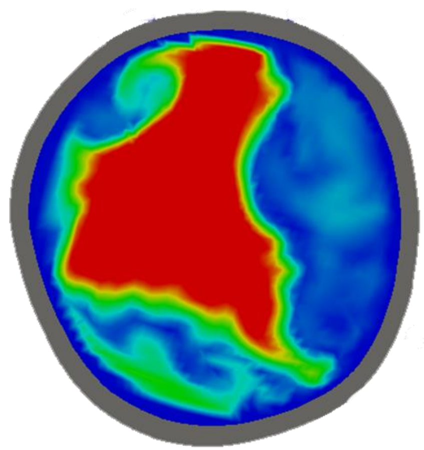
$$E = 12.6\ MPa$$
$$\nu = 0.45$$
$$\rho = 2000\ kg/m^3$$

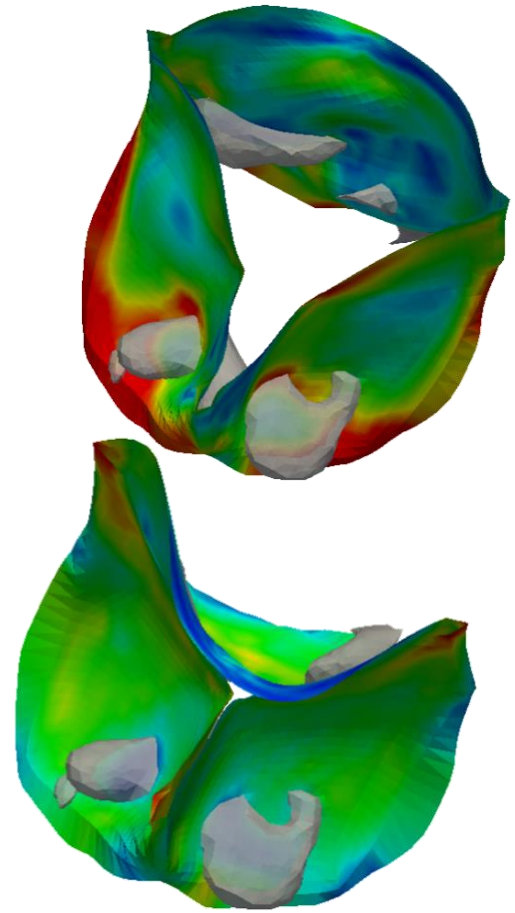
TAVI: an FSI study

I STEP
Pre-TAVI Cardiac cycles



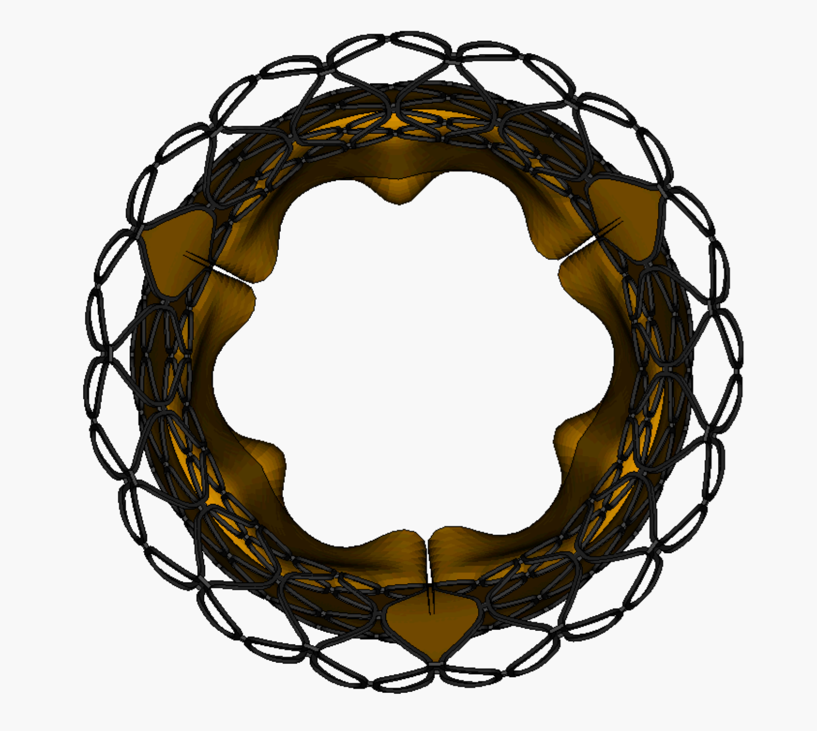


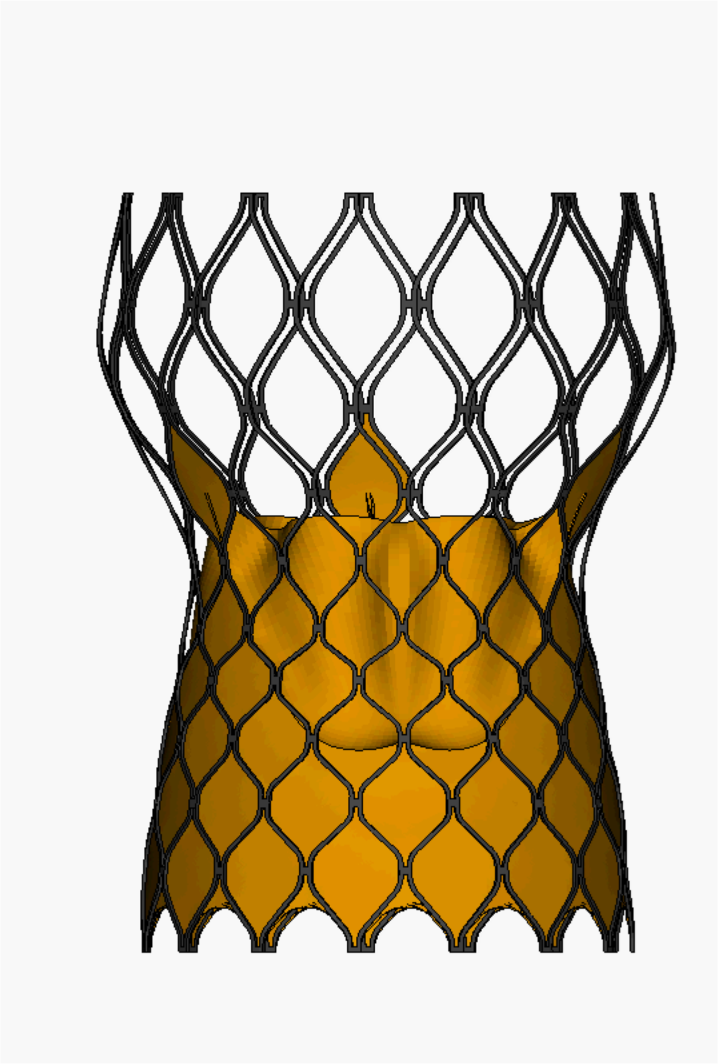




TAVI: an FSI study

II STEP
Implantation

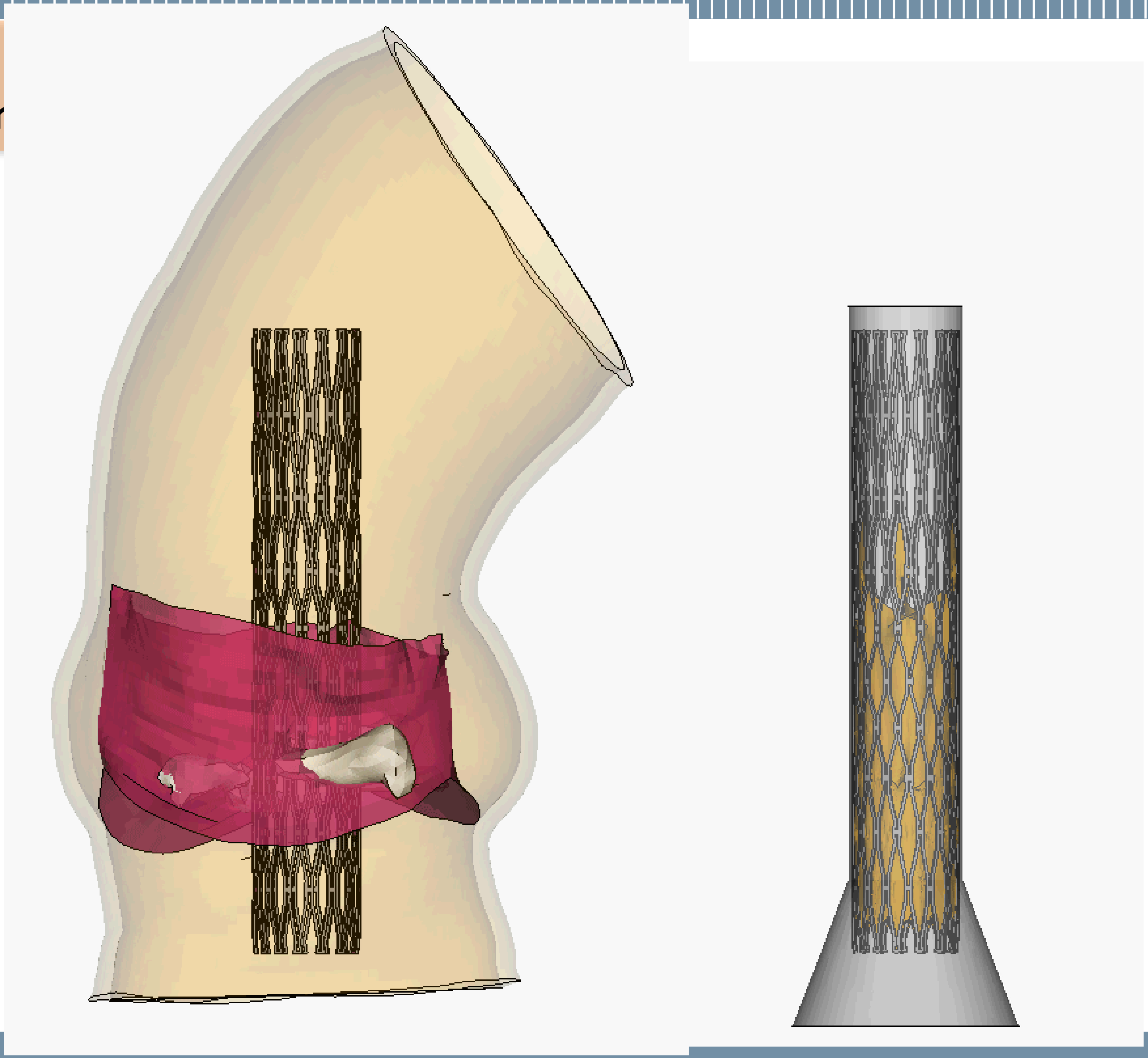




TAVI: an FSI study

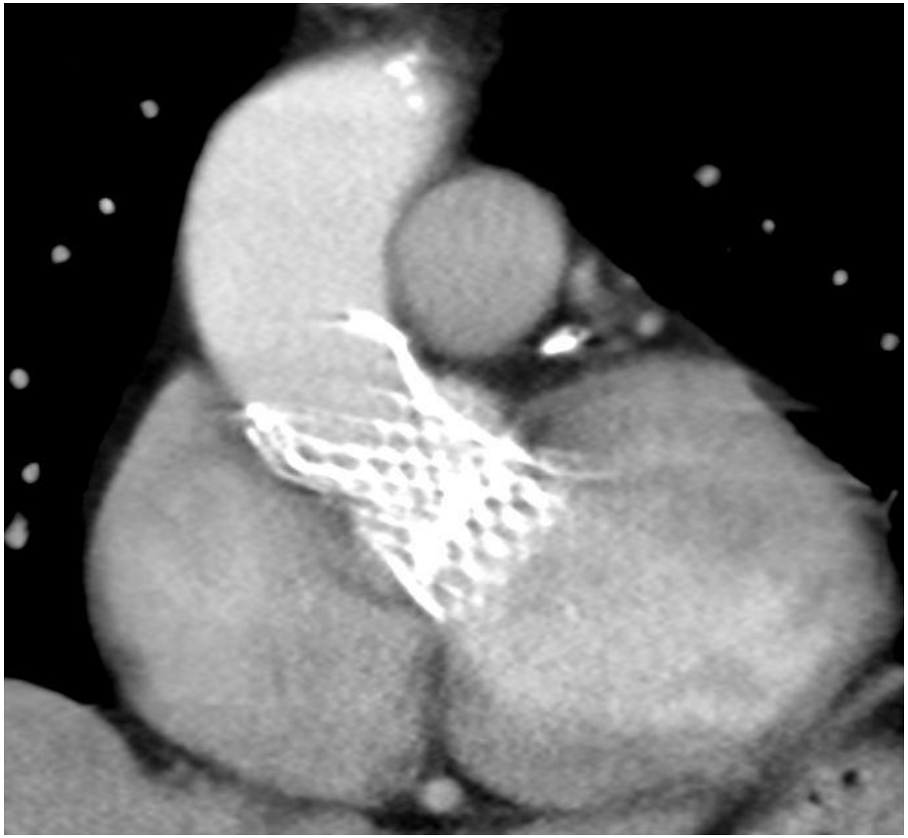
II STEP

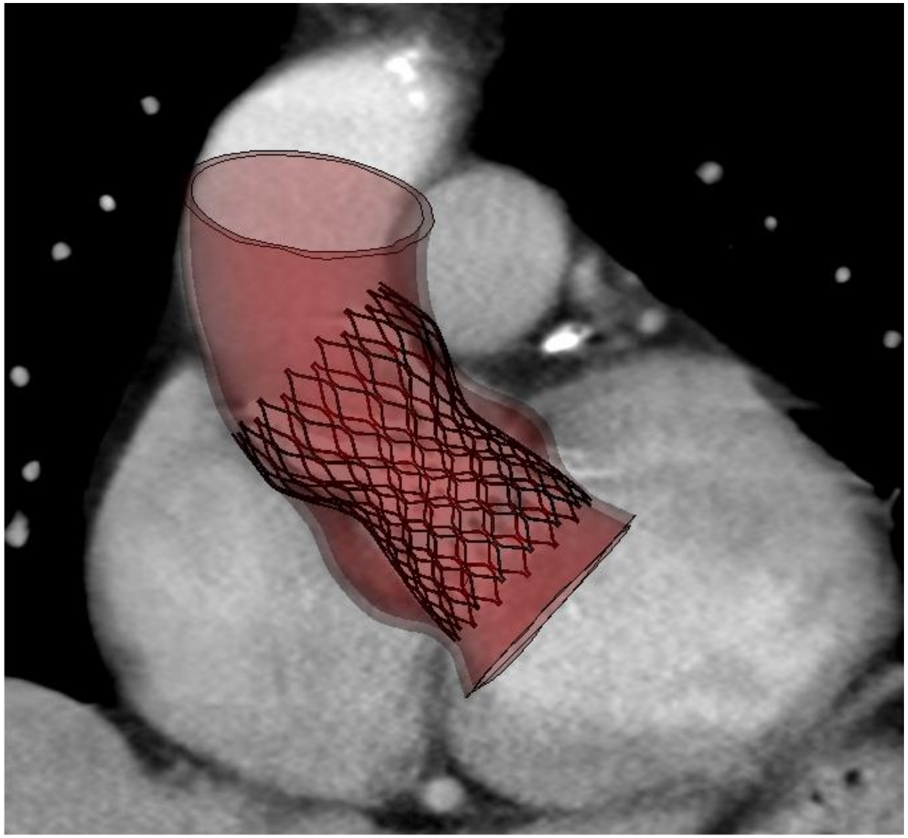
Implantation



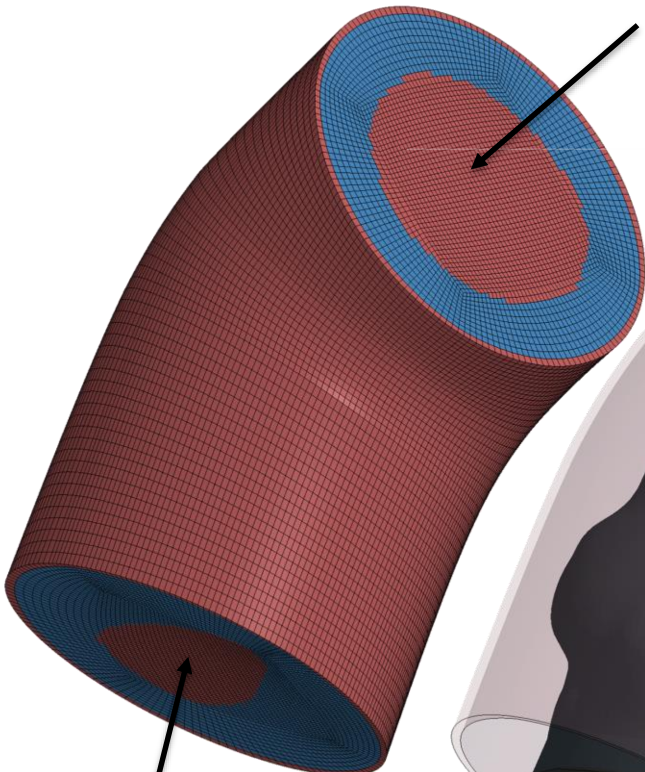
TAVI: an FSI study

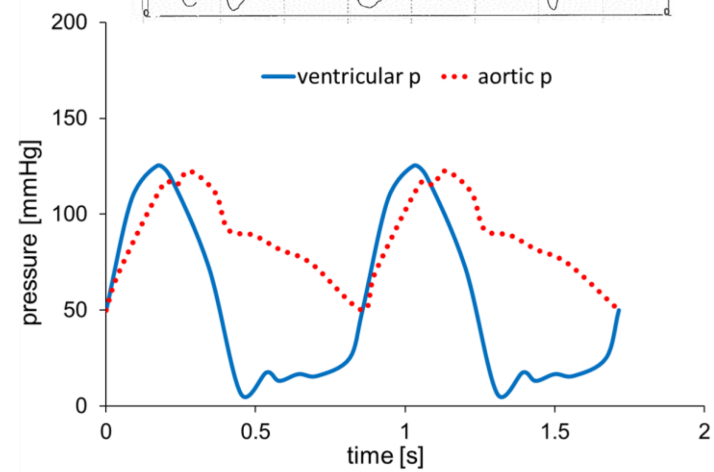
II STEP
Implantation





III STEP
Cardiac Cycle

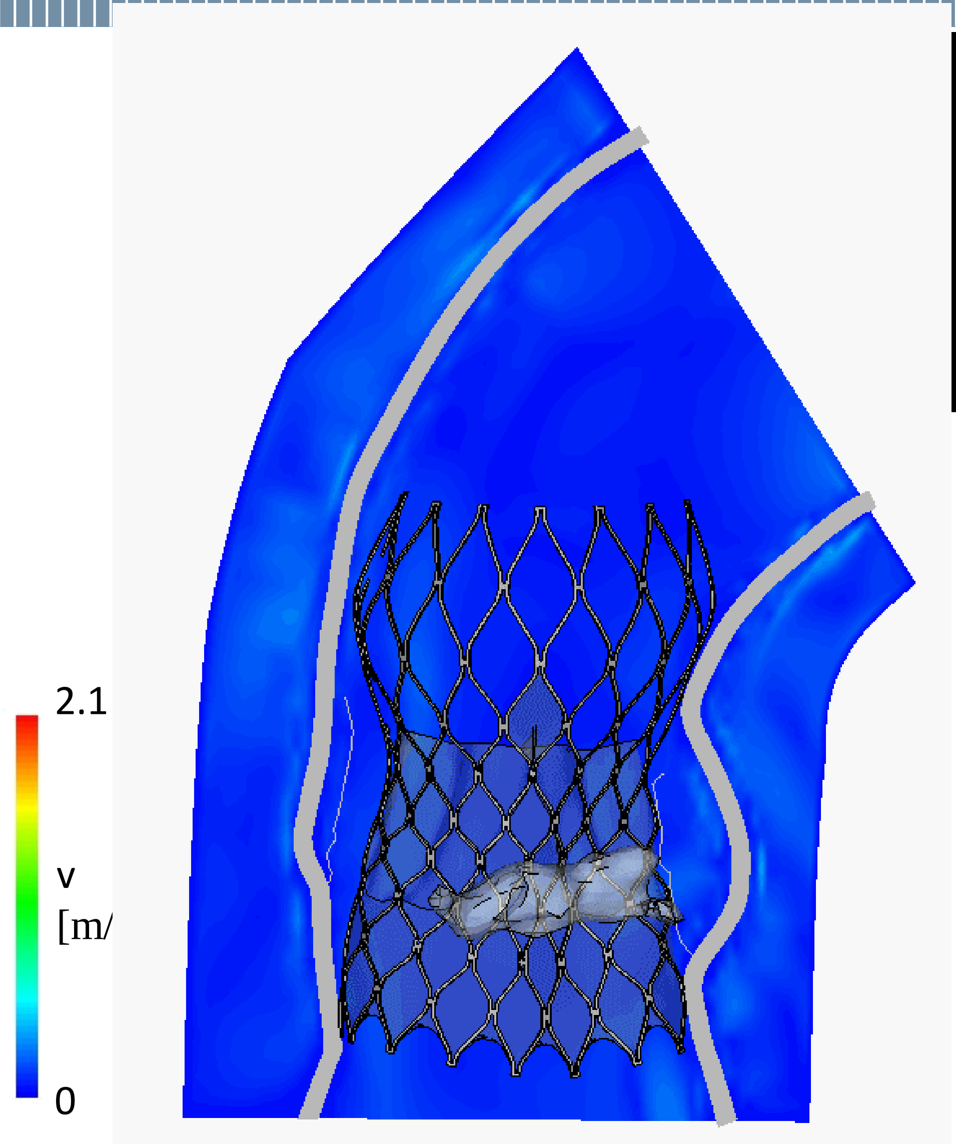


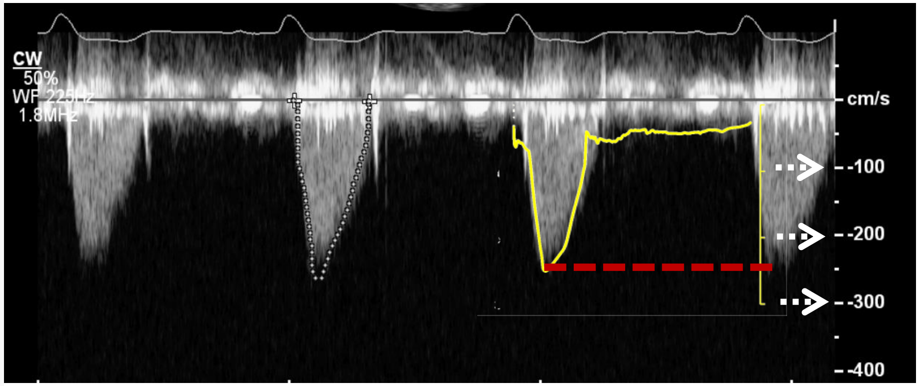


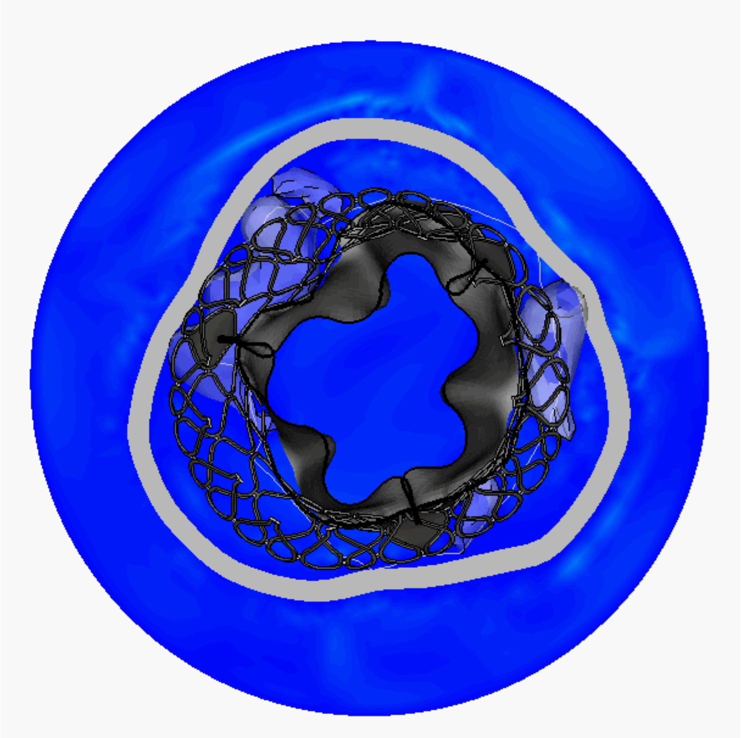
113,216 **hexahedral Eulerian**
one-point elements
*ELFORM=11

Newtonian fluid
*MAT_NULL
$\rho = 1060\ kg/m^3$
$\mu = 3.5\ cP$

TAVI: an FSI study







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