The effect of element formulation on FSI heart valve simulations

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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

**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

\[
\rho = 1100 \, \text{kg/m}^3 \\
E = 3 \, \text{MPa} \\
\nu = 0.49 \\
\text{Thickness} = 0.4 \, \text{mm} \\
\text{BC: fixed commissural edges}
\]

**Fluid:** blood in a rigid tube

\[
\rho = 1060 \, \text{kg/m}^3 \\
\mu = 3.5 \, \text{cP} \\
\text{BC: physiological pressure gradient}
\]
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**
- $B_1$
- $B_2$
- $B_3$
- $B_2 - T_2$
- $B_2 - T_8$

Geometric Orifice Area [mm$^2$]

- $S_1$
- $S_2$
- $S_3$

Time [s]

$B_1$
- $B_2$
- $B_3$
- $B_2 - T_2$
- $B_2 - T_8$

Time [s]
Accuracy of FSI Heart Valves Simulations

\( S_2 \): Belytschko-Lin-Tsay reduced-int, Hg Viscosity, Damp 1-5
\( S_2 \text{-BL} \): Belytschko-Leviathan, Damp 1-5
\( S_2 \text{-HgS} \): Belytschko-Lin-Tsay reduced-int, Hg Stiffness, Damp 1-5
\( S_2 \text{-FI} \): full-int, Damp 1-5
\( S_2 \text{-T} \): thickness enhanced reduced-int, Damp 1-5
\( S_2 \text{-D}_{0.1} \): \( S_2 \) model, Damp 0.1-0.1
\( S_2 \text{-D}_{5} \): \( S_2 \) model, Damp 5-5

*ELFORM=2 *IHQ=2
*ELFORM=8
*IHQ=4
*ELFORM=16
*ELFORM=25
**Accuracy of FSI Heart Valves Simulations**

\( B_2 \): quadratic full-int, Damp 0.1-1

\( B_2 \text{-FI} \): linear full-int, Damp 0.1-1

\( B_2 \text{-FI}_{\text{Adv}} \): linear advance full-int, Damp 0.1-1

\( B_2 \text{-RI-HgV} \): reduced-int Viscous, Hg Viscosity , Damp 0.1-1

\( B_2 \text{-RI-HgS} \): reduced-int Stiffness, , Hg Stiffness , Damp 0.1-1

\( B_2 \text{-D}_{0.05} \): \( B_2 \) model, Damp 0.05-0.05

\[ *\text{ELFORM}=3 \]

\[ *\text{ELFORM}=2 \]

\[ *\text{ELFORM}=-2 \]

\[ *\text{ELFORM}=1 \text{ } *\text{IHQ}=2 \]

\[ *\text{ELFORM}=1 \text{ } *\text{IHQ}=4 \]
Accuracy of FSI Heart Valves Simulations

Von-Mises Stress

0 [MPa] 0.8
Accuracy of FSI Heart Valves Simulations

$S_2$-FSI$_1$

$S_2$-FSI$_2$

$S_2$-FSI$_3$

$S_2$-FSI$_{2q}$

GOA [mm$^2$] vs. time [s]

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**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
- $S_2 - FSI_2 - Sf_3$: 3 scale factor BC

![Graph showing GOA vs time for different conditions](image)
Accuracy of FSI Heart Valves Simulations

$B_2$: quadratic full-int Damp 0.1-1
$B_2$–$\text{FSI}_2$: 1 scale factor BCs
$B_2$–$\text{FSI}_2$-$\text{Sf}_2$: 2 scale factor BCs
$B_2$–$\text{FSI}_2$-$\text{Sf}_3$: 3 scale factor BCs

![Graph showing GOA [mm$^2$] vs. time [s] for different simulations.](image-url)

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Accuracy of FSI Heart Valves Simulations
Contents of the speech

Study on the Accuracy of FSI Heart Valves Simulations

Transcatheter Aortic Valve Implantation: an FSI study

**Aim:** 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

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TAVI: an FSI study

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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

- 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:

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PATIENT-SPECIFIC DOMAIN: AORTA

CT images segmentation

35,640 hexahedral fully integrated elements

*ELFORM=2
Hyperelastic matrix with embedded fibres

\*MAT_USER_DEFINED_MATERIAL

**a:** circumferential direction

**b:** longitudinal direction

\[ W = C_{10} (I_1 - 3) + \frac{k_1}{2k_2} [e^{k_2 (I_4 - 3)^2} - 1] + \frac{k_3}{2k_4} [e^{k_4 (I_6 - 3)^2} - 1] + \frac{k}{2} (J - 1)^2 \]

- \( C_{10} = 5 \text{ kPa} \)
- \( \nu = 0.49 \)
- \( \rho = 1100 \text{ kg/m}^3 \)
- \( k_1 = 50.31 \text{ kPa} \)
- \( k_2 = 0.56 \)
- \( k_3 = 82.51 \text{ kPa} \)
- \( k_4 = 57.53 \)

Holzapfel-Gasser-Odgen model

Vande Geest et al., 2006
PATIENT-SPECIFIC DOMAIN: NATIVE VALVE

Commissure reference points

End-diastole configuration

Linear elastic

*MAT_ELASTIC

\[ E = 4 \, MPa \]

\[ \nu = 0.45 \]

\[ \rho = 1100 \, kg/m^3 \]
TAVI: an FSI study

**Linear elastic**

*MAT_ELASTIC*

\( E = 12.6 \, MPa \)

\( \nu = 0.45 \)

\( \rho = 2000 \, kg/m^3 \)

**PATIENT-SPECIFIC DOMAIN: CALCIFICATIONS**

38,429 tetrahedral elements

*ELFORM=10
I STEP
Pre-TAVI Cardiac cycles

velocity [m/s]  0  4

1st Princ $\sigma$ [MPa]  0  0.4

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II STEP
Implantation
TAVI: an FSI study

II STEP
Implantation
TAVI: an FSI study

II STEP
Implantation

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**TAVI: an FSI study**

**III STEP**
Cardiac Cycle

- Aortic outlet
- Ventricular inlet

**Newtonian fluid**

*MAT_NULL

\[
\rho = 1060 \text{ kg/m}^3
\]

\[
\mu = 3.5 \text{ cP}
\]

113,216 hexahedral Eulerian one-point elements

*ELFORM=11

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TAVI: an FSI study

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Thank you for the attention

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26th Congress of the European Society of Biomechanics

MILANO

12-15 July 2020

Save the date!

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