Fully-coupled FSI Simulation Of Bioprosthetic Heart Valve Using Smoothed Particle Hydrodynamics

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INTRODUCTION

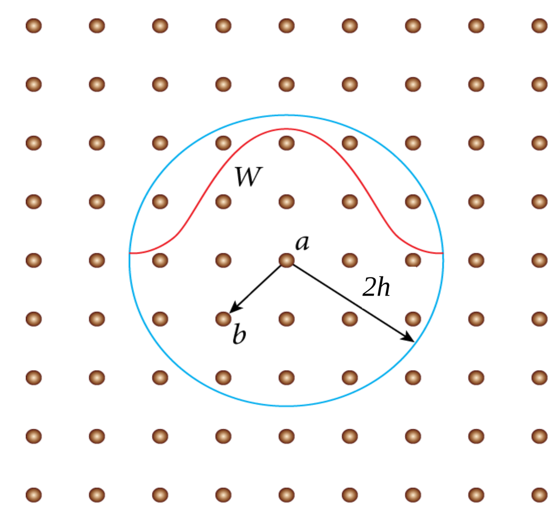
- Clinically, bioprosthetic heart valves (BHV) are often used to replace the malfunctioning native heart valves.
- Transcatheter aortic valve (TAV) replacement is an alternative therapy to surgical valve replacement for high-risk patients with severe aortic stenosis.
- In recent years, there has been great effort put in understanding the hemodynamics and mechanics of BHVs.
- Fluid-structure interaction (FSI) simulation is the most accurate computer modelling method to capture hemodynamic and structural details through BHVs.

Objective: Develop a novel FSI model that could capture the hemodynamics and structural response of BHVs during the full cardiac cycle.

METHODS

Smoothed Particle Hydrodynamics (SPH)

- SPH is a meshless, Lagrangian particle-based method



The property of particle 'a' is determined by the properties of its neighboring particles based on an interpolating kernel function W

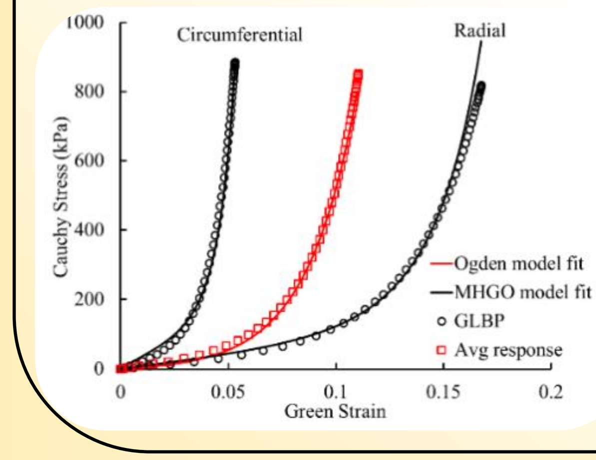
- Blood properties: $\rho_0 = 1056$ kg/m^3, $\mu = 0.0035$ Pa · s

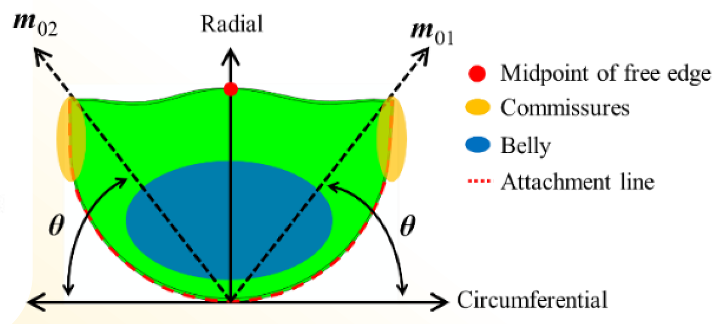
Finite Element (FE) Modeling

- TAV model: 23 mm generic TAV model adopted from Li and Sun[1]
- Leaflets with a thickness of 0.25 mm modeled using large-strain brick (C3D8R) elements in Abaqus/Explicit 6.13
- Constitutive models for bovine pericardium:

➢ Isotropic Ogden model: $W = \sum_{i=1}^{N} \frac{2\mu_i}{\alpha_i^2}\left(\bar{\lambda}_1^{\alpha_i} + \bar{\lambda}_2^{\alpha_i} + \bar{\lambda}_3^{\alpha_i} - 3\right)$

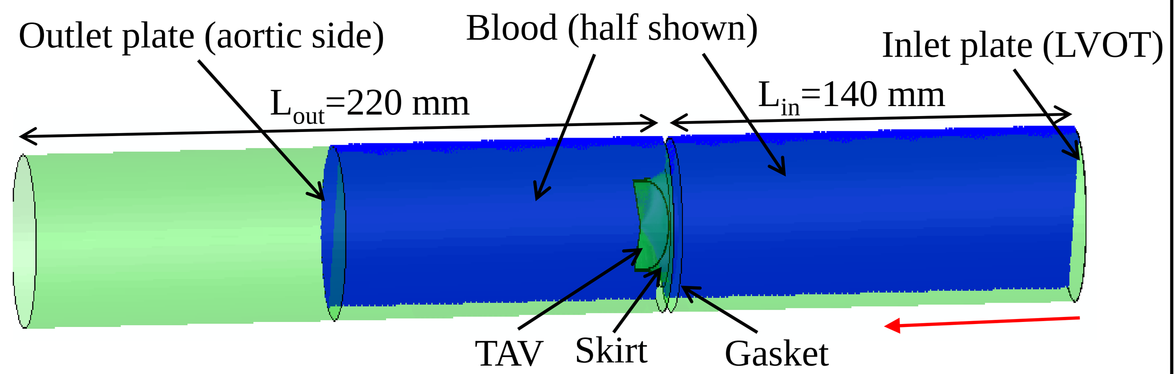
➢ Anisotropic MHGO model: $W = C_{10}\{\exp[C_{01}(\bar{I}_1 - 3)] - 1\} + \frac{k_1}{2k_2}\sum_{i=1}^{2}\{\exp[k_2(\bar{I}_{4i} - 1)^2] - 1\} + \frac{1}{D}(J-1)^2$



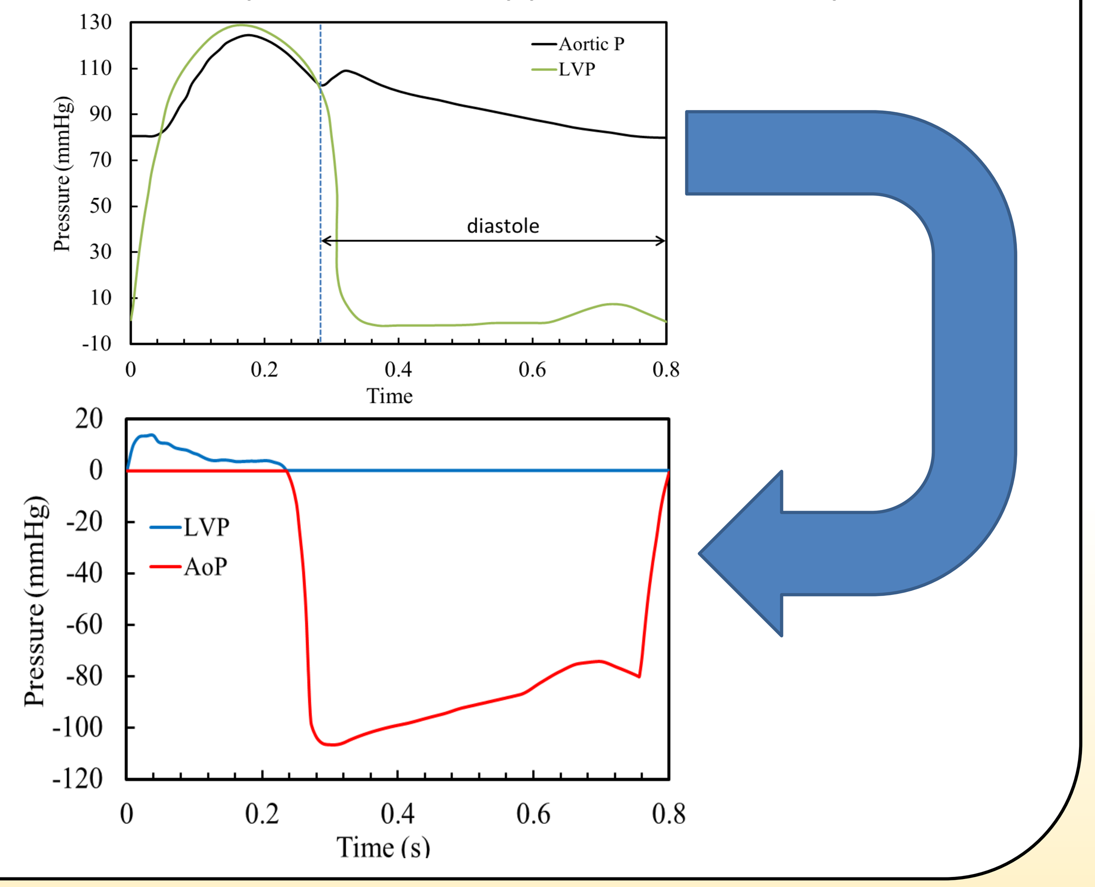


MHGO model	C_{10}(kPa)	C_{01}	k_1 (kPa)	k_2	θ(°)	D (kPa^{-1})
	30.03	3.47	74.5	63.19	43.11	1.00e–5
Ogden model	μ_1(kPa)	a_1	μ_2(kPa)	a_2		
	19.58	67.74	260.56	27.47		

FE-SPH Model for TAV Simulation

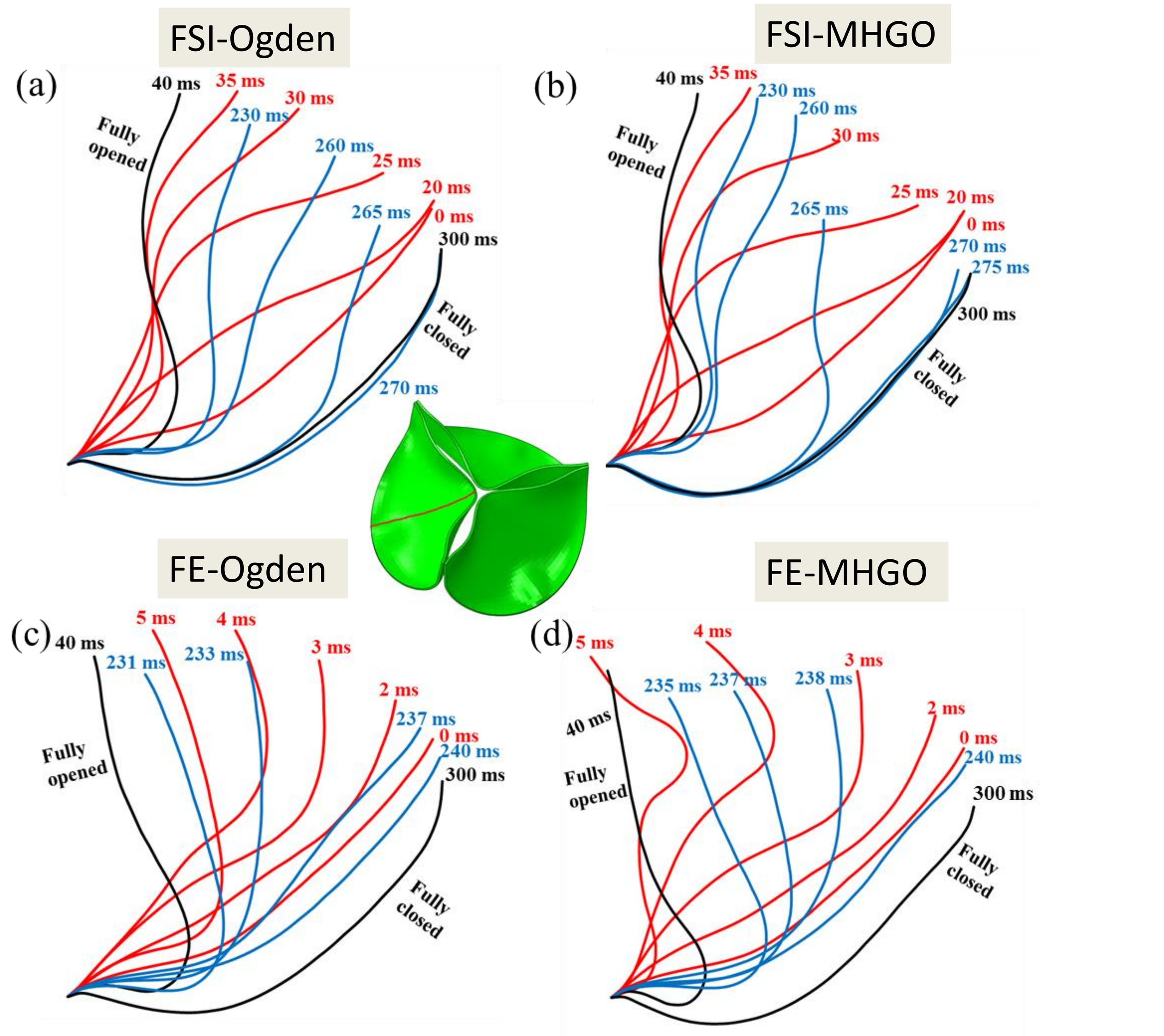


- SPH particles initially uniform distributed with a spatial resolution of 0.9 mm, resulting in approximately 370,000 PC3D elements.
- Pressure drop waveforms applied on the two plates



RESULTS AND DISCUSSION

TAV Opening and Closing Kinematics



	FSI-Ogden	FSI-MHGO	FE-Ogden	FE-MHGO	In vivo data [2]
RVOT (ms)	40	40	5	6	57.5±11.1
RVCT (ms)	35	35	8	9	39.5±5
ET (ms)	270	270	240	240	329±63

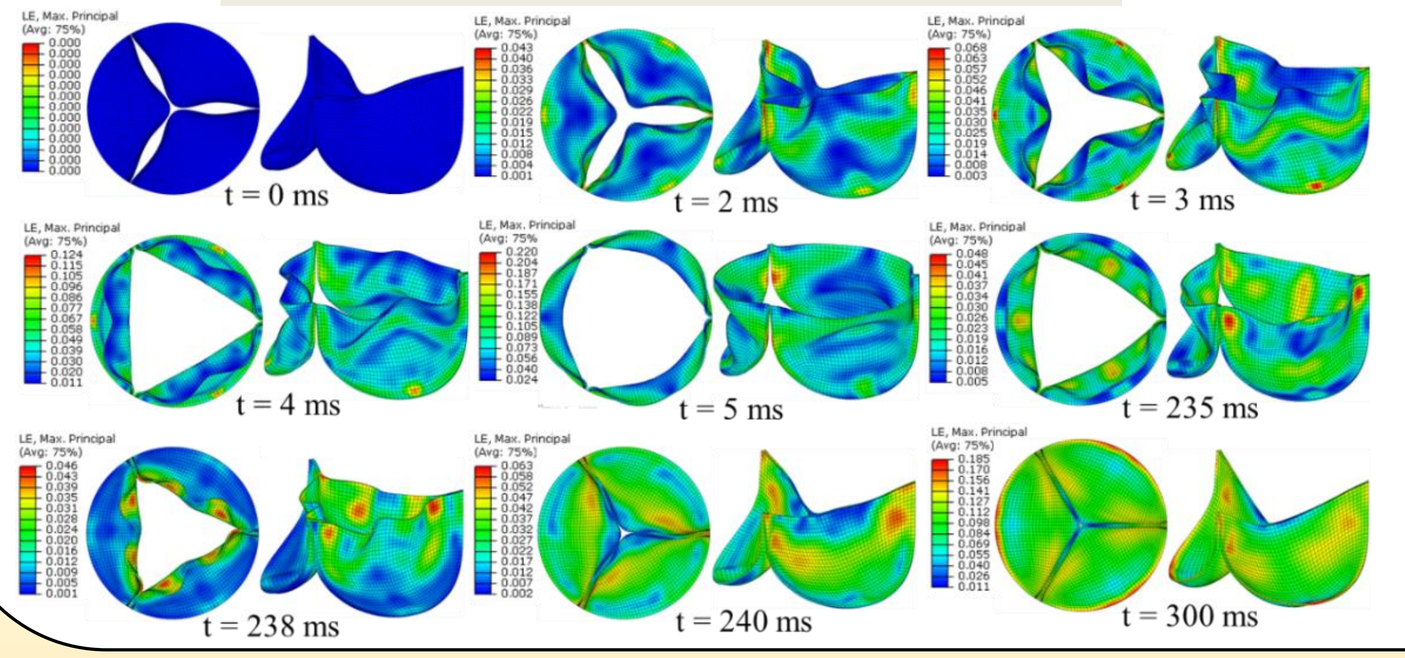
RVOT: rapid valve opening time; RVCT: rapid valve closing time; ET: ejection time

- FE models exhibit unrealistic fast opening and closing processes.
- Opening configurations from FE models are unrealistic.

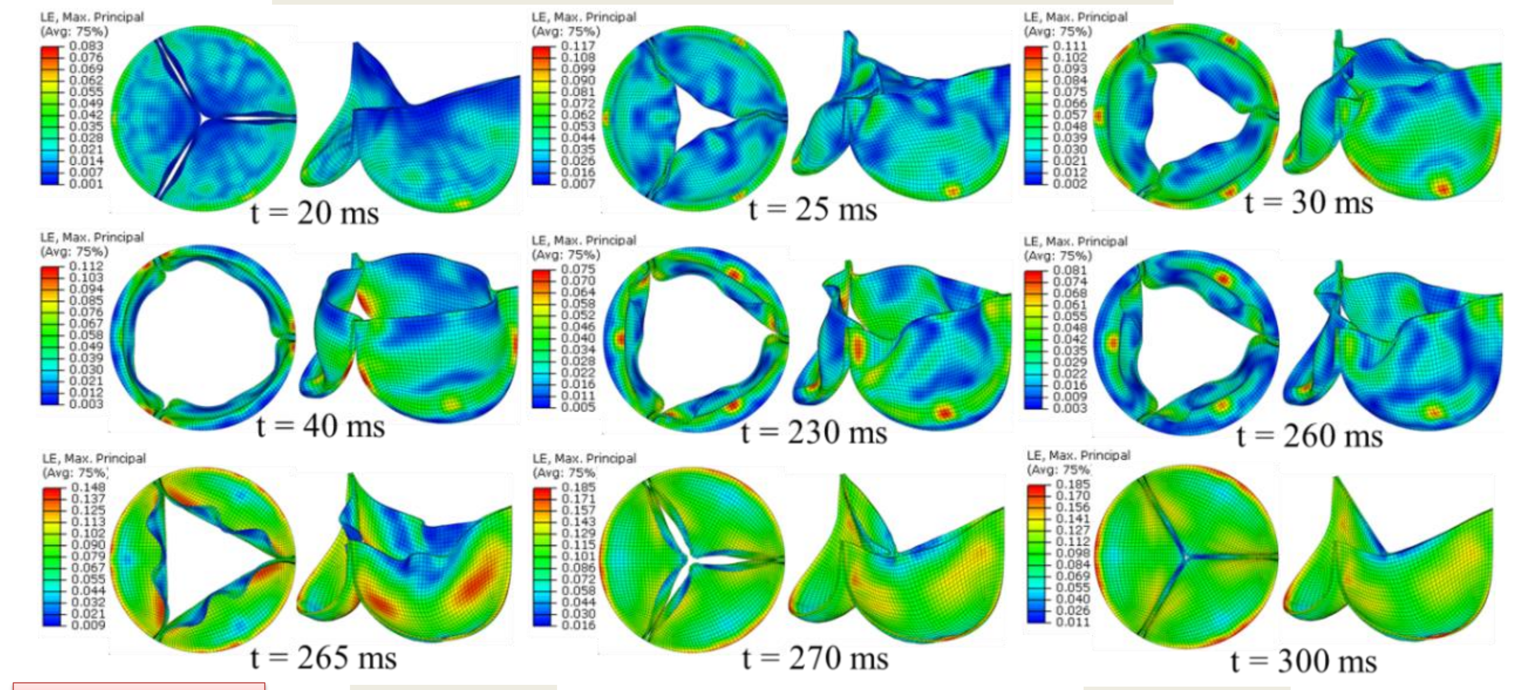
Reason: Uniformly distributed pressure load on the leaflets in FE models is not the case in reality, thus overestimated the force in the free edge region.

Structural Stress and Strain Responses

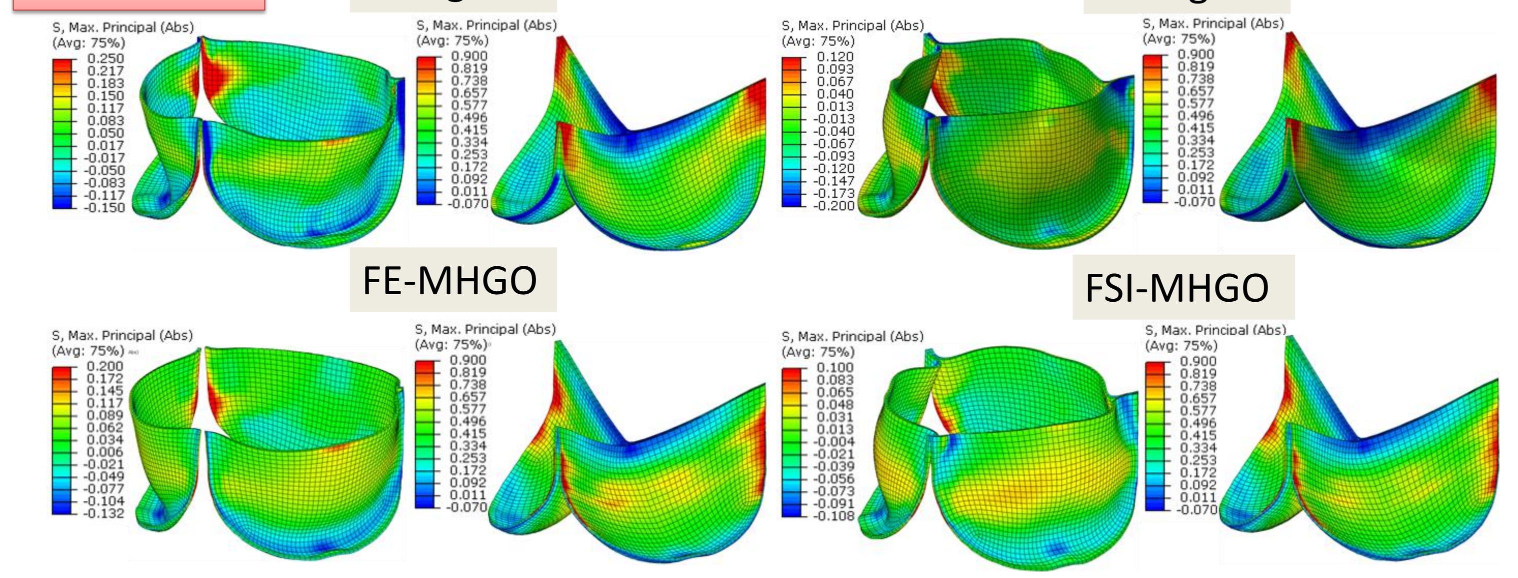
FE-MHGO, maximum principal logarithmic strain



FSI-MHGO, maximum principal logarithmic strain



Stress (MPa)

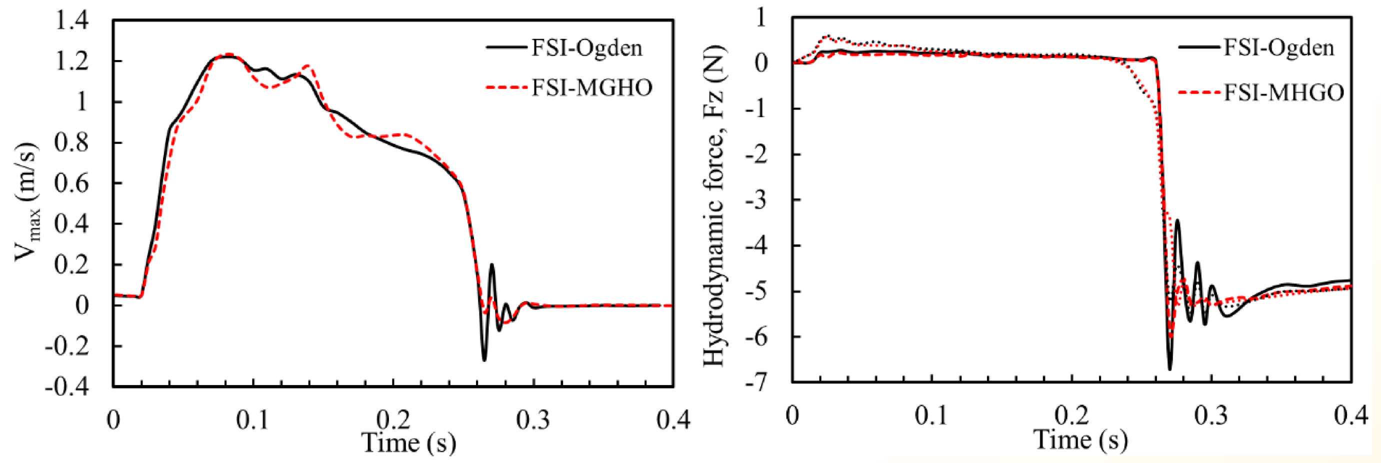


- FE model has larger peak strain and stress during the opening phase.
- In the fully-closed configuration, FE and FSI models have very similar strain and stress distribution.
- The high stress region in MHGO models shifted downwards from the commissure region and distributed along the attachment line.

Hemodynamics

Model	MSPD (mmHg)	PSPD (mmHg)	EOA (cm²)	RV (ml)
FSI-Ogden	4.9	12.0	1.22	3.2
FSI-MGHO	4.9	11.6	1.52	3.1

MSPD: Mean systolic pressure drop; PSPD: Peak systolic pressure drop; EOA: Effective orifice area; RV: Regurgitant volume



- Hemodynamic parameters are comparable to the normal performance after TAV intervention
- Smaller oscillations in velocity and hydrodynamic force curves during the closing phase are due to the water hammer effect.
- The peak hydrodynamic force on the valve would exceed the hydrostatic pressure force by 24% during the closing.

Conclusions

- The FE-SPH coupled FSI model is capable of modeling the overall structural and hemodynamic characteristics of TAVs during the whole cardiac cycle.
- The FSI model is essential to capture the accurate kinematics of the valve opening and closing.
- Water hammer effect during the closing phase should be considered in the valve durability assessment.

References: 1. Li, K, and W. Sun. *Annal Biomed Eng*. 2010. 2. Leyh, R.G., et al., Circulation, 1999.

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