Università di Pisa

Corso di Laurea Magistrale in Ingegneria Biomedica

Development of a fast high fidelity FSI workflow to simulate polymeric aortic valves: a RBF mesh morphing study

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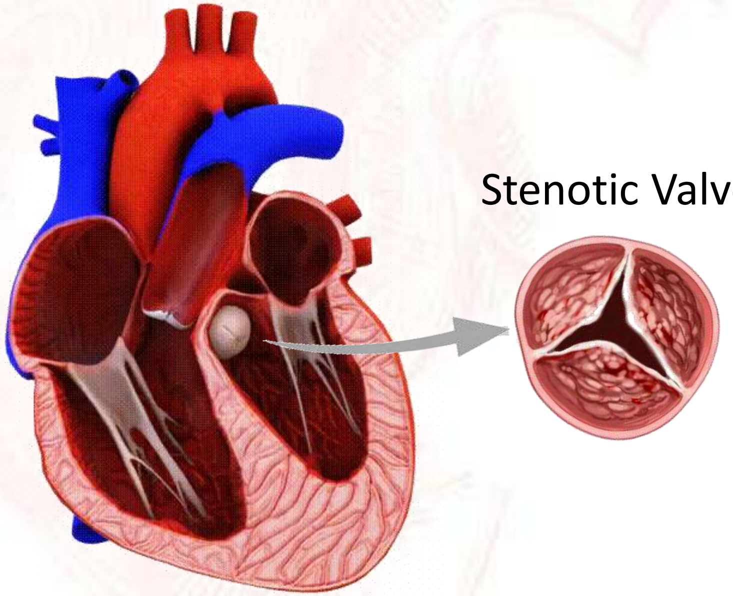
A. A. 2018/2019

Introduction

2018: cardiovascular diseases are the first cause of death in the world *[1]*

→ Aortic Stenosis: shrinkage of the aortic orifice


Stenotic Valve

Replacement

→ Biological prosthesis

→ Mechanical valves

Polymeric-Prosthetic Heart Valves (P-PHVs)

- Crimpable
- Less inclined to coagulation problem
- Customizable
- Easy to be produced
- Cheap

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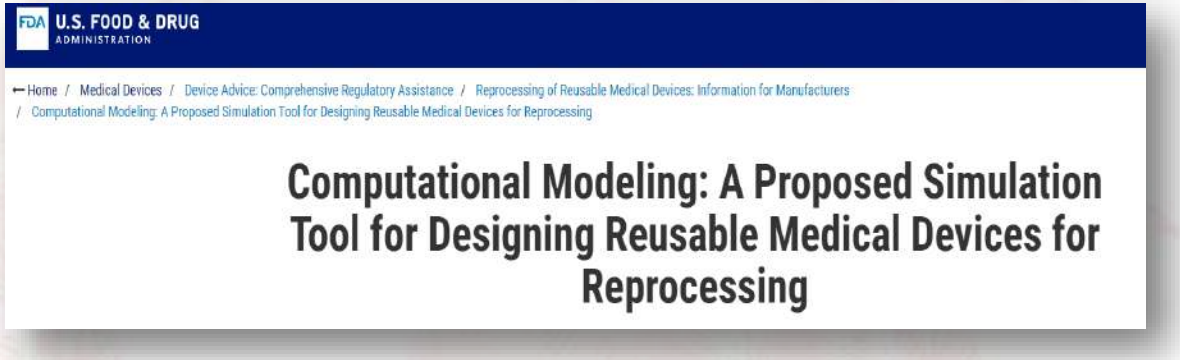
[1] World Health Organization: The top 10 causes of death

Introduction

Currently, FDA[2] and ASME[3] are forcing on the advancement and widespread adoption of new approaches based on numerical simulation which require better computational tools that are fast, accessible and individually adaptable

[2]



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Computational Modeling: A Proposed Simulation Tool for Designing Reusable Medical Devices for Reprocessing

[3]

Codes & Standards > Find Codes & Standard > V V 40 Assessing Credibility of Compu...

Assessing Credibility of Computational Modeling through Verification and Validation: Application to Medical Devices

V V 40 - 2018

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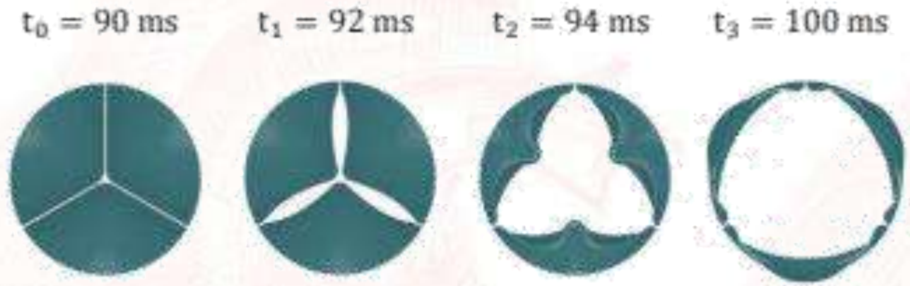
[2] U.S. Food & Drug Administration
[3] American Society of Mechanical Engineers

State of the Art - Finite Element Analysis (FEA)

Structural simulations

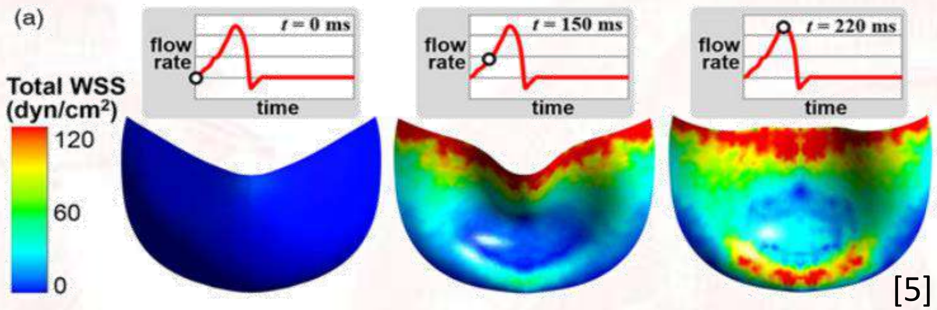


[4]

Output parameters:

- Equivalent von-Mises stress
- Equivalent strain
- Maximum displacement
- Maximum Geometric Orifice Area (GOA_{max})
- Maximum Coaptation Area (CA_{max})

Fluid-Structure Interaction (FSI) analysis



[5]

Output parameters:

- Wall Shear Stress (WSS)
- Volumetric Flow Rate (VFR)

$$\tau_w = \mu\left(\frac{\partial u}{\partial y}\right)_{y=0} = 32\mu\frac{Q}{\pi d^3}$$

High computational time to solve simulations

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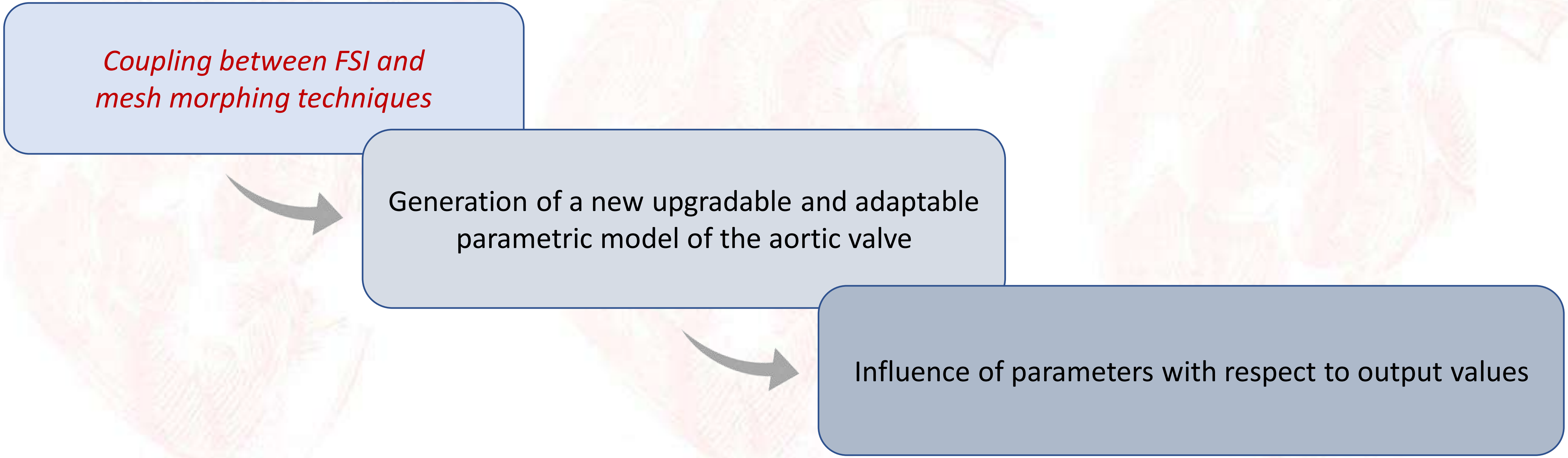
[4] *Pfensig et al,* Biomedical Engineering. 3(2):631–634, 2017

[5] *Cao et al.*, Computer methods in biomechanics and biomedical engineering. 19(6):603–613, 2016.

Aim of this work

Development of a novel numerical approach able to reduce computational time with ***fast-high fidelity***



Coupling between FSI and mesh morphing techniques

Generation of a new upgradable and adaptable parametric model of the aortic valve

Influence of parameters with respect to output values

Theoretical background - Mesh morphing

Method for changing the shape of a surface, preserving its topology: nodal positions are only updated

Based on Radial Basis Functions (RBF)

To interpolate in the space a scalar function s(x) defined at discrete points, giving the exact values at original points

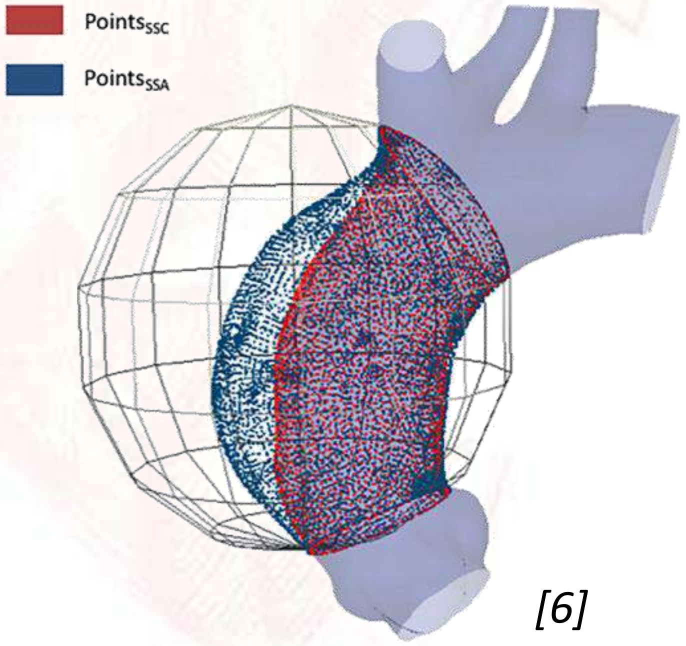
$$s(x) = \sum_{i=1}^{N} \gamma_i \varphi\left(\left\|x - x_{s_i}\right\|\right) + h(x)$$

$$h(x) = \beta_1 + \beta_2 x + \beta_3 y + \beta_4 z$$

↓ *3D-space*

$$\begin{cases} s_x(x) = \sum_{i=1}^{N} \gamma_i^x \varphi\left(\left\|x - x_{s_i}\right\|\right) + \beta_1^x + \beta_2^x x + \beta_3^x y + \beta_4^x z \\ s_y(x) = \sum_{i=1}^{N} \gamma_i^y \varphi\left(\left\|x - x_{s_i}\right\|\right) + \beta_1^y + \beta_2^y x + \beta_3^y y + \beta_4^y z \\ s_z(x) = \sum_{i=1}^{N} \gamma_i^z \varphi\left(\left\|x - x_{s_i}\right\|\right) + \beta_1^z + \beta_2^z x + \beta_3^z y + \beta_4^z z \end{cases}$$

γ_i: weights of the model
$\varphi(\cdot)$: RBF
x: generic position
x_{s_i}: source point
h(x): polynomial term



[6]

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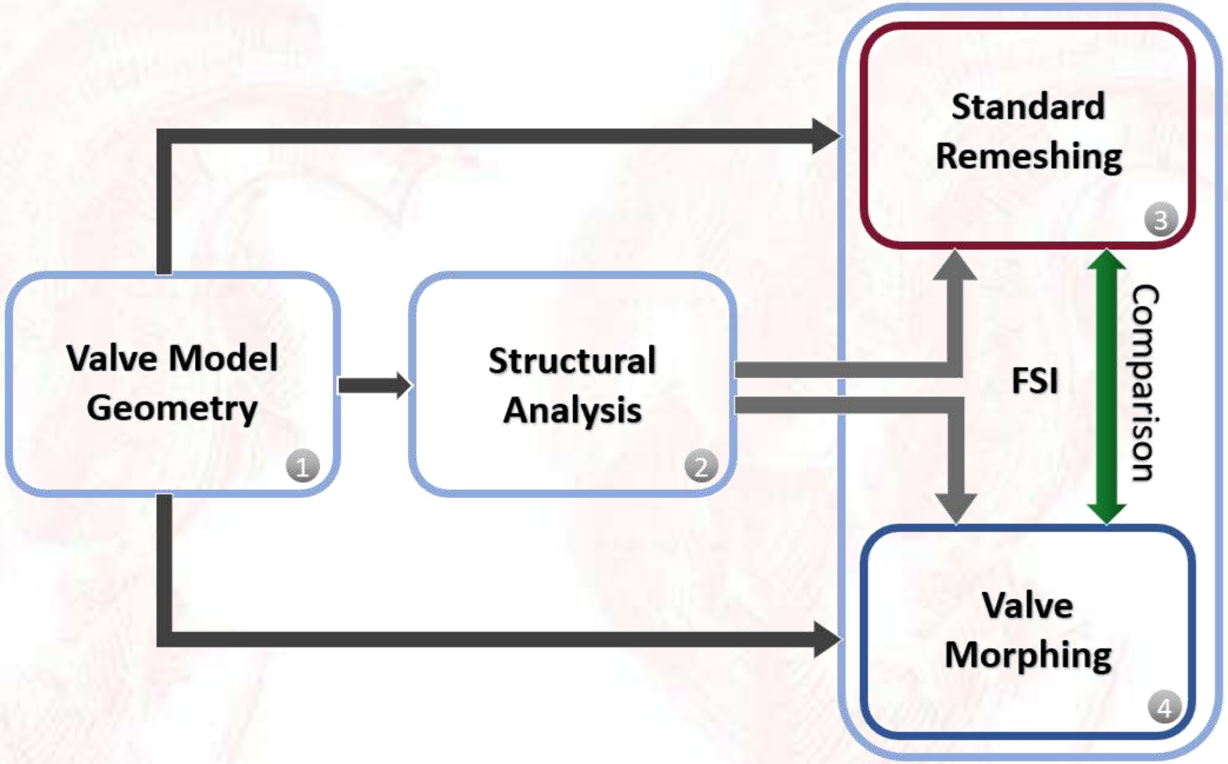
[6] *Capellini et al.* Journal of biomechanical engineering. 140(11): 110007, 2018.

Material and Methods

1. Valve design
    - Python & SpaceClaim
2. Structural analysis
    - Ansys Workbench Mechanical
3. Remeshing – FSI
    - Ansys Workbench Mechanical & Fluent System Coupling
4. ***Morphing – FSI***
    - **Fluent & RBF Morph Add-On**



M&M – Valve design

Parametric model

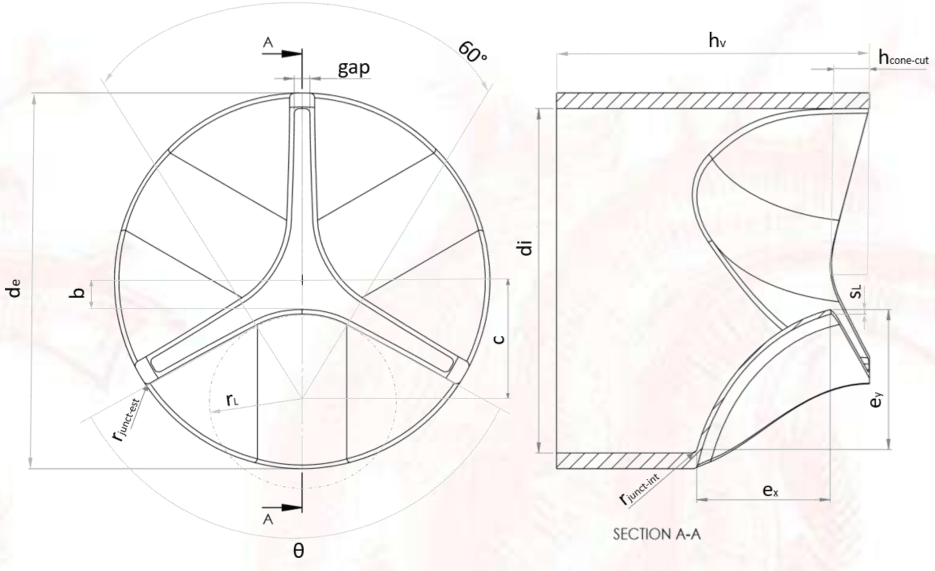
Identification of a surgical candidate

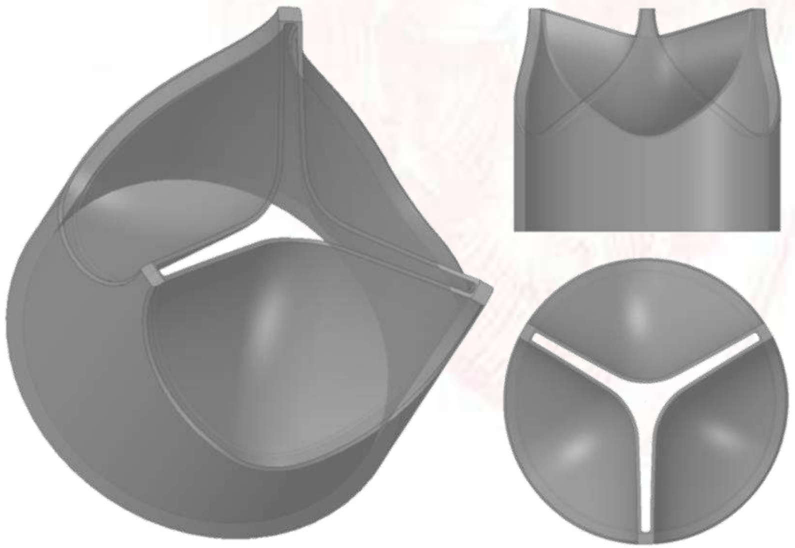
Design parameters

FIXED*

Parameter	Meaning	Value
r_e	External radius of the circular ring	Fixed: 12 mm
r_i	Internal radius of the circular ring	Fixed: 11 mm
θ	Revolution angle of the leaflets	Fixed: 120°
s_l	Thickness of the leaflets	Fixed: 0,3 mm
h_v	Height of the whole valve	Fixed: 20 mm
e_x	Ellipse-x parameter for the entrainment	Parametrized
e_y	Ellipse-y parameter for the entrainment	Parametrized
r_l	Radius of the internal arc which defines the upper surface of the leaflet	Parametrized
g	Semi-gap between one leaflet and the other one in proximity to the ring	Parametrized
$r_{junct-est}$	Junction radius between the external face of the leaflet and the ring	Parametrized
$r_{junct-int}$	Junction radius between the internal face of the leaflet and the ring	Parametrized
$h_{cone-cut}$	Maximum internal cutting height to generate Lunula angle of the valve	Parametrized

*@ patient specific level





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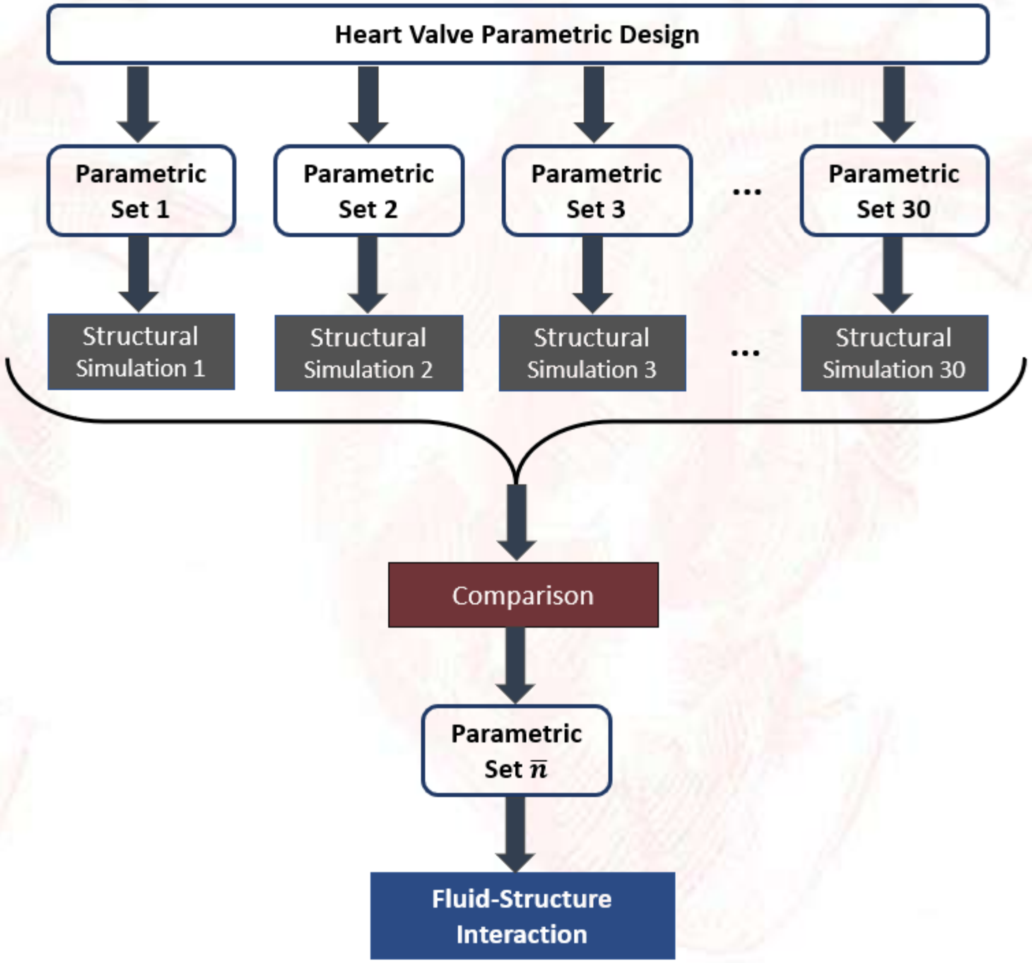


Heart Valve Parametric Design

Parametric Set 1

Parametric Set 2

Parametric Set 3

…

Parametric Set 30

Structural Simulation 1

Structural Simulation 2

Structural Simulation 3

…

Structural Simulation 30

Comparison

Parametric Set $\bar{n}$

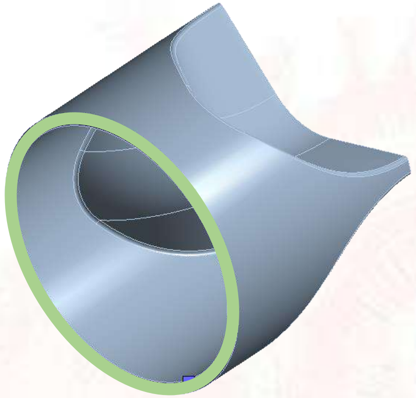
Fluid-Structure Interaction

*@ patient specific level

M&M – Structural simulations

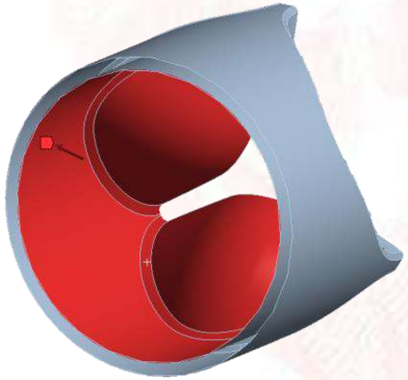
ANSYS Mechanical

- Material properties: isotropic linear elastic (E= 3 MPa, ν= 0.4)
- Element type: tetrahedral (from 237533 to 368730)
- Boundary condition: **bottom surface** of the circular **ring fixed in displacement**



Opening

- 15 opening simulations (O_1-O_{15})
- Transvalvular systolic pressure



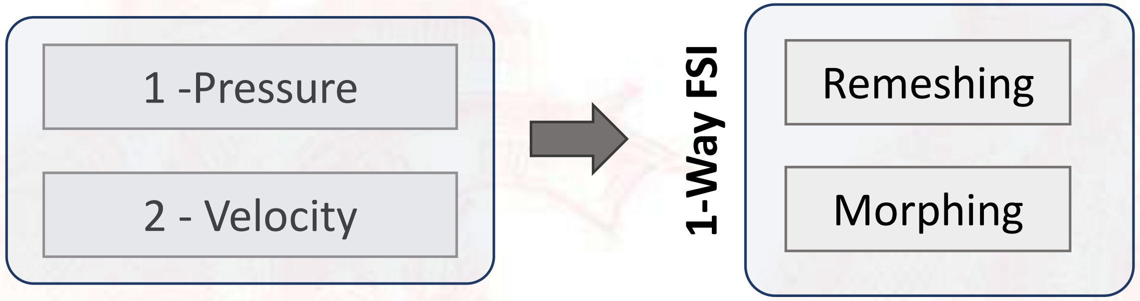
Closing

- 15 closing simulations (C_1-C_{15})
- Transvalvular diastolic pressure

M&M – Fluid-Structure Interaction

- **From structural analysis: Parametric set 15**

Two inlet boundary conditions



1 -Pressure

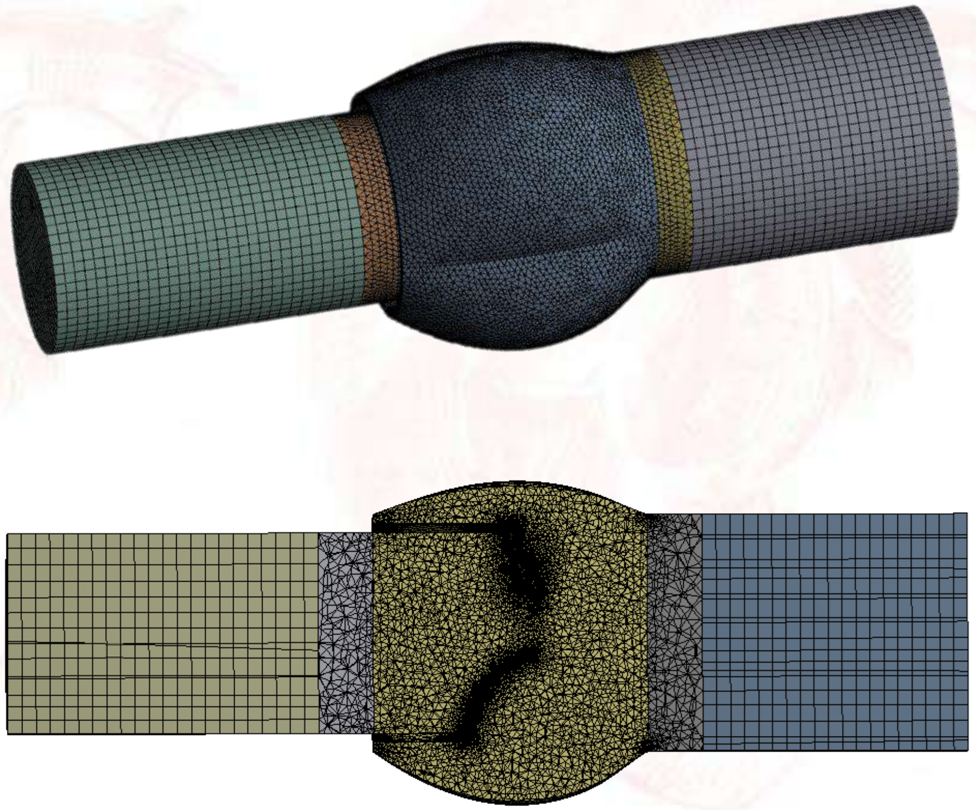
2 - Velocity

1-Way FSI

Remeshing

Morphing

Tetra-hexahedral Mesh



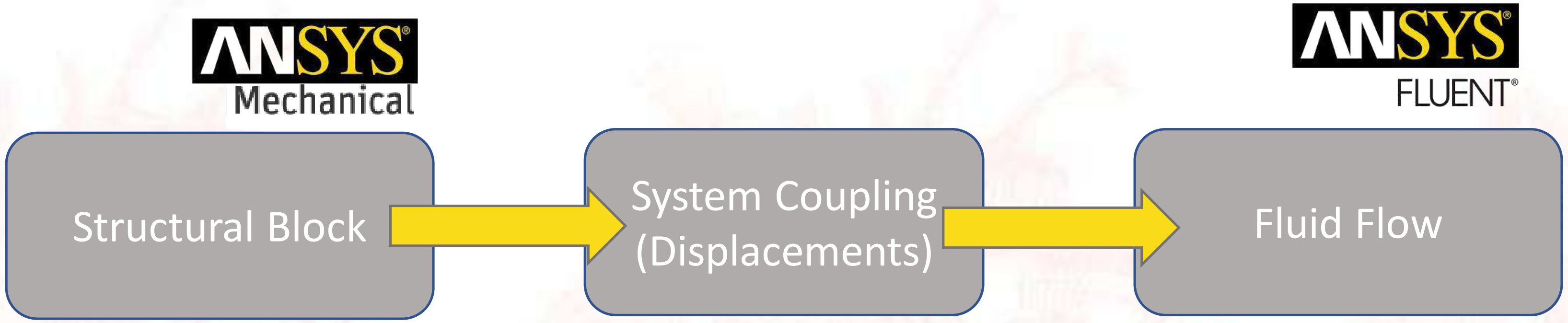
Fluid Setting:

- Newtonian fluid (μ= 4 cP) Viscous-Laminar
- ρ= 1000 kg/m^3
- Number of elements 1.5 million
- Time step= 1e-5 s
- Simulation time= 14 ms

Structural Setting:

- Number of elements 0.5 million
- Transvalvular systolic pressure @ ventricular side

M&M – Fluid-Structure Interaction *Remeshing-FSI*



ANSYS Mechanical

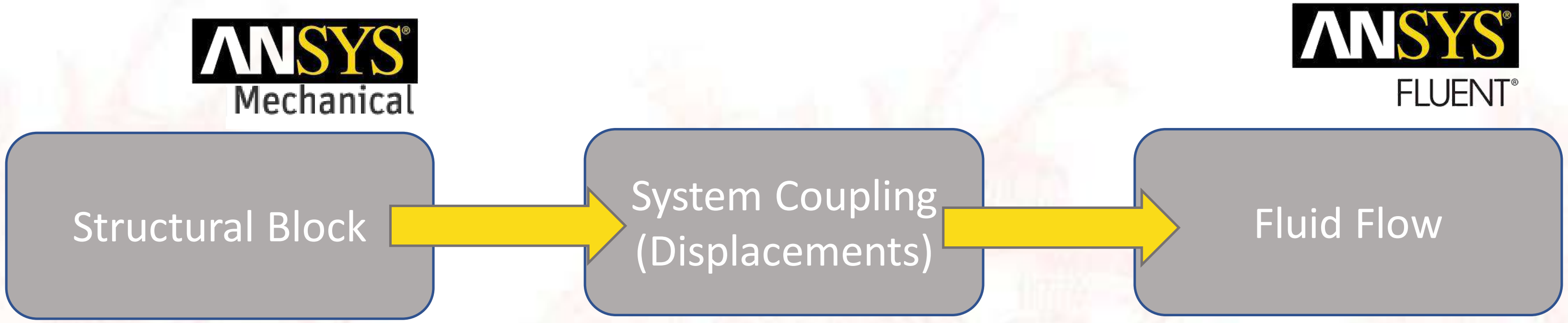
Structural Block

System Coupling (Displacements)

ANSYS FLUENT

Fluid Flow

M&M – Fluid-Structure Interaction *Remeshing-FSI*



Dynamic meshing tools:

1) Spring-Based Smoothing
2) **Remeshing**

Starting conditions

- Maximum starting Skewness=0.694
- Minimum element length=0.1 mm
- Maximum element length=1.8 mm

Remeshing if →

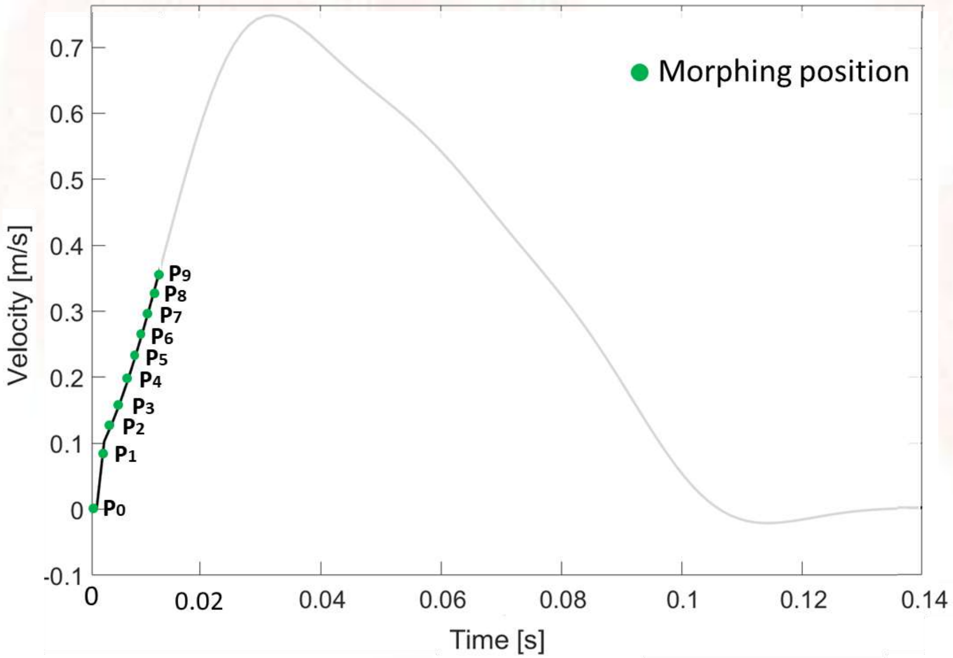
Limit conditions

- Skewness > 0.72
- Minimum element length < 0.06 mm
- Maximum element length > 2.5 mm

M&M – Fluid-Structure Interaction *Morphing-FSI*

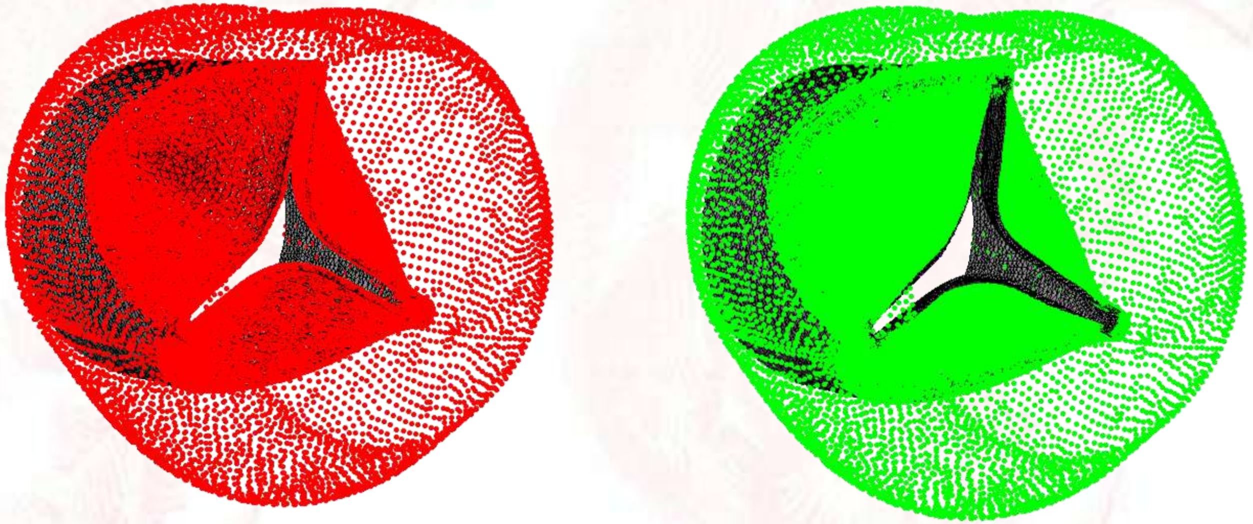
First strategy – one single direction of morphing

Source and Target points extracted with M-APDL by sampling the valve displacement every 3 mm



Source points

Target points



RBF: φ(r)=r

M&M – Fluid-Structure Interaction *Morphing-FSI*

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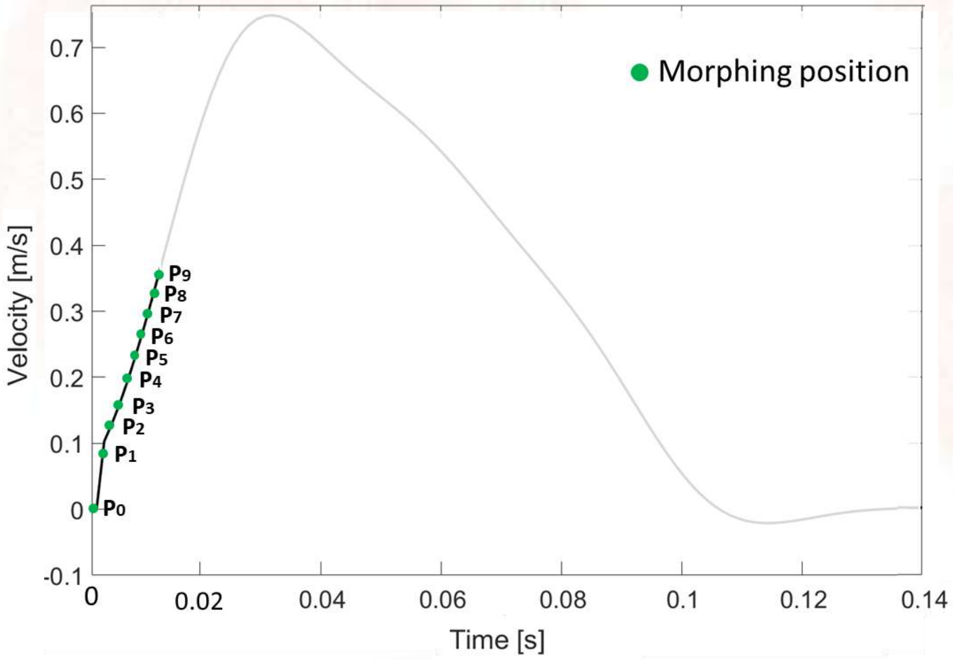

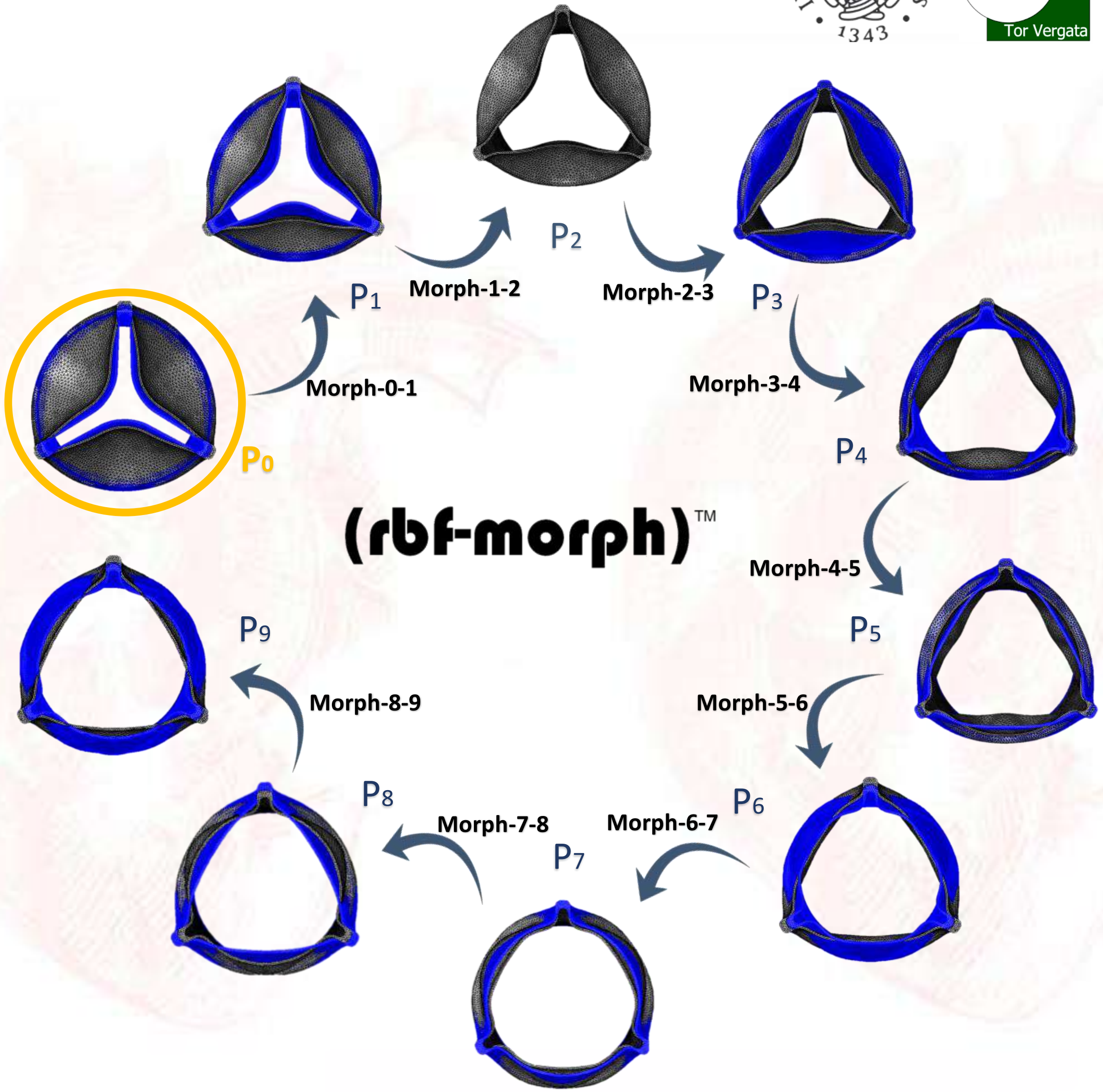

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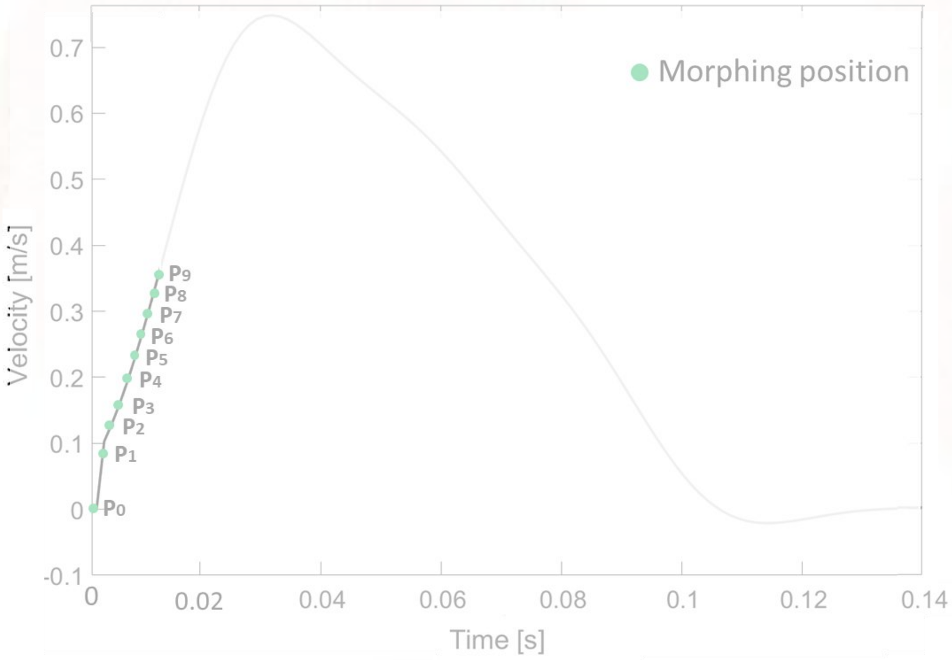
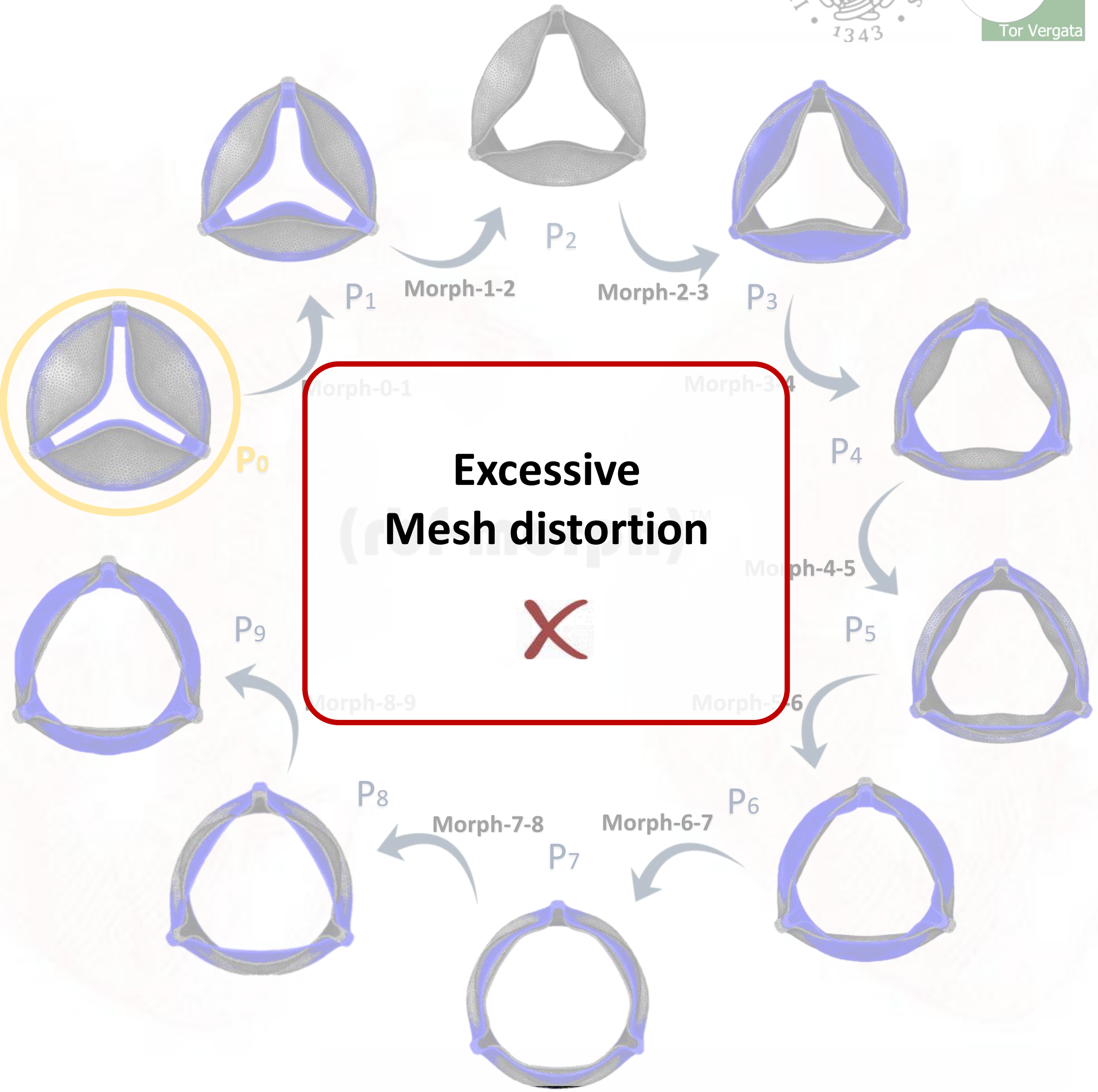




Excessive Mesh distortion

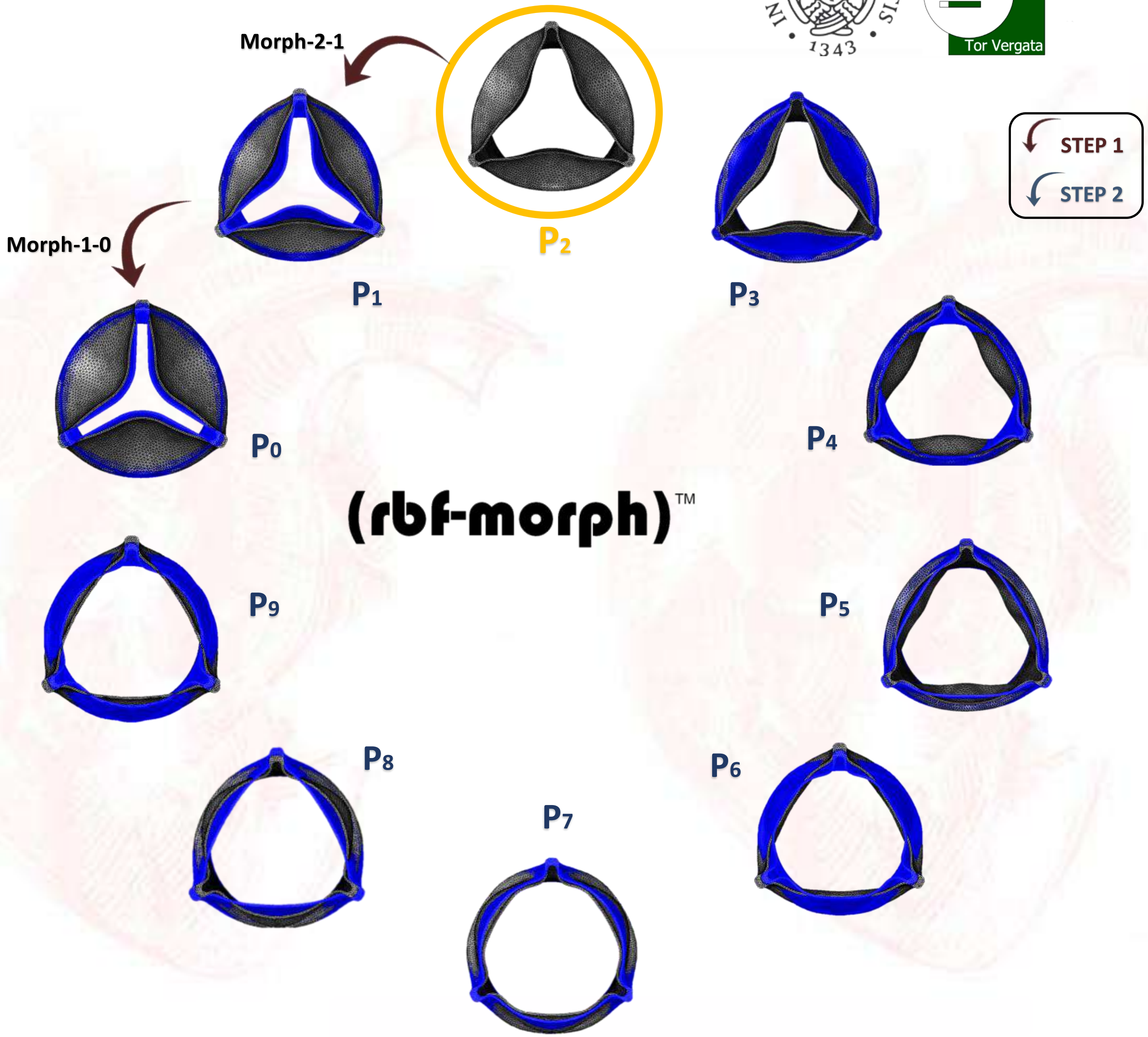
✗

M&M – Fluid-Structure Interaction *Morphing-FSI*

New morphing procedure

Step 1: from P_2 to P_0

- To reach initial position
- Saving of the mesh with a deformation already in place
- Initialization of the flow



M&M – Fluid-Structure Interaction *Morphing-FSI*

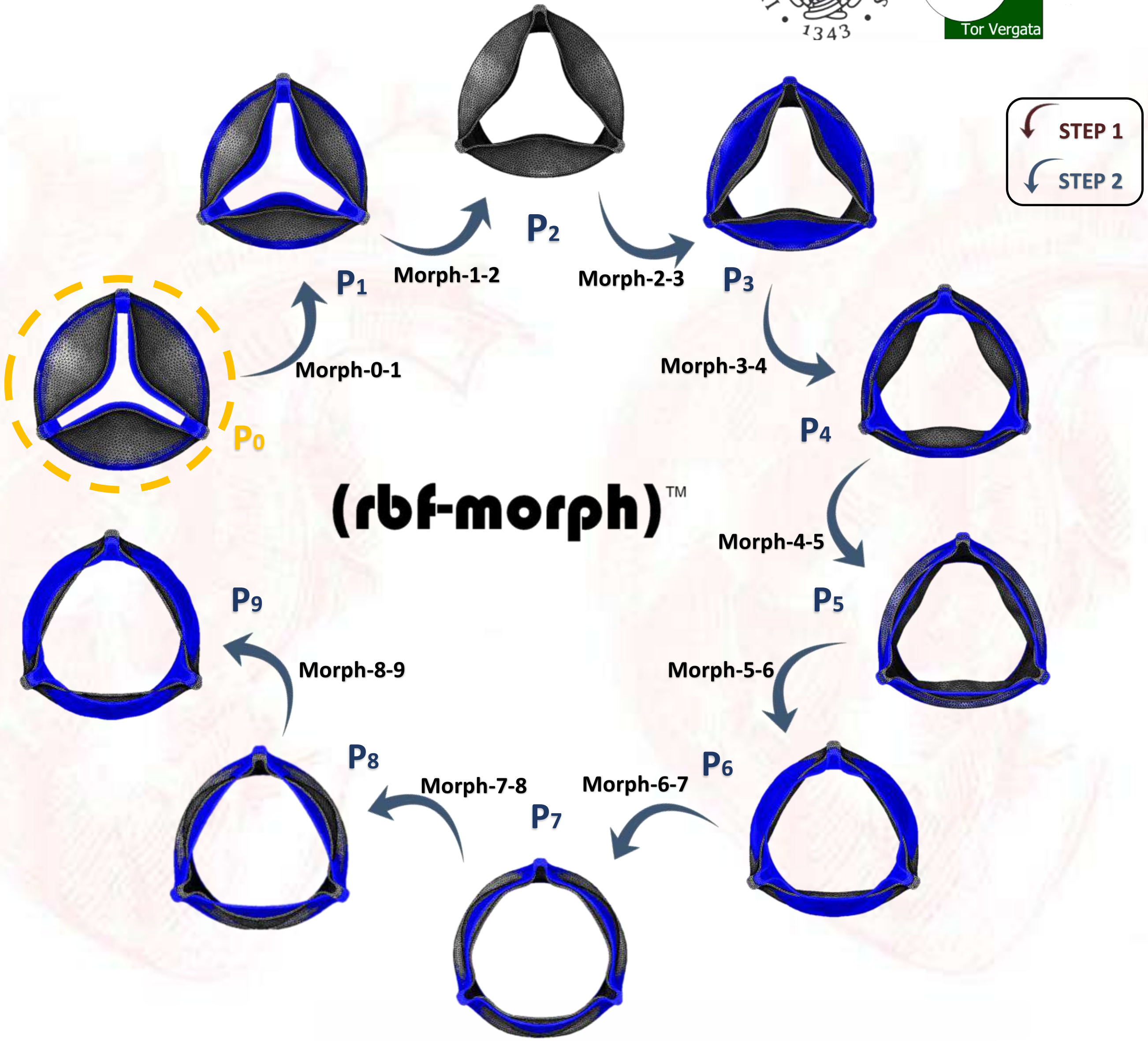
New morphing procedure

Step 1: from P_2 to P_0

- To reach initial position
- Saving of the mesh with a deformation already in place
- Initialization of the flow

Step 2: from P_0 to P_9

- To morph all the opening of the valve



M&M – Fluid-Structure Interaction *Morphing-FSI*

New morphing procedure

Step 1: from P_2 to P_0

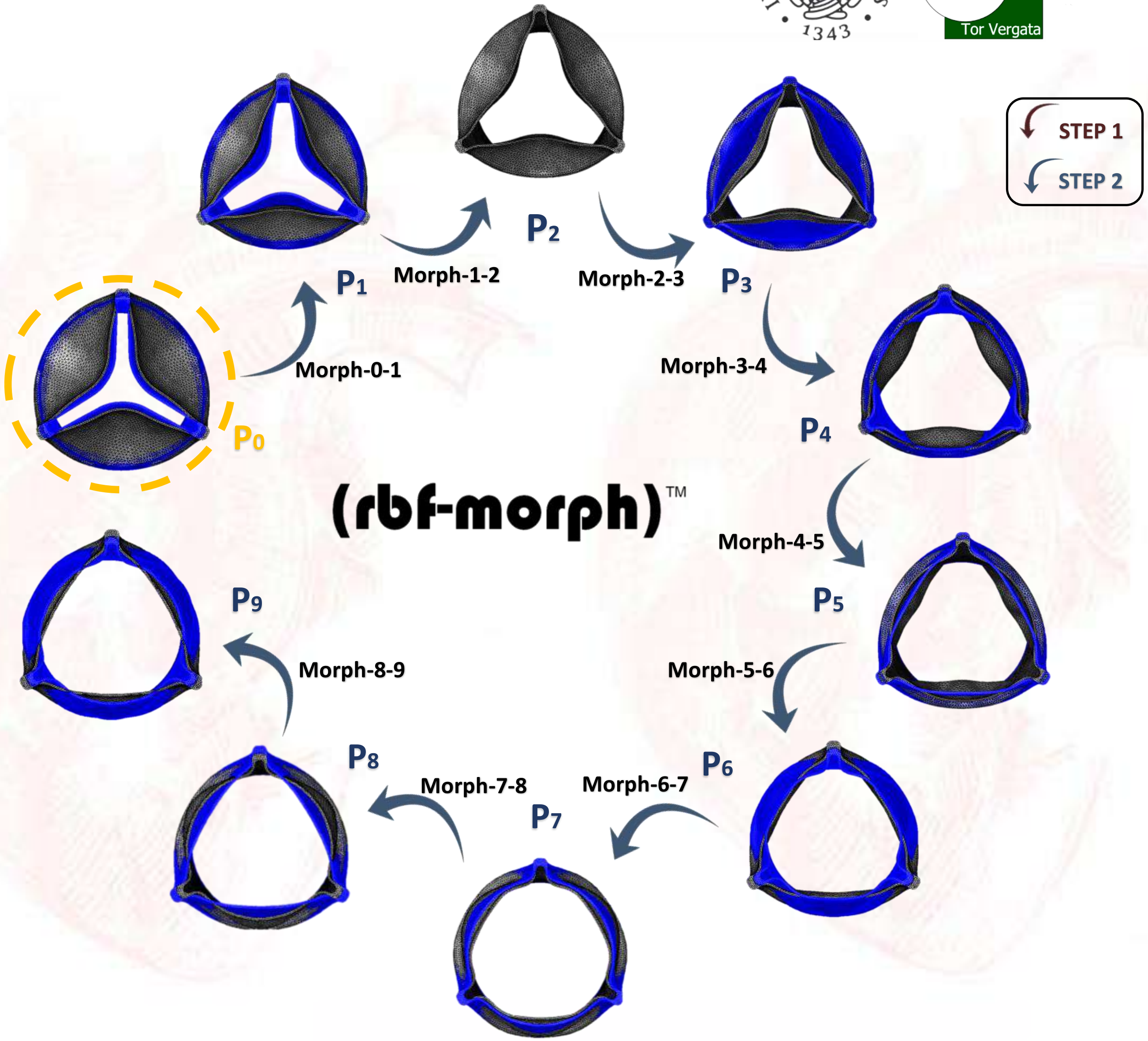
- To reach initial position
- Saving of the mesh with a deformation already in place
- Initialization of the flow

Step 2: from P_0 to P_9

- To morph all the opening of the valve

Scheme program

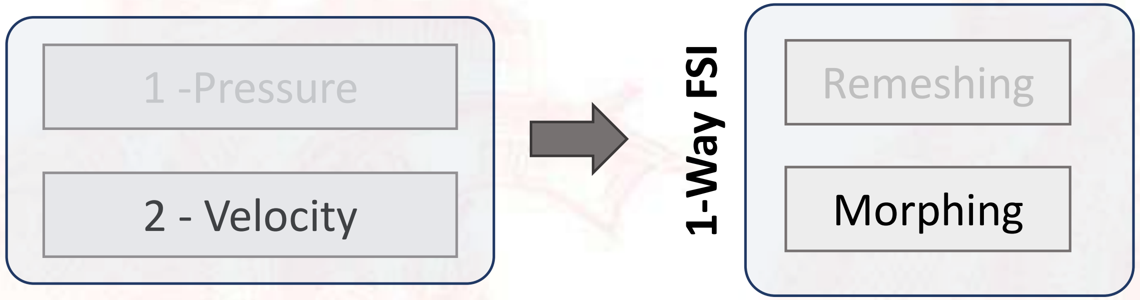
$$A_0(t) = \begin{cases} 0, & \text{if } t\ = \ 0 \\ \left(\frac{t}{t_1}\right)^2, & \text{if } 0 < t < t_1 \\ 1, & \text{if } t \geq t_1 \end{cases} \qquad A_i(t) = \begin{cases} 0, & \text{if } t \leq t_i \\ \frac{t-t_i}{t_{i+1}-t_i}, & \text{if } t_i < t < t_{i+1} \\ 1, & \text{if } t \geq t_{i+1} \end{cases}$$



M&M – Fluid-Structure Interaction

Complete opening simulation

Only one inlet boundary condition



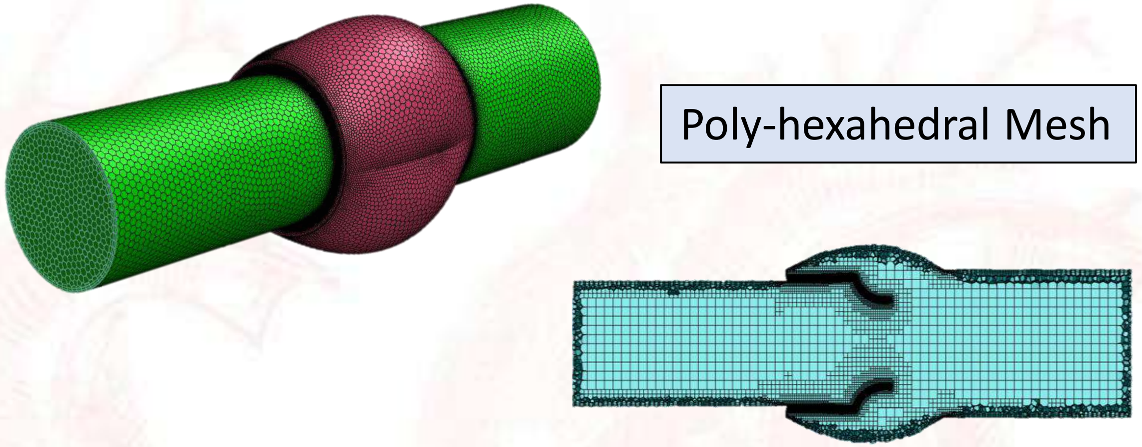
1 -Pressure

2 - Velocity

1-Way FSI

Remeshing

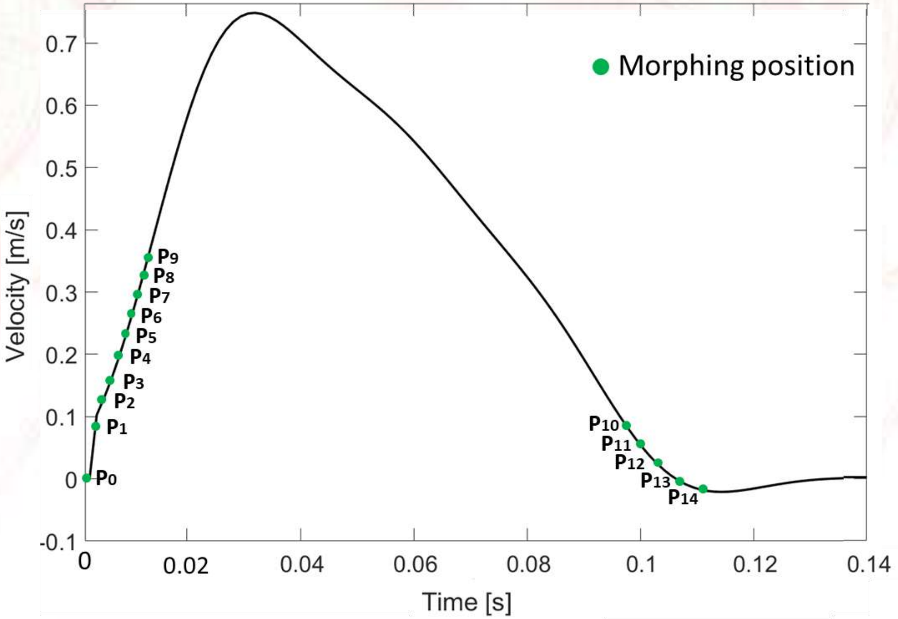
Morphing



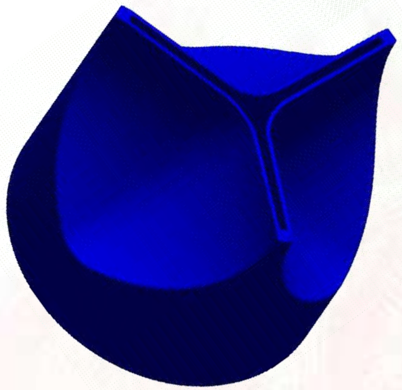
Poly-hexahedral Mesh

<u>Fluid Setting</u>:
- Newtonian fluid (μ= 4 cP) Viscous-Laminar
- ρ= 1000 kg/m^3
- Number of elements 0.9 million
- Time step= 5e-5 s
- Simulation time: 110 ms

<u>Structural Setting</u>:
- Number of elements 0.5 million
- Transvalvular systolic pressure @ ventricular side

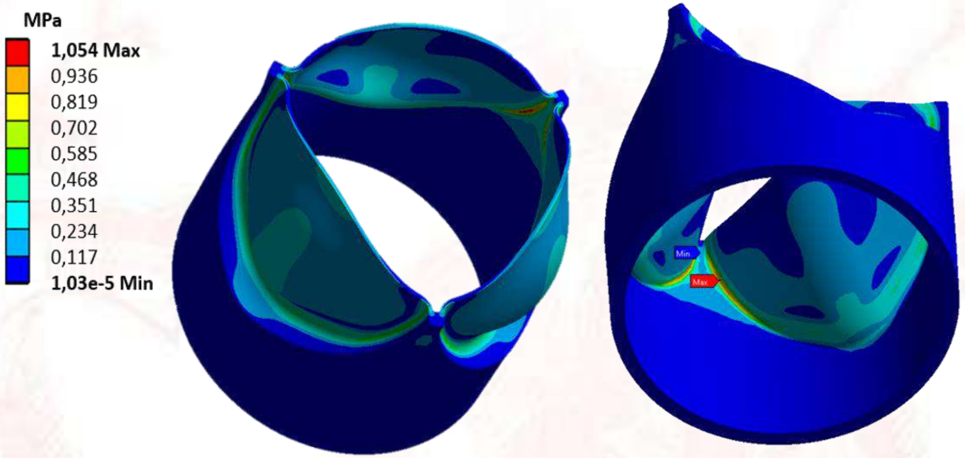


Results – Structural simulations



Opening O_{15}

- Maximum eq. von-Mises stress: 1.05 MPa
- Maximum eq. strain: 0.344
- Maximum displacement: 8.74 mm
- GOA_{max}: 363.6 mm^2 *[7]*



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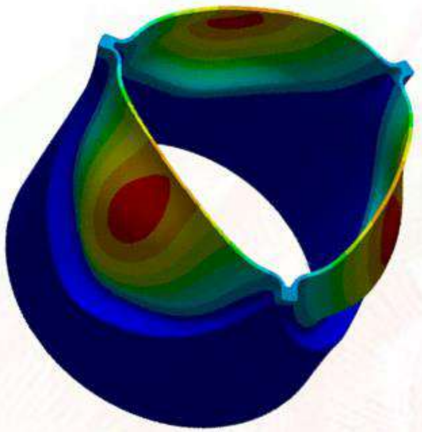
[7] Luraghi et al., Cardiovascular engineering and technology. 9(4):723–738, 2018

Results – Structural simulations



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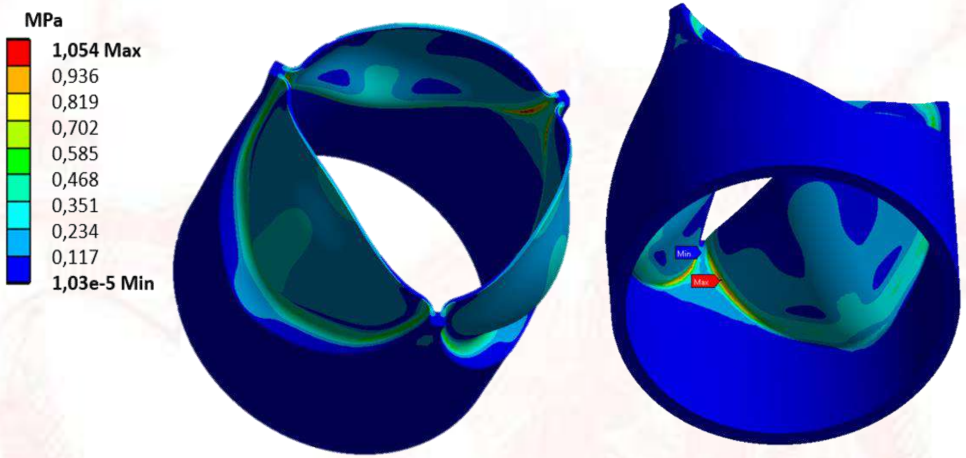
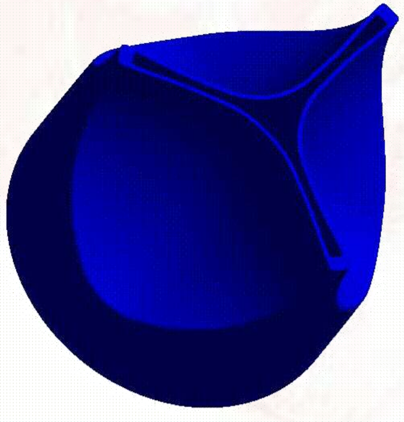
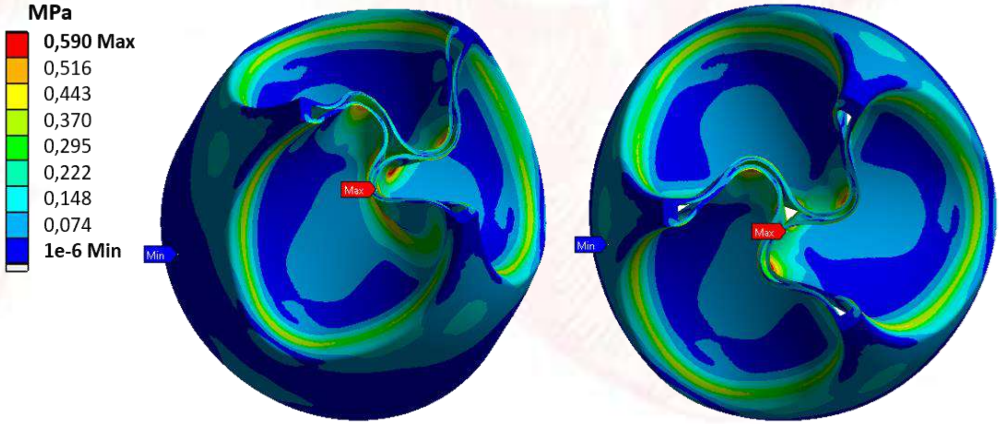




Closing C_{15}

- Maximum eq. von-Mises stress: 0.59 MPa
- Maximum eq. strain: 0.21
- Maximum displacement: 6.18 mm
- CA_{max} : 28.6 mm^2 *[8]*



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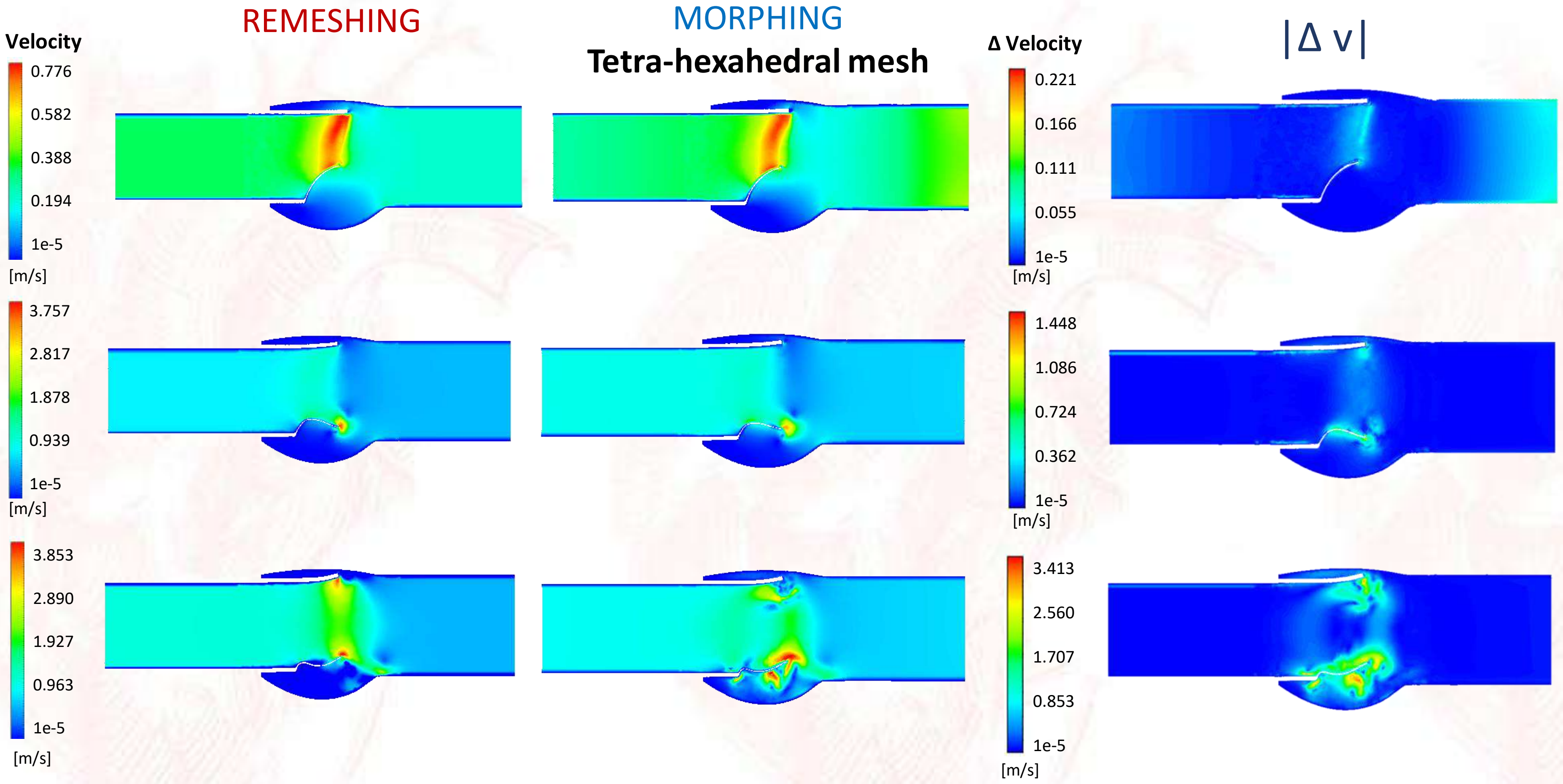
[7] Luraghi et al., Cardiovascular engineering and technology. 9(4):723–738, 2018

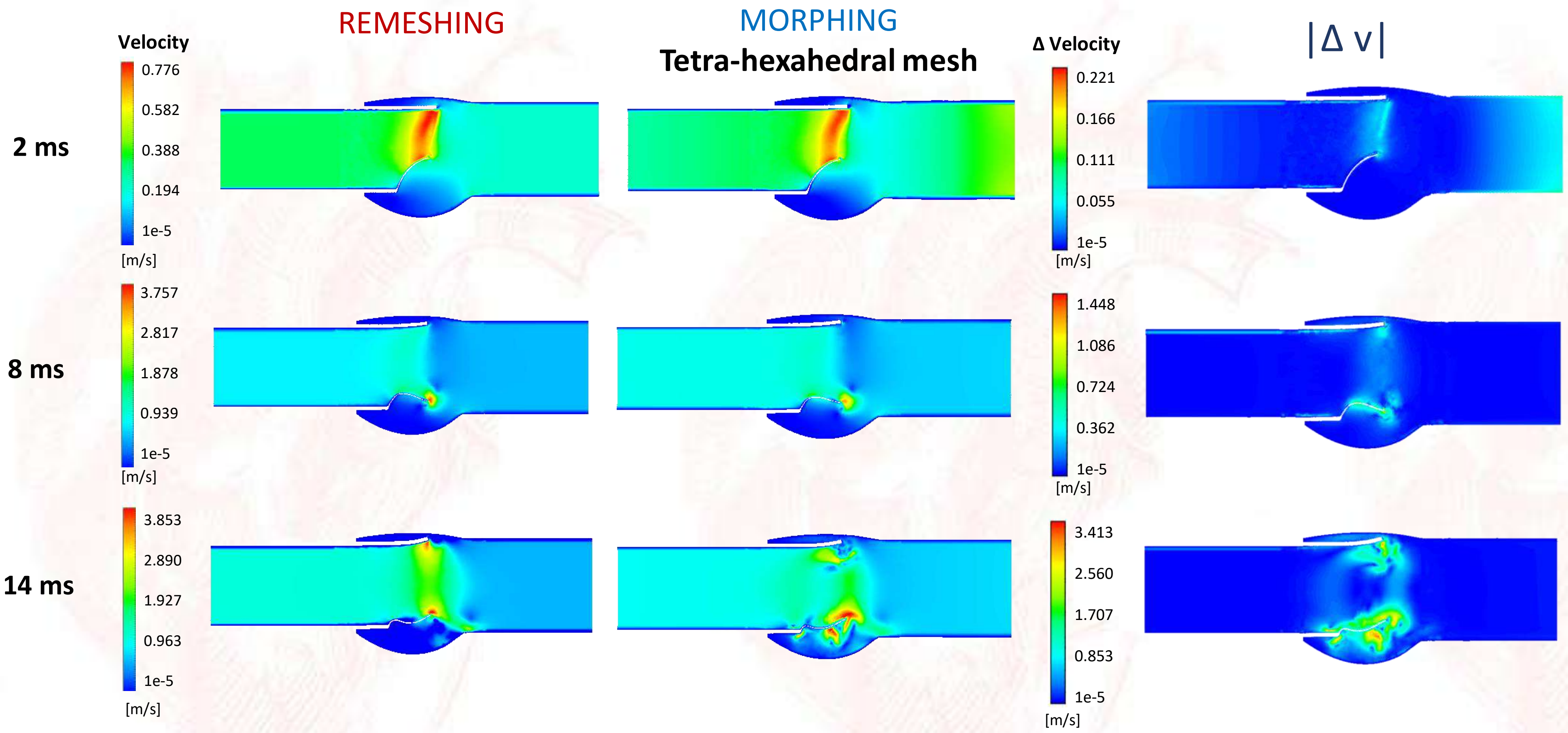
[8] Pfensig et al., Biomedical Engineering. 3(2):631–634, 2017

Results – Pressure inlet FSI



	Δv_{max}	Δv_{mean}
2 ms	-6.97%	+3.21%
8 ms	+2.66%	+1.00%
14 ms	+0.87%	+4.44%

Results – Pressure inlet FSI



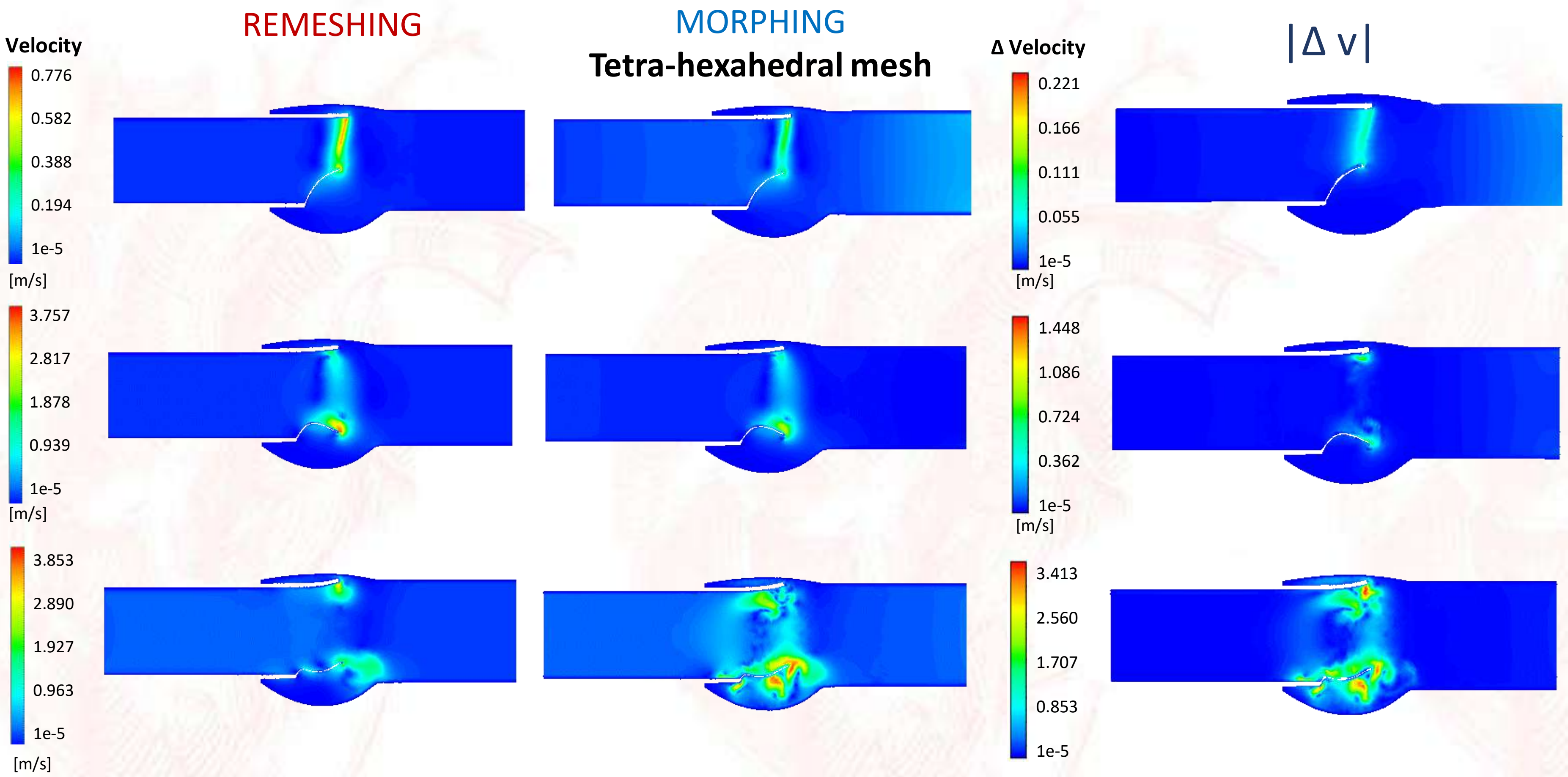
	Δv_{max}	Δv_{mean}
2 ms	-6.97%	+3.21%
8 ms	+2.66%	+1.00%
14 ms	+0.87%	+4.44%

Computational time

Remeshing: 6283 minutes
Morphing: 396 minutes

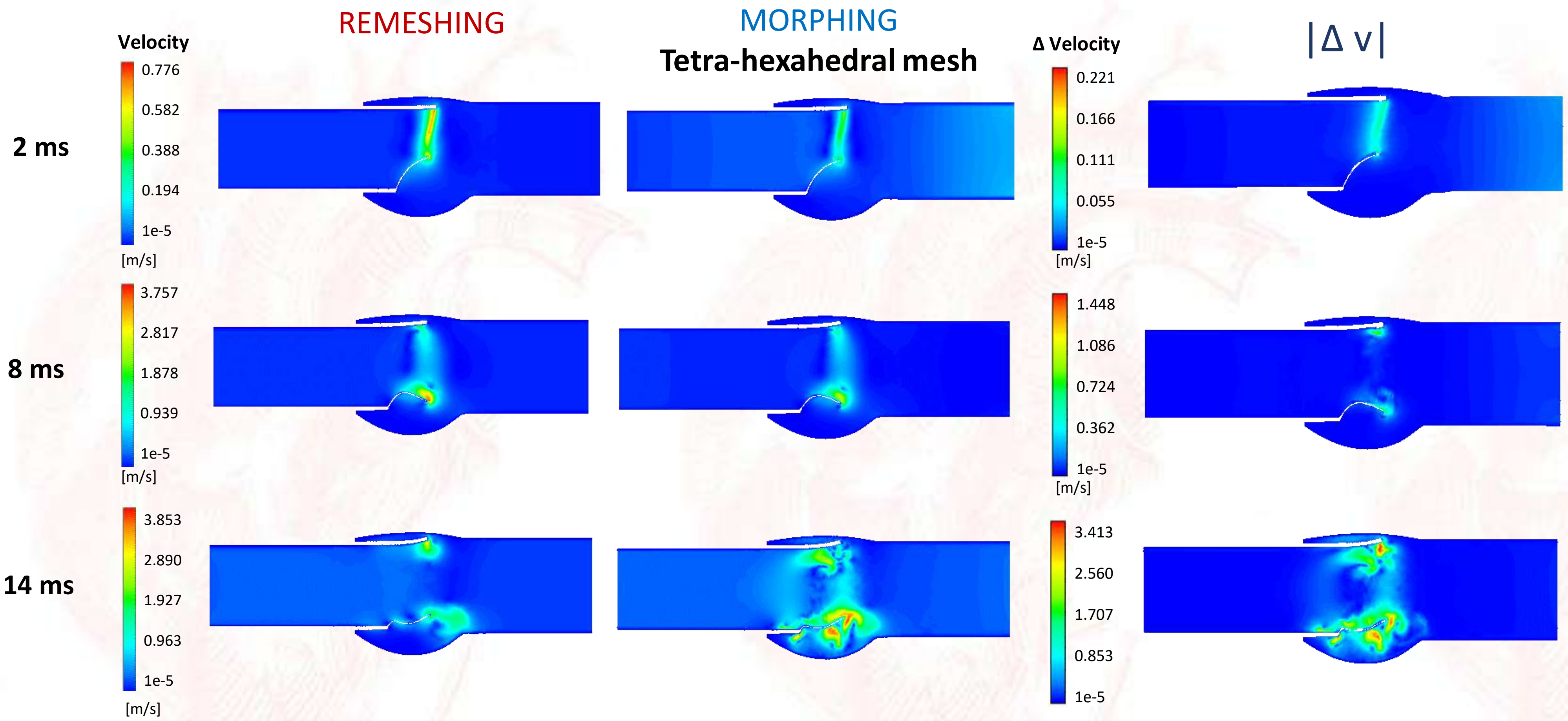
→ **16 times faster**

Results – Velocity inlet FSI



	Δv_{max}	Δv_{mean}
2 ms	-8.16%	+3.11%
8 ms	-3.12%	-1.98%
14 ms	+5.32%	+13.72%

Results – Velocity inlet FSI



	Δv_{max}	Δv_{mean}
2 ms	-8.16%	+3.11%
8 ms	-3.12%	-1.98%
14 ms	+5.32%	+13.72%

Computational time

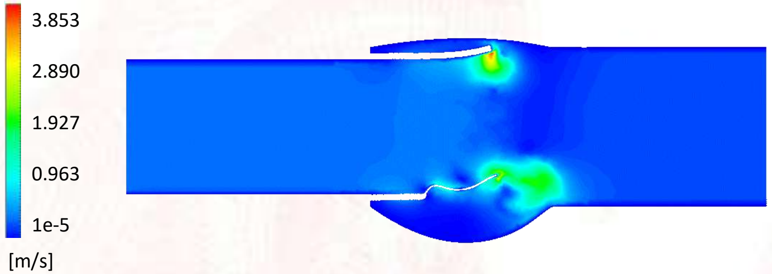
Remeshing: 7211 minutes
Morphing: 475 minutes

→ **15 times faster**

Results – Full opening FSI

14 ms

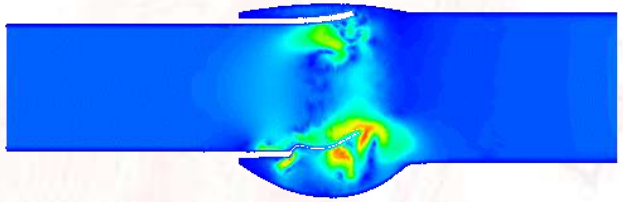
REMESHING



Max Velocity 3.891 m/s
Mean Velocity 0.401 m/s

MORPHING

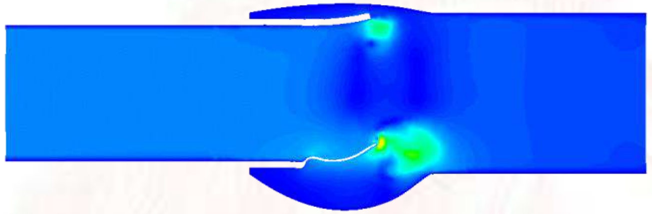
Tetra-hexahedral mesh



Max Velocity 3.688 m/s
Mean Velocity 0.456 m/s

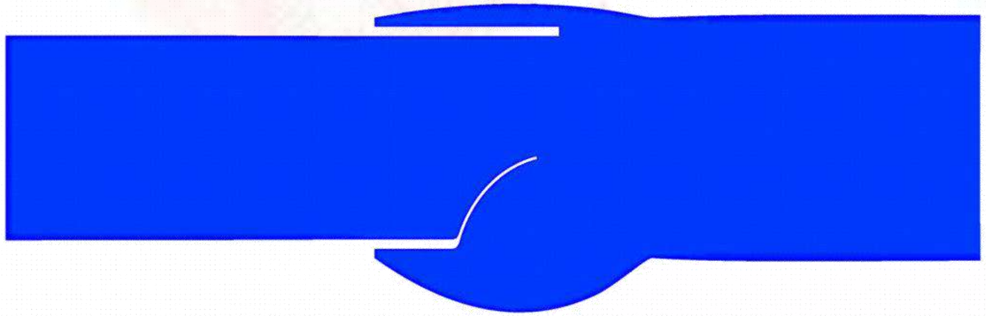
MORPHING

Poly-hexahedral mesh

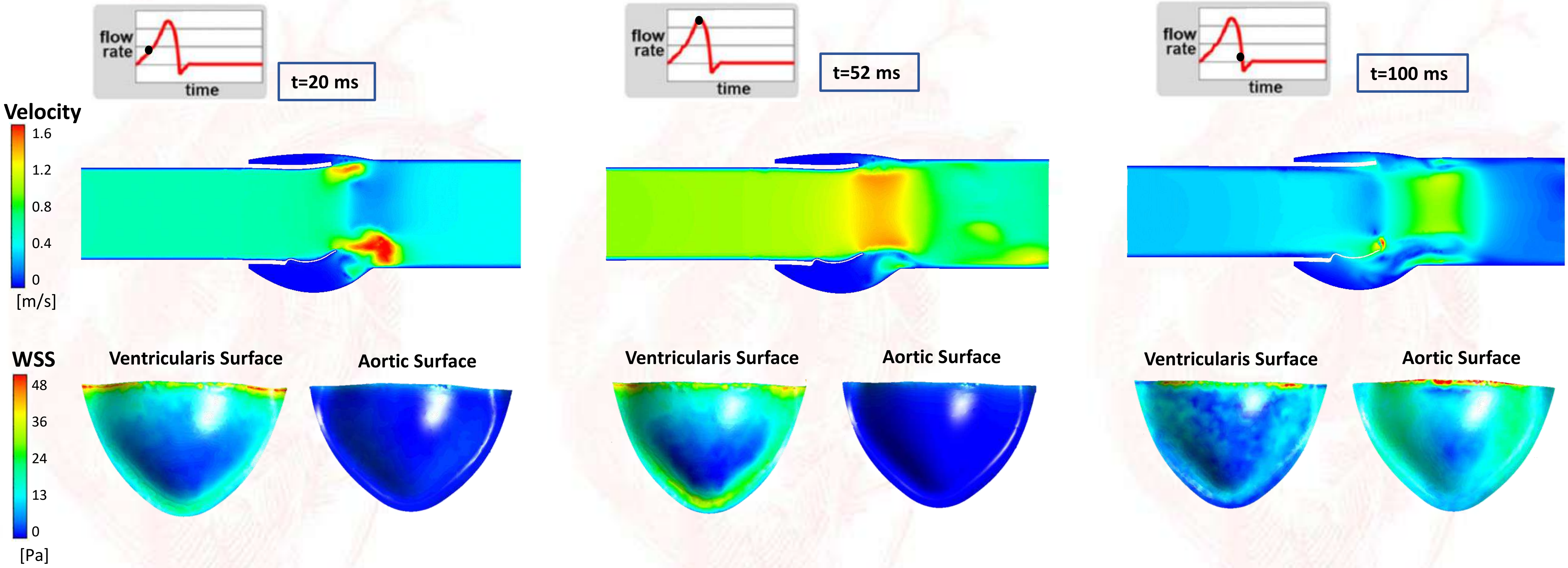


Max Velocity 3.683 m/s
Mean Velocity 0.403 m/s

Δv_{max}	-5.32%	-5.35%
Δv_{mean}	+13.72%	**+0.50%**



Results – Full opening FSI



$\mathrm{WSS}_{\mathrm{max}} = 47.58$ Pa
$\mathrm{WSS}_{\mathrm{mean}} = 6.99$ Pa

$\mathrm{WSS}_{\mathrm{max}} = 47.64$ Pa *[9]*
$\mathrm{WSS}_{\mathrm{mean}} = 7.46$ Pa *[10]*

$\mathrm{WSS}_{\mathrm{max}} = 46.12$ Pa
$\mathrm{WSS}_{\mathrm{mean}} = 7.51$ Pa

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[9] *Cao et al.*, Computer methods in biomechanics and biomedical engineering. 19(6):603–613, 2016.
[10] *Burwash, Journal of Biomechanics.* 9(2):92–99, 2014.

Conclusions

- High fidelity workflow to solve FSI simulations faster than 15 times in comparison to standard remeshing procedures with similar results

- Based on a parametric patient-specific heart valve design

- Output values consistent with State of the Art

Future developments

- Implementation of a 2-Way FSI (remeshing and morphing)

- Closing FSI simulation

Towards a complete cardiac cycle…

Thank you for the attention