Multiphysics Simulations in LS-DYNA

Facundo Del Pin

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November 8th, 2022

Livermore LS-DYNA Meeting 2022

Ansys

Outline

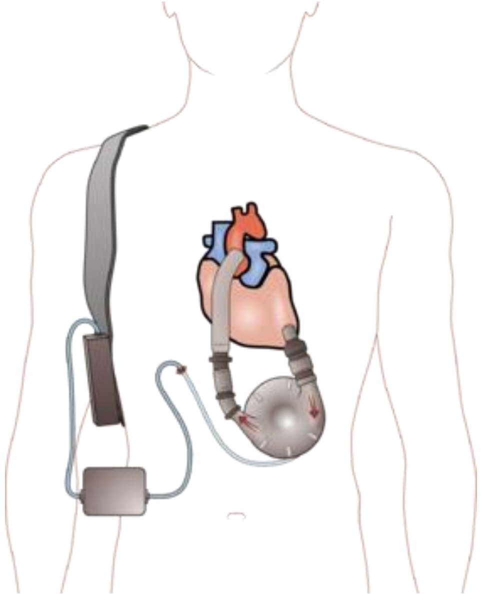
- Healthcare
  - Cardiac modeling: Control volume approach
  - New features in Electrophysiology
  - Prosthetic heart valves
  - Simpleware (AS Cardio) collaboration
  - Intradermal injections
  - Ultrasound Computer Tomography simulation
  - Orthopedics, sawbones implant simulation
- Transient FSI in external aero applications
- DEM coupling
- Gap closure models
- Sonobuoy application
- Summary

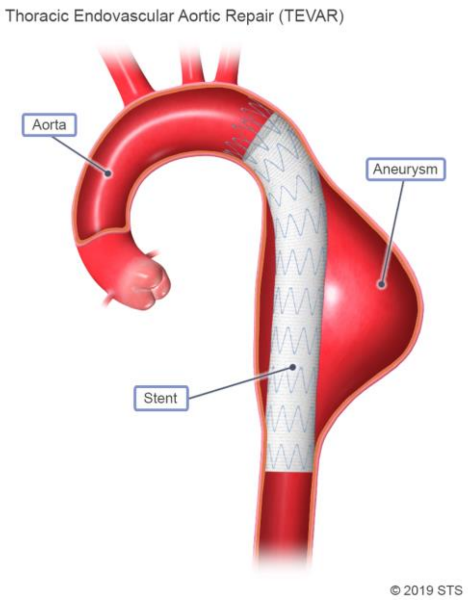
Cardiac Modeling

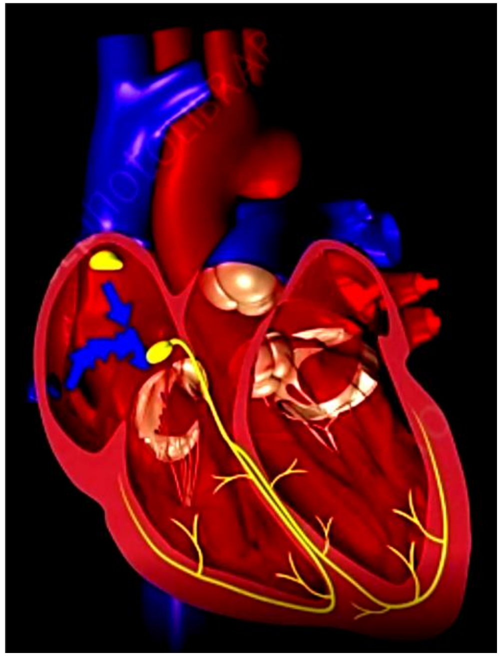
Cardiac Modeling 101

And why is the heart a Multiphysics problem…

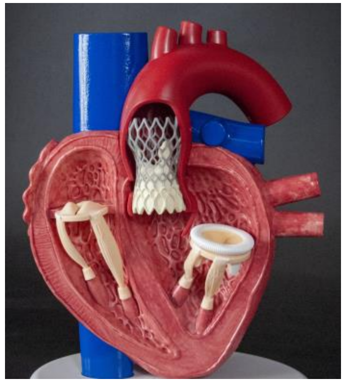
Electrophysiology : how the electrical wave propagates in the conduction system (the muscle of the heart).
Mechanical: how heart deforms due to blood filling and electrical stim.
Fluid dynamics: how blood moves during the cardiac cycle

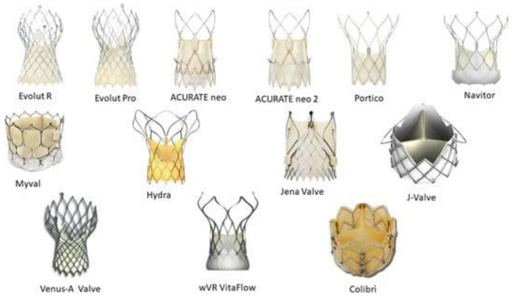


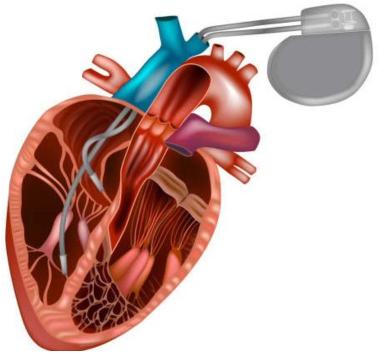


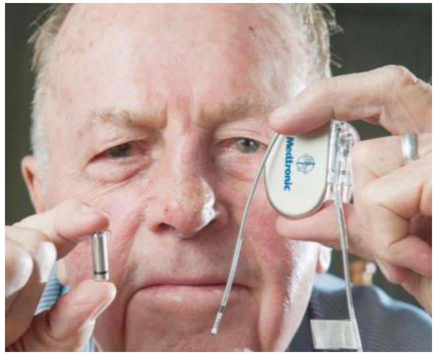


A healthy heart pumps
2000 gallons of blood a day

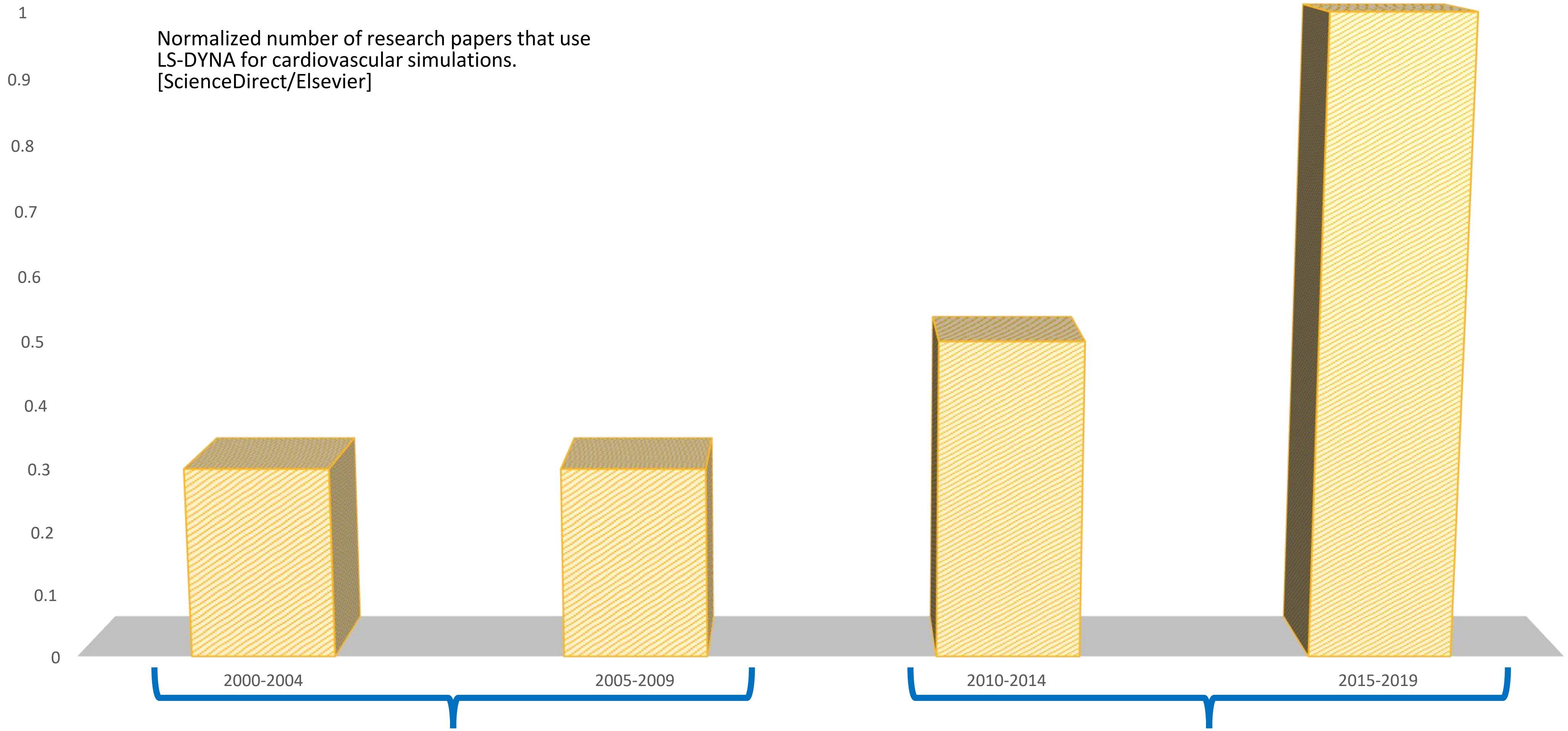








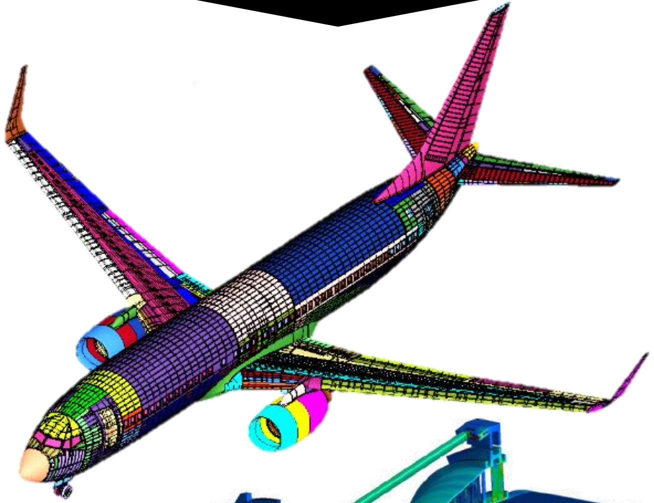
Use of LS-DYNA in the academic community for cardiovascular simulations

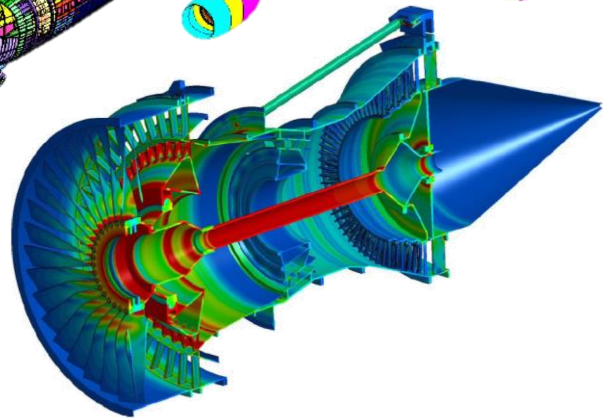


Wide acceptance of LS-DYNA as a leading tool in the academic community for cardiovascular simulation.

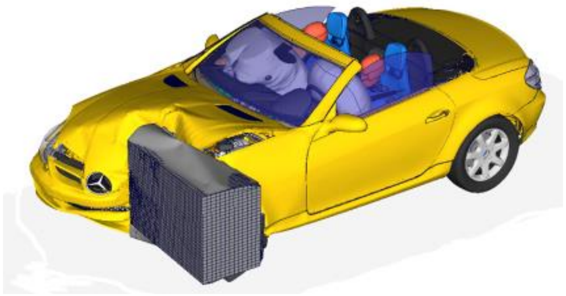
LS-DYNA simulation: the next step

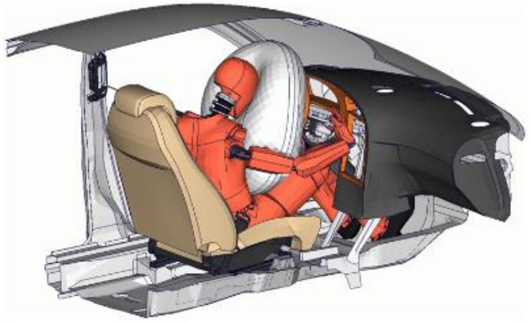
Aerospace



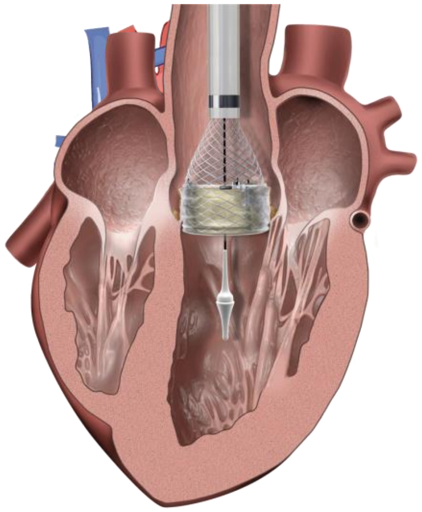


Automotive





Healthcare



Billions of dollars and thousands of lives saved annually in experimental testing through high fidelity LS-DYNA simulations

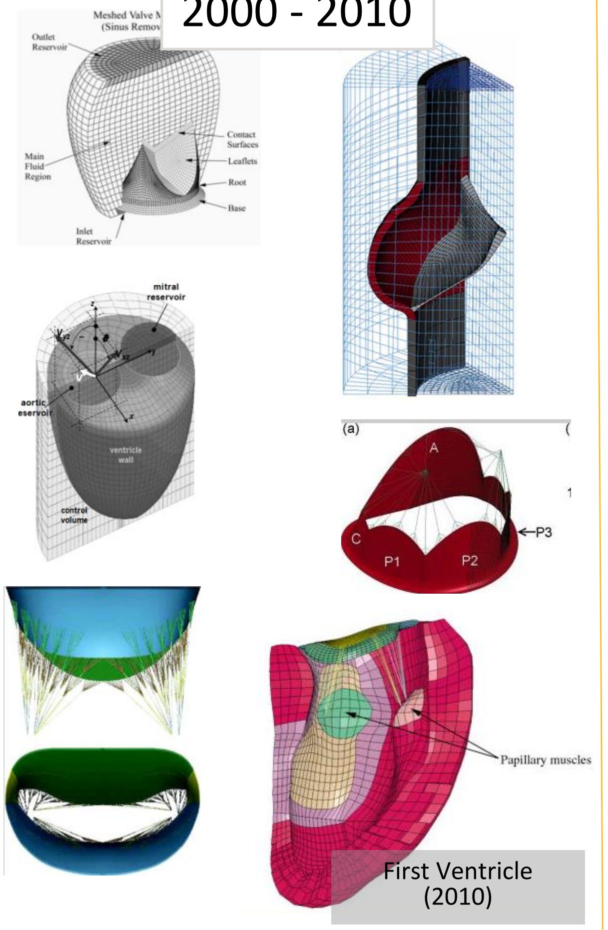
LS-DYNA can help the healthcare industry improve devices and therapies through pervasive simulations

Complexity evolution of cardiac models in LS-DYNA

Traditional approach

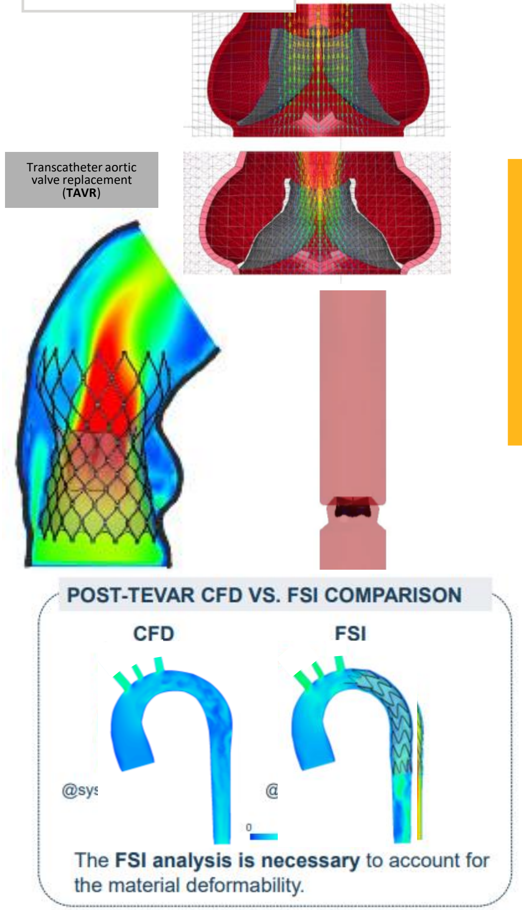
Isolated heart components modelled. Mainly valves including modern prosthetic TAVR.

2000 - 2010



First Ventricle (2010)

2010 - 2020

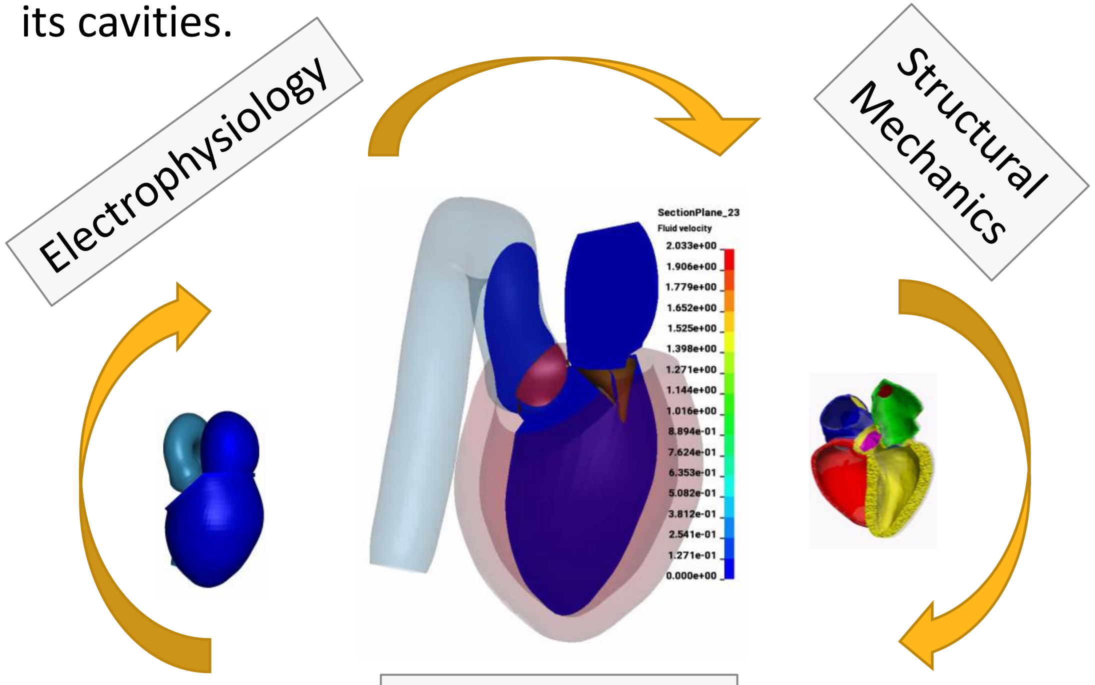


The **FSI analysis is necessary** to account for the material deformability.

Current development

Focused on the full heart as an organ.

The heart is a pump whose engine are electric impulses that contract fibers at the heart walls in such a way that blood is moved in and out of its cavities.



Fluid Mechanics

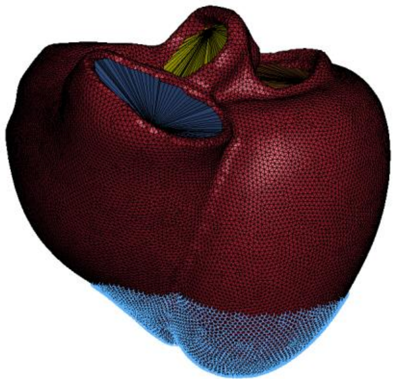
Mechanics

Key features:

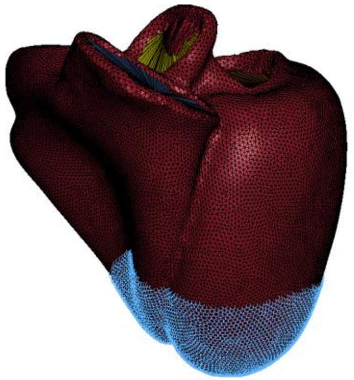
- ***MAT_295** for passive and active
  - Holzapfel Gasser Ogden (2009)
- **Zero-pressure simulation** relies on
  - **CONTROL_REFERENCE_CONFIGURATION*
  - Rausch, et al (2017)

- **Boundary conditions** are crucial for physiological results
  - Omnidirectional springs on the valves
  - Directional springs on the pericardium
    - Direction: apex to mitral valve center
    - Value: scaled from the position

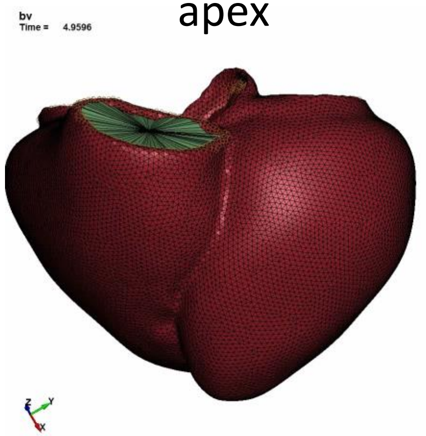
End-diastolic (pressurized)



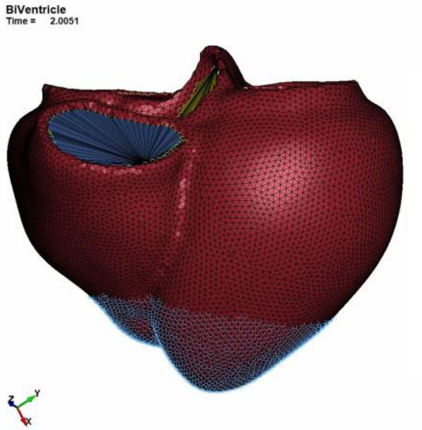
Stress-free

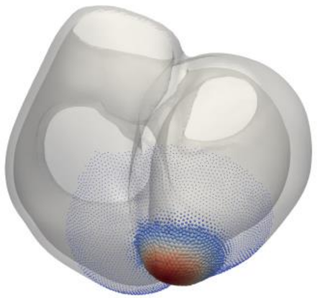


Unconstrained apex



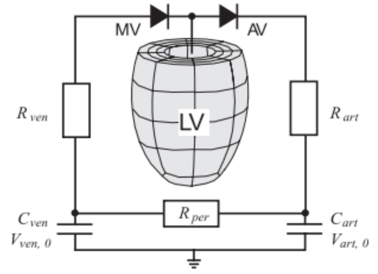
Pericardium



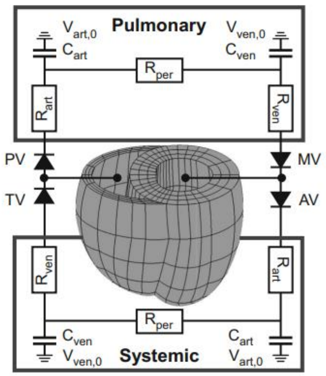


Control Volume

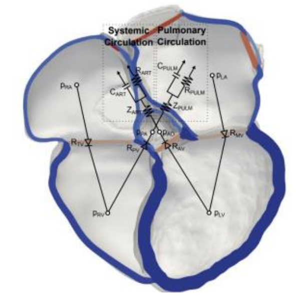
- 4 models available in package
  - Open loop: LeftVentricle, BiVentricle
  - Closed loop: LeftVentricle, BiVentricle



Bovendeerd et al.



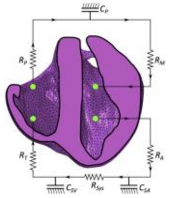
Pluijmert et al.



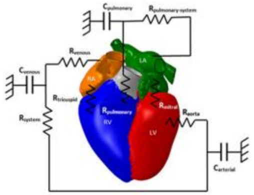
Strocchi et al.

- Open-loop developed in LS-DYNA *DEFINE_FUNCTION*
  - Pseudo C, no need of compilation

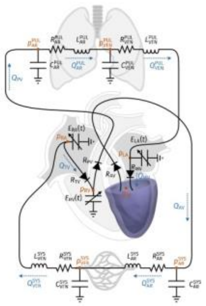
- Ongoing discussion with TwinBuilder team to make the development easier



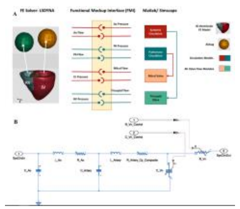
Sack et al.



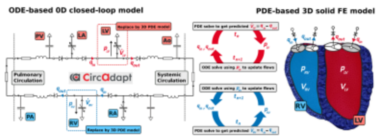
Wisneski et al.



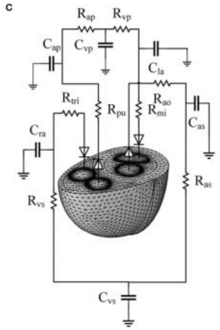
Regazzoni et al.



Y. Zhang et al.



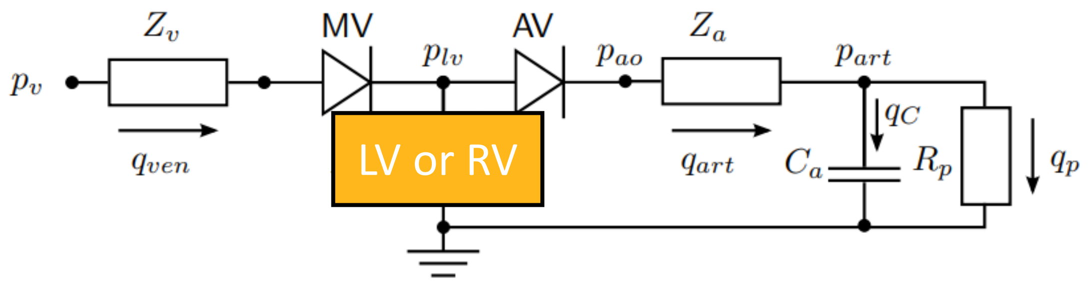
C.M. Augustin, M.A.F. Gsell, E. Karabelas et al.

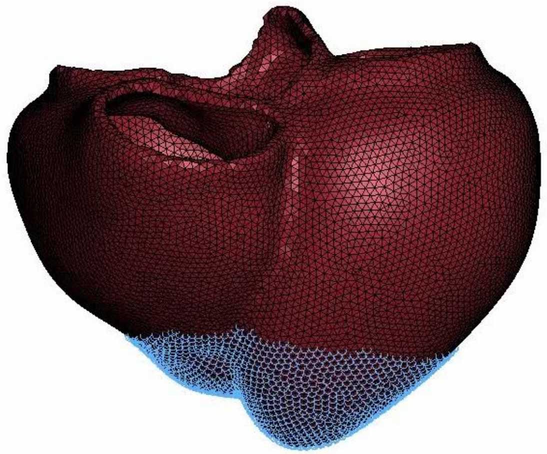


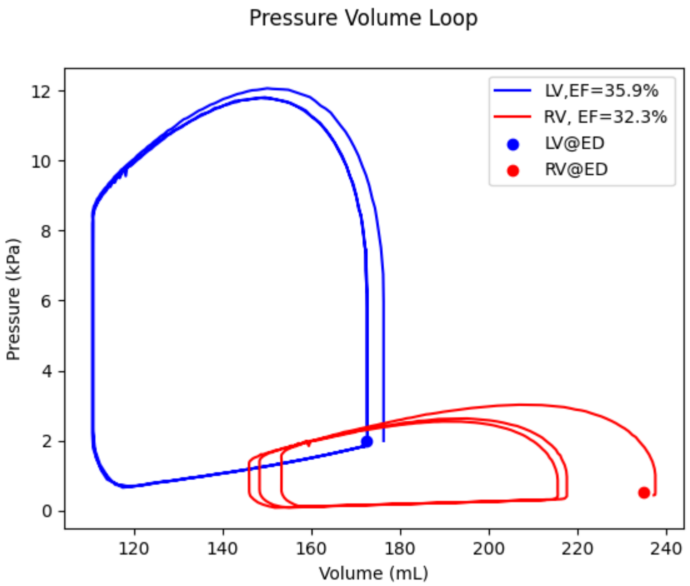
Ahmad Bakir et al.

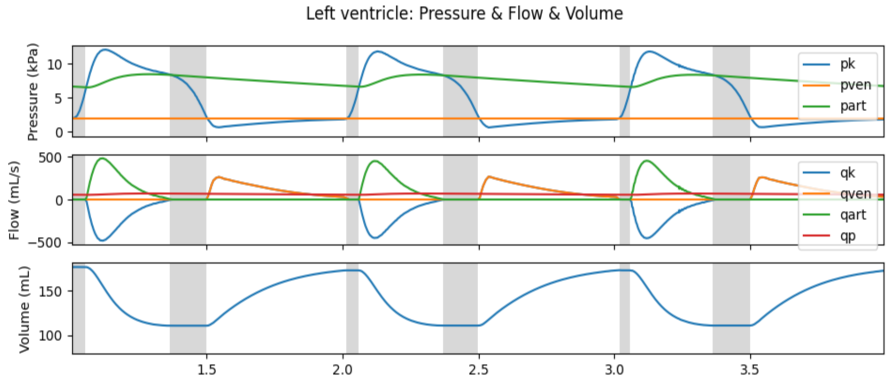
Control Volume: example

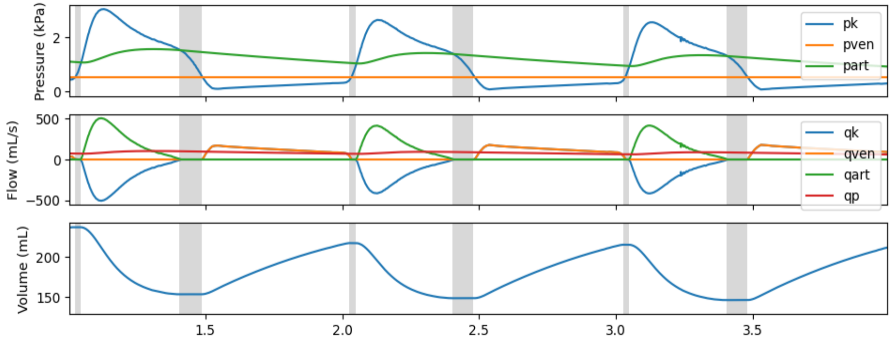
- Bi-Ventricle model with Open-loop
  - Constant preload
  - Afterload: 3-element Windkessel
  - Parameters from literature (not tuned)
  - Imposed activation curve











Key novel features in **Electrophysiology**

- Features involved in **ECG** applications:
  - Electrophysiology calibration from ECGs
  - Prediction of drug effects on ECGs

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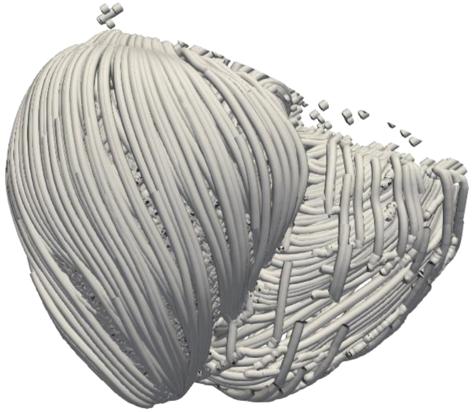
- **Fiber orientation** in biventricular geometries



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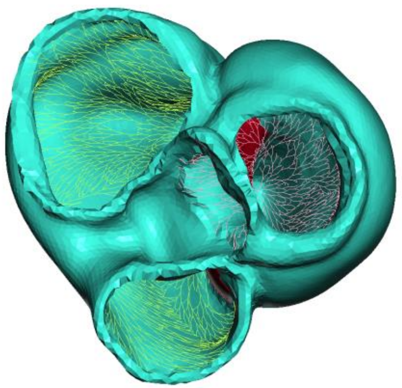

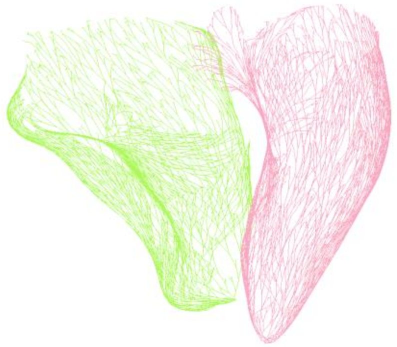

- Features involved in ECG applications:
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- Fiber orientation in biventricular geometries
- Creation and connection of **Purkinje nodes** and myocardial nodes

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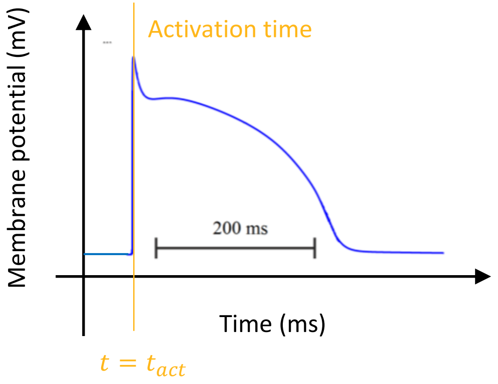

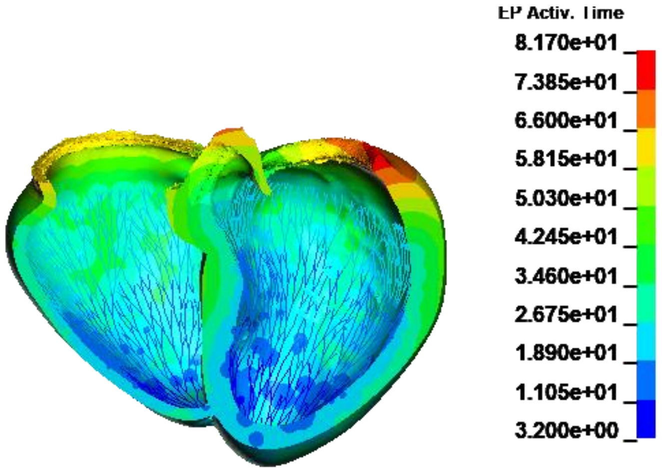

- Fiber orientation in biventricular geometries
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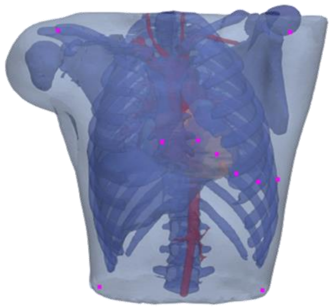
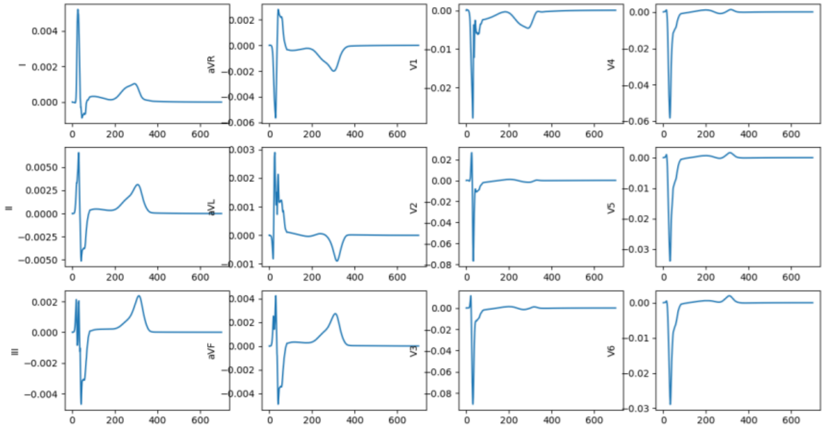
- **Pseudo ECGs** computation and export





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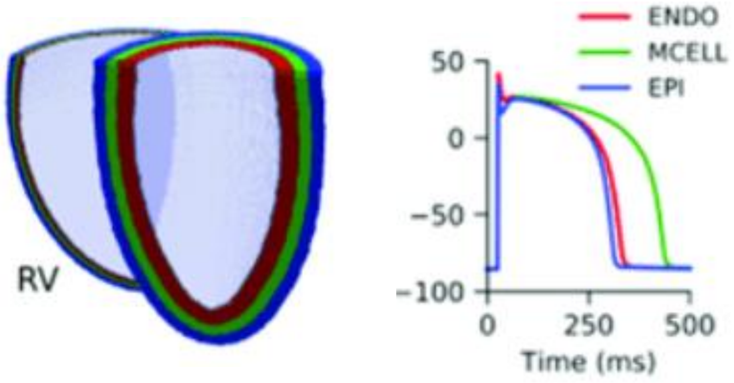
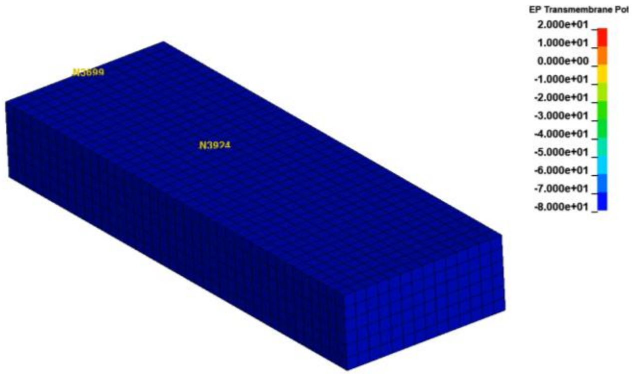
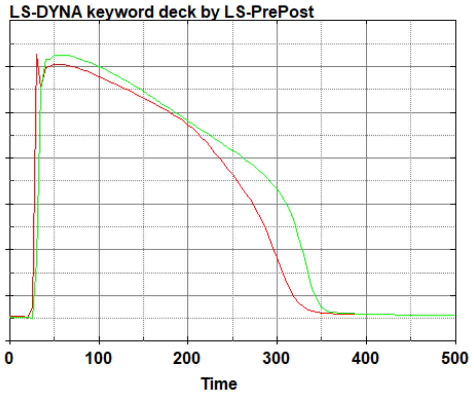
- **Cell model heterogeneity** through wall thickness



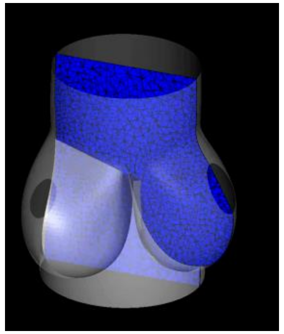


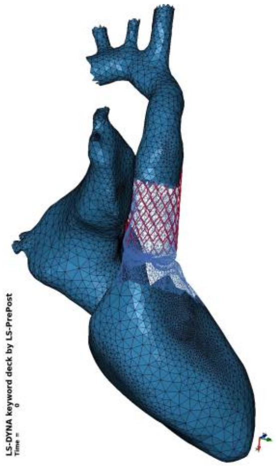


Fluid Structure Interaction: Prosthetic Heart Valves

- **New metrics** allow the LS-DYNA results to be used directly to estimate the risk of thrombosis.
- For **TAVR valves** LS-DYNA can perform the full process of stent crimping, deployment and FSI.
- **Gap closure** model to produce more realistic valve sealings.
- New treatment of shell elements to improve the **pressure jumps** on leaflets seams.
- Ongoing work to perform **FSI using IGA** structures.

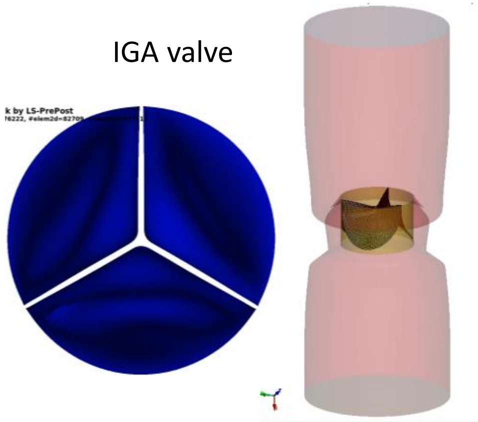
Residence Time





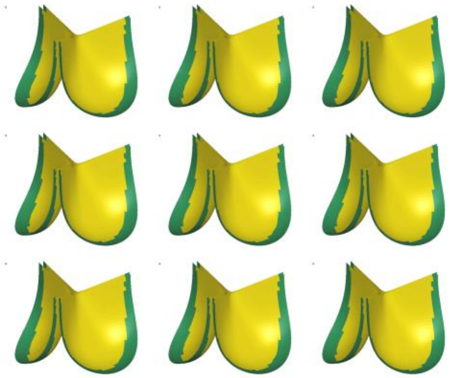
Stent crimping and deployment

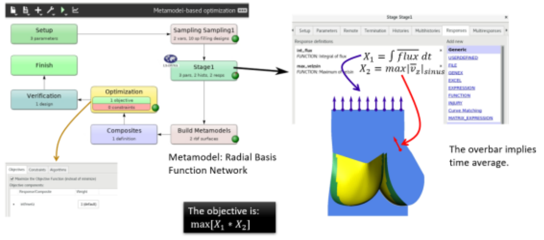
IGA valve



Optimization of prosthetic heart valve workflow using LS-DYNA and LS-Opt. The goal is to prevent blood stagnation behind the leaflets by optimizing the leaflet thickness.

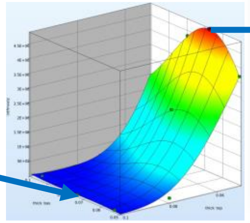
Valve designs

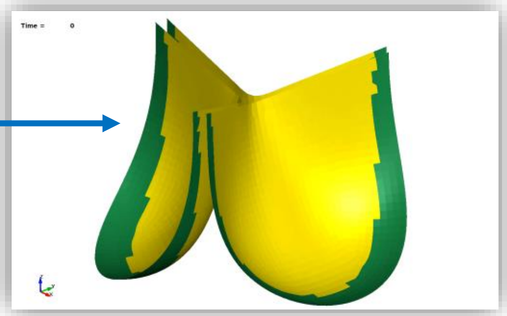




Optimal design

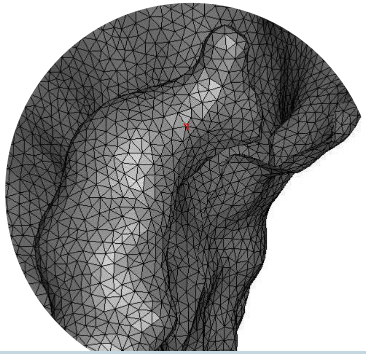
Initial design



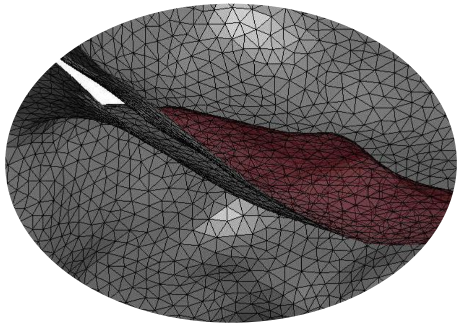


Heart Model with **Simpleware** AS Cardio

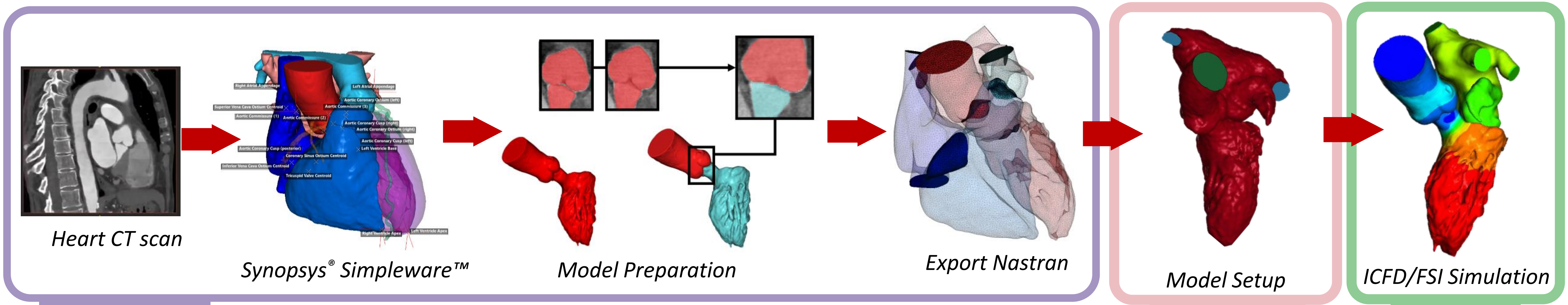
- Simpleware AS Cardio is an **automated segmenter** for cardiology.
- The **workflow has been established and optimized** on the model preparation using Simpleware to LS-DYNA ICFD and structural analysis of cardiovascular system.
- **Minimum manual work** is needed from scans to model, and the preparation time is largely reduced.



Smooth mesh of small structures in left ventricle



No intersecting surfaces near mitral valve



Simpleware

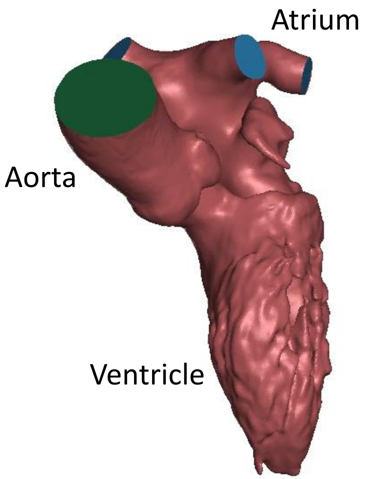
Automated process from medical image to simulation ready model in 10-15 mins

LS-Prepost

LS-DYNA

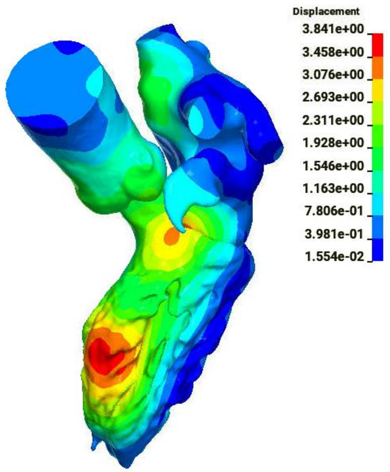
Needs only a few minutes

Heart Model with **Simpleware** AS Cardio: Applications

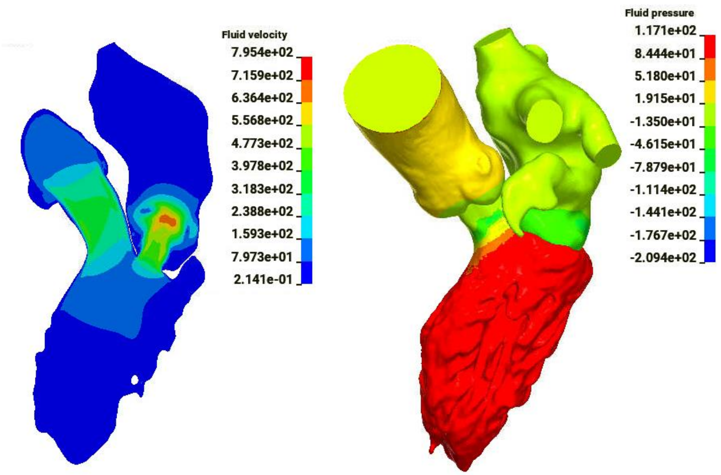


Contracting Left Heart

- Early stage of the contraction of left ventricle. Valves are not included.
- Prescribed motion of the heart wall with pressure driven flow inside.



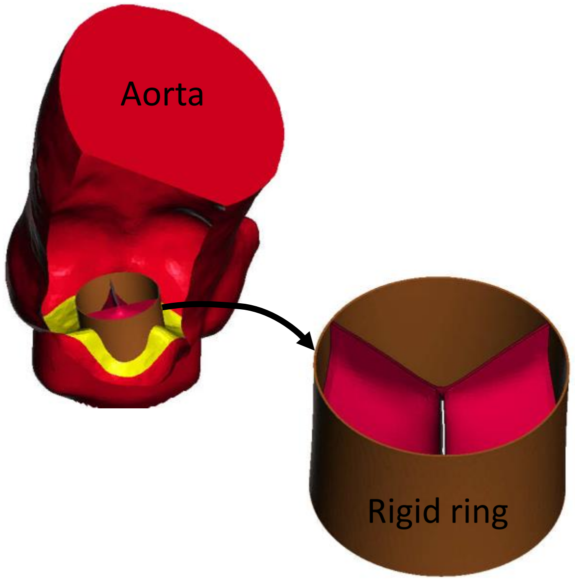
Wall displacement

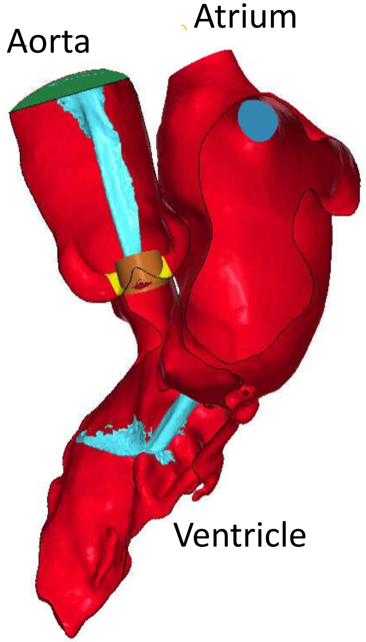


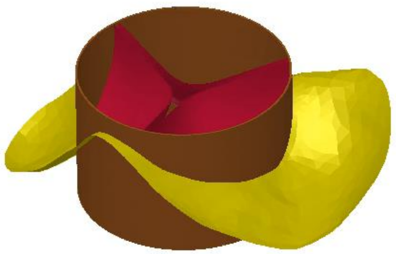
Flow velocity and pressure fields

Artificial Aortic Valve

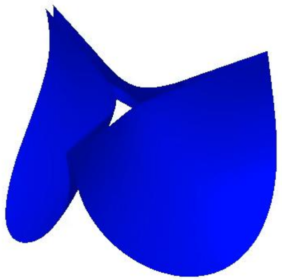
- Artificial valves placed at the center of the image derived aortic valve.
- Fixed heart wall and rubber valves fixed at base.







Iso-surface of the velocity magnitude

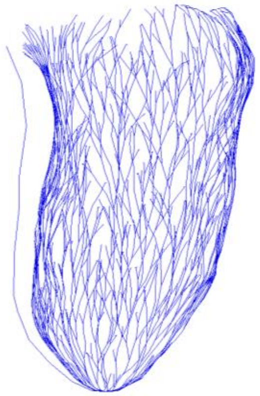


leaflets open and close

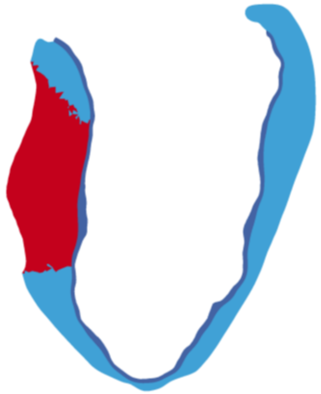
Heart Model with **Simpleware** AS Cardio: Applications

Electrophysiology

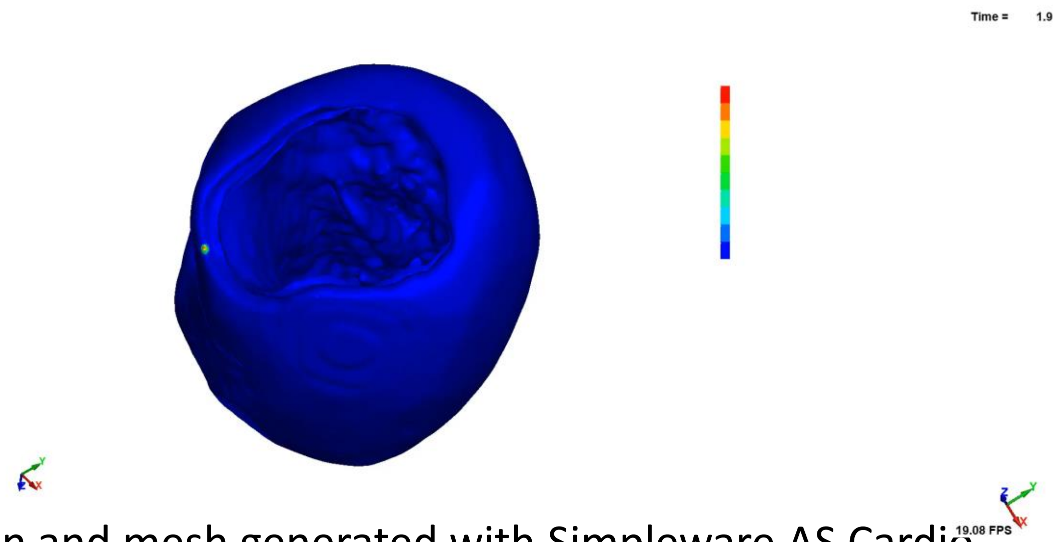
- Two-layer myocardium
- Two step approach:
  - Simplified Purkinje network generation
  - Electric wave propagation

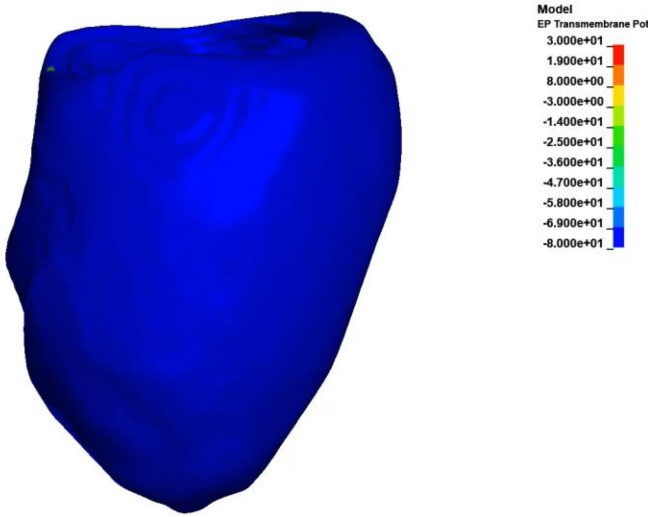


Simplified Purkinje Network



Section View

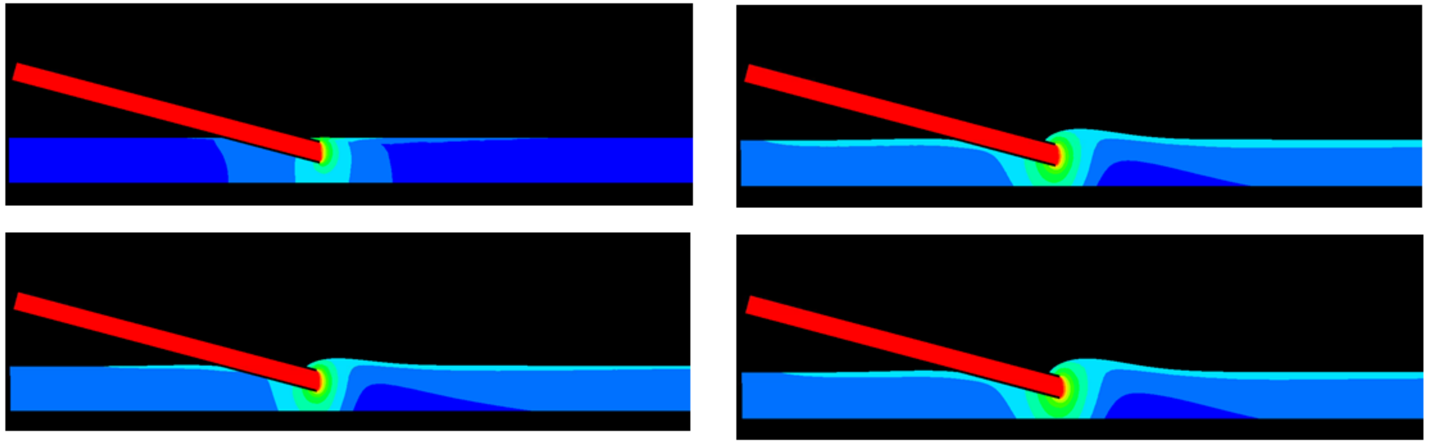




Segmentation and mesh generated with Simpleware AS Cardio

New development supporting Species Transport Phenomena.

With the increase in vaccination campaigns during the COVID-19 outbreak, the med Industry started using numerical models for coupled physics to study the drug delivery through the human tissue as well as for the delivery on other devices like the one used by patients with other conditions like diabetes.

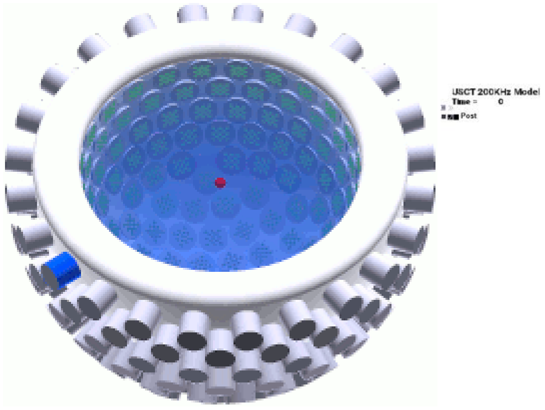


Acoustic spectral element method and its application in medical imaging

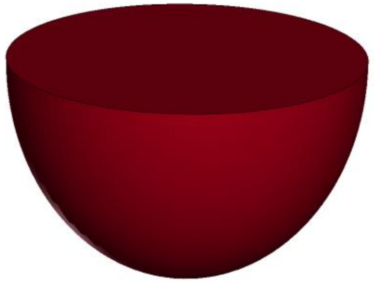
- LS-DYNA has a **new acoustic spectral element method**
  - The shape functions for the geometry are of a lower order than the interpolation functions for the element pressure
  - The interpolation functions for the pressure employ Legendre polynomials of orders 2→15
  - **High accuracy with reasonable CPU cost**
  - **suitable for modeling high frequencies** and ultrasonic acoustic wave propagation

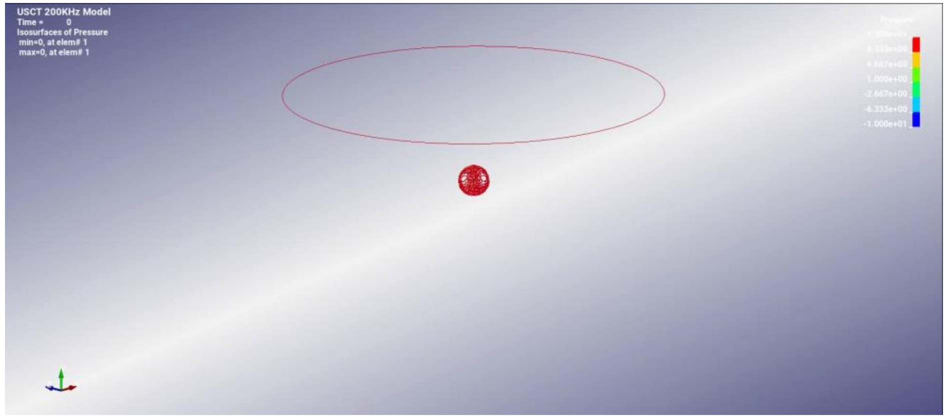
- Application in Medical imaging
  - USCT - **Ultrasound Computer Tomography**
  - Tissue in water
  - Ultrasonic pulse from one transducer
  - Scattered signal measured on all others
  - Each transducer takes a turn

200 KHz pressure pulse

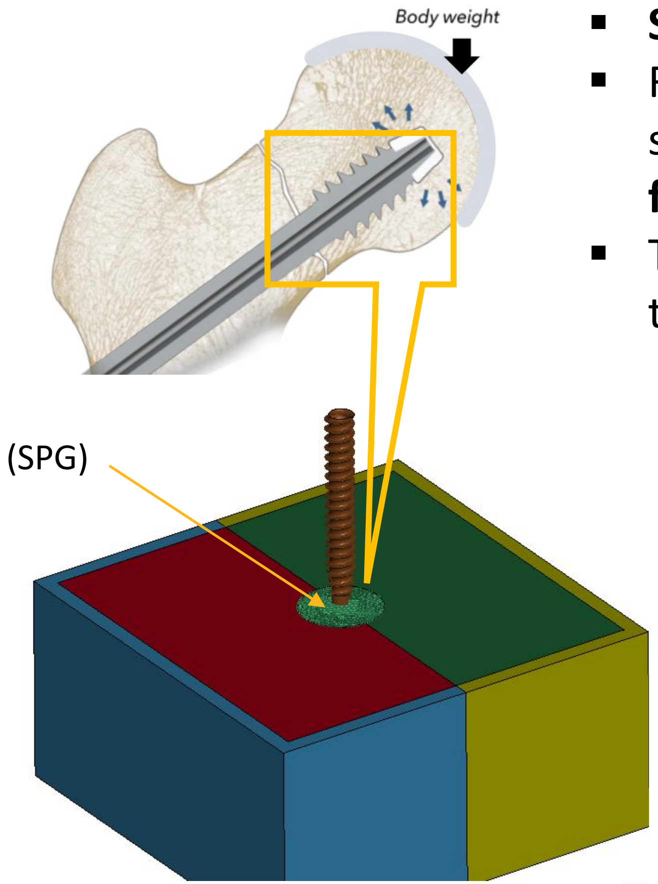


6,048,000 N=5 SE hexahedra
757,442,101 equations
Solution for 200 µs (57,967 steps)
11 hrs 26 min wall time (112 cores)



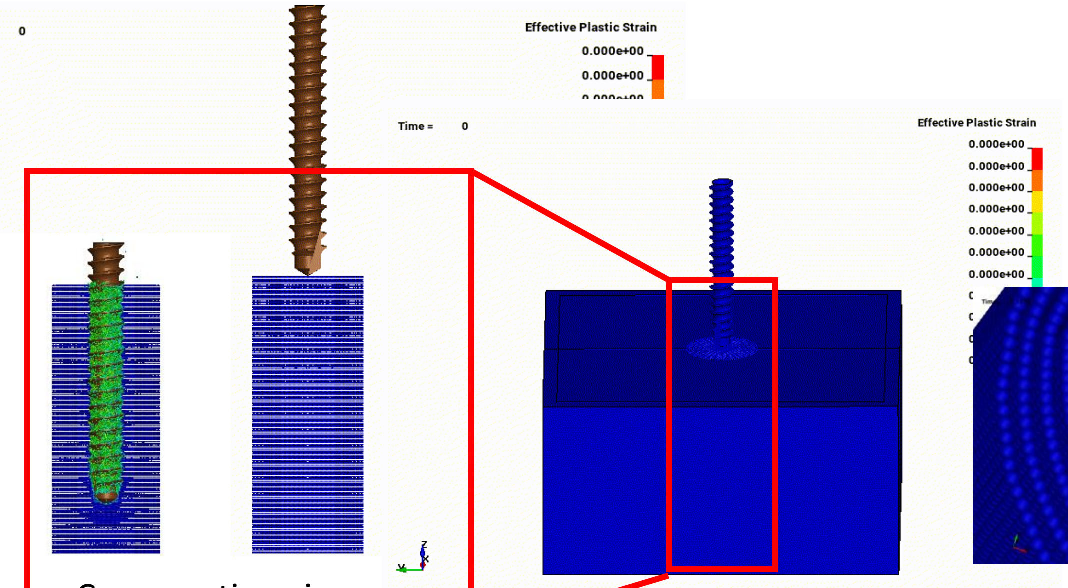


Sawbones implant simulation by SPG method



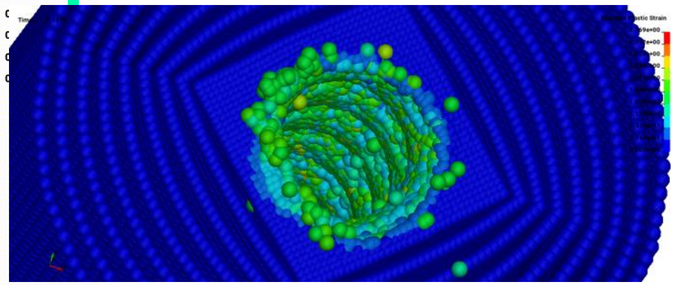
- **Surgical screws** are adopted by surgeons to join the bone fragments with implants.
- Finite element method based on the element deletion technique has difficulty to simulate the thread forming process of sawbones, thus unable to **capture the pullout force and predict the implant sustainability**.
- The **Smoothed Particle Galerkin (SPG)** method is a new numerical method in LS-DYNA to model the bone materials in orthopedic and dental implant process.

Bone block model with a Screw: The screwing area of bone is simulated by SPG method, and the rest area of bone is simulated by FEM.



Cross-section view

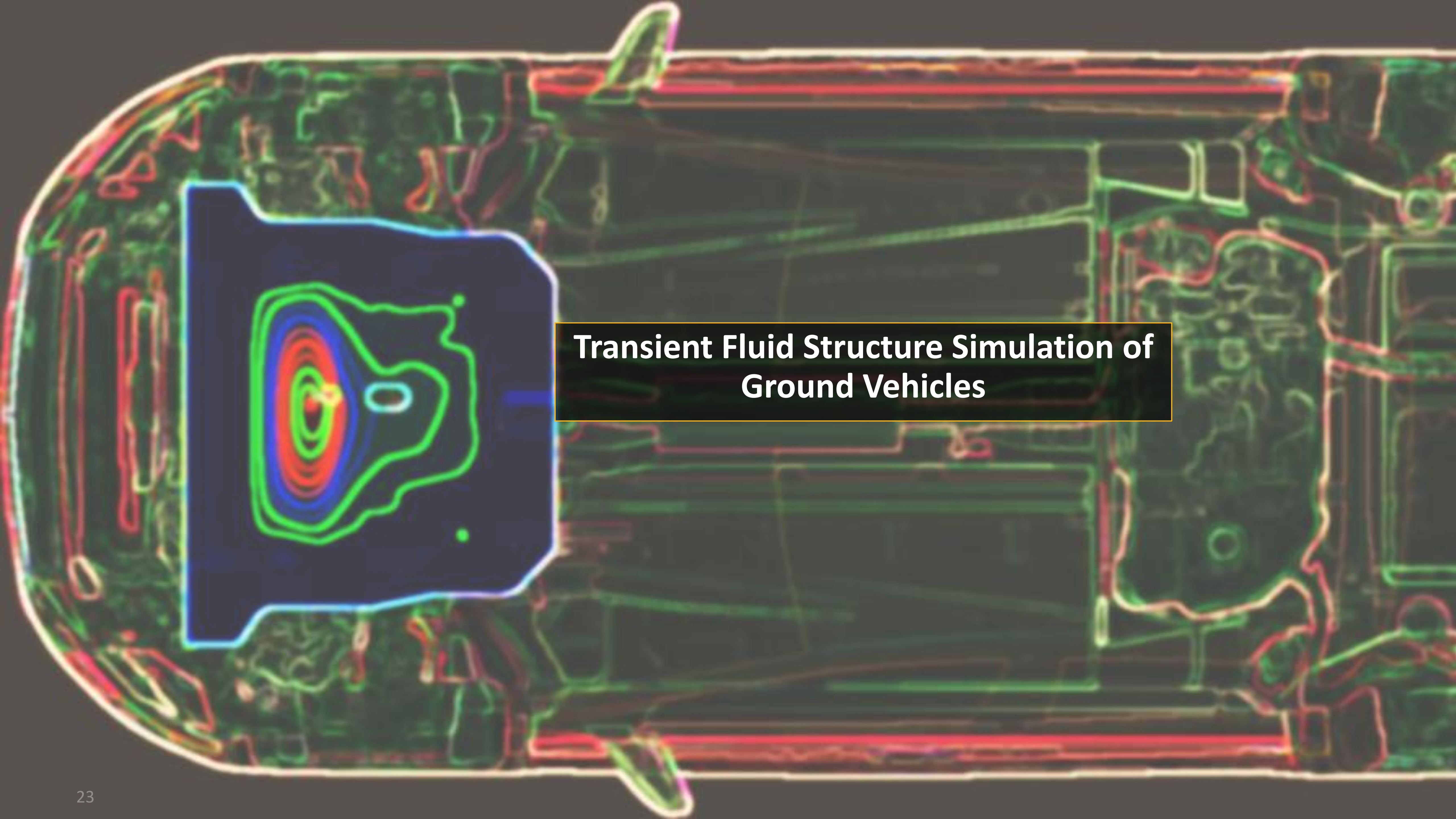
The screwing/pullout process



No element deletion and threads are captured sharply

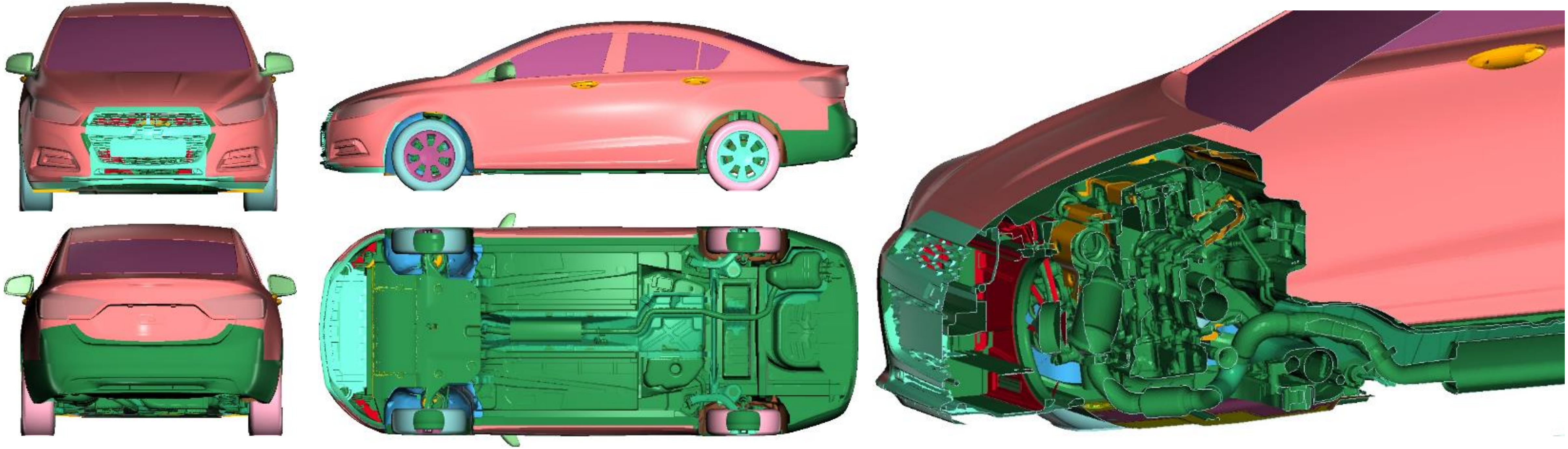
Non-Healthcare applications

Transient Fluid Structure Simulation of Ground Vehicles



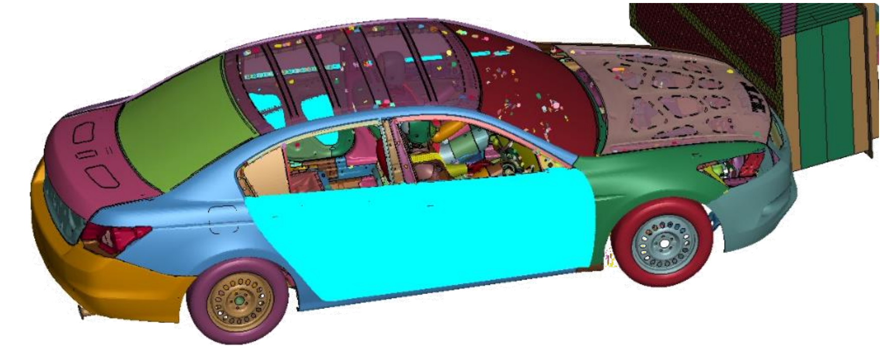
Transient Fluid Structure Interaction: mid-size sedan

- Highly detailed underhood and underbody.
- The model also includes heat exchangers with porous media.
- A part of the vehicle will be flexible instead of rigid and will deform in time due to the transient fluid loads.

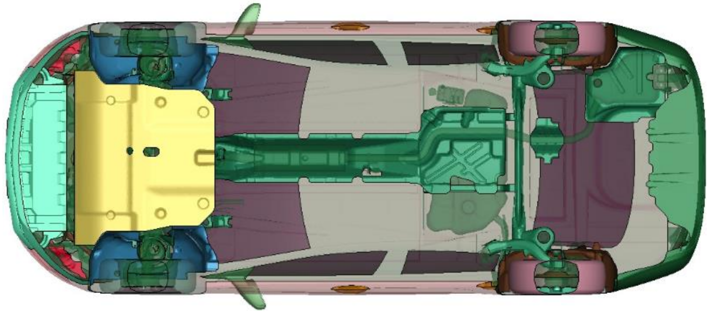


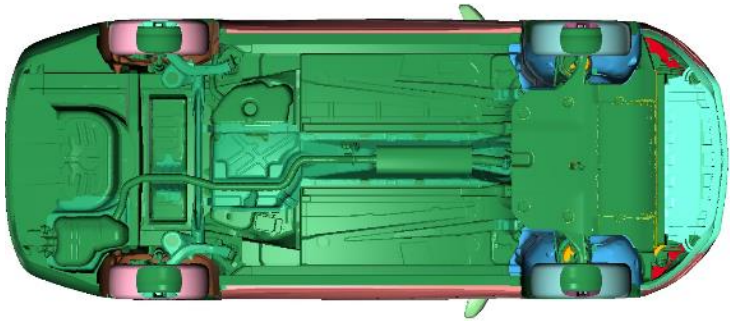
Transient Fluid Structure Interaction: FSI

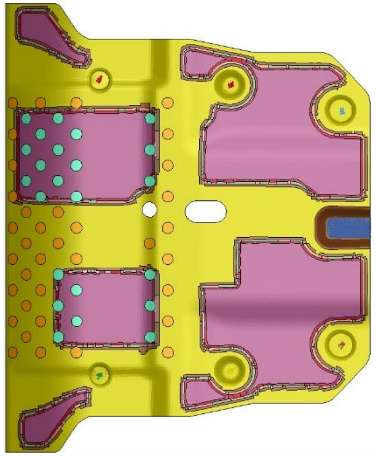
- The main idea is to use a CFD model that is already working and convert some rigid parts into flexible.
- Include into the CFD input deck parts from crash analysis models.
- That only one new keyword is added to the CFD model to convert it into a coupled FSI simulation: *ICFD_BOUNDARY_FSI.



crash model for a mid-size sedan vehicle

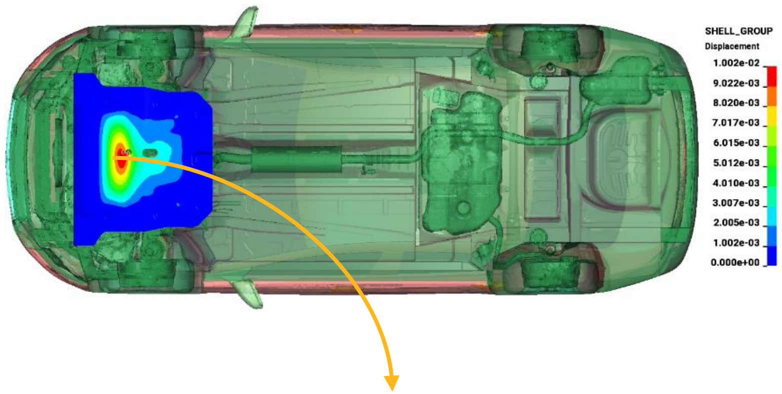




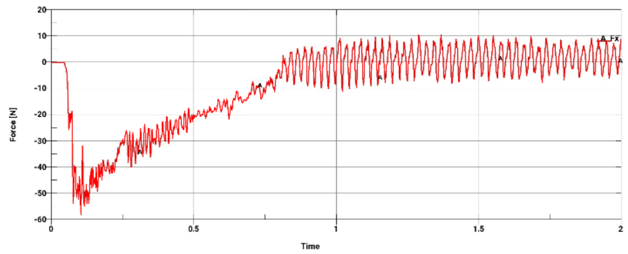


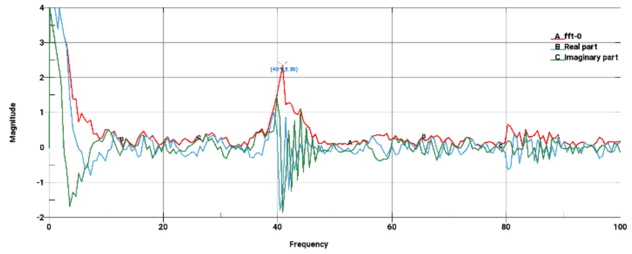
Underbody panel used in the FSI simulation. On top the panel in the CFD domain.

Transient Fluid Structure Interaction: results

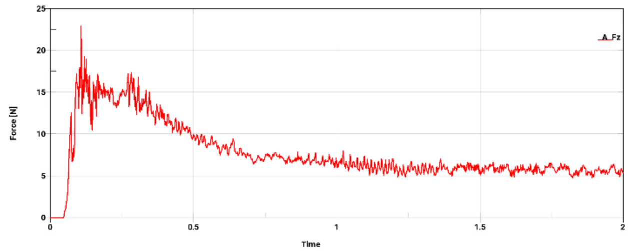


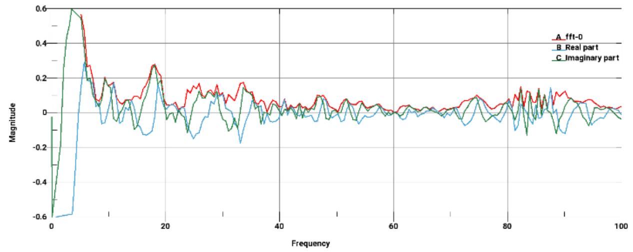
Fx

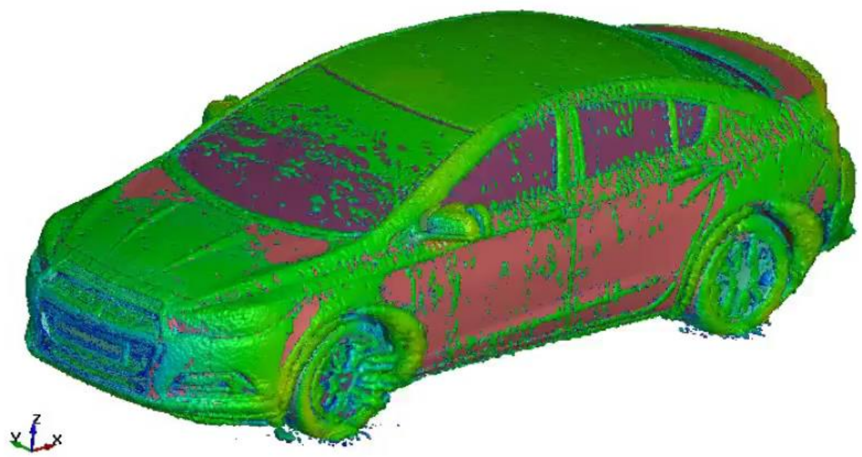




Fz





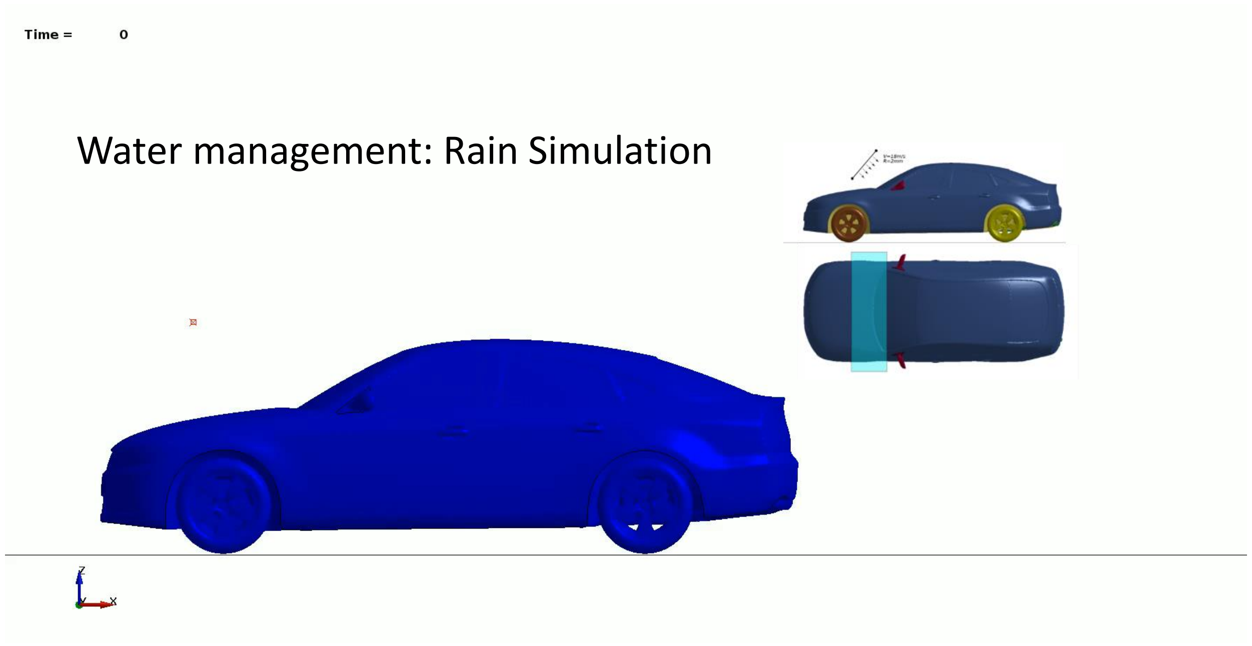


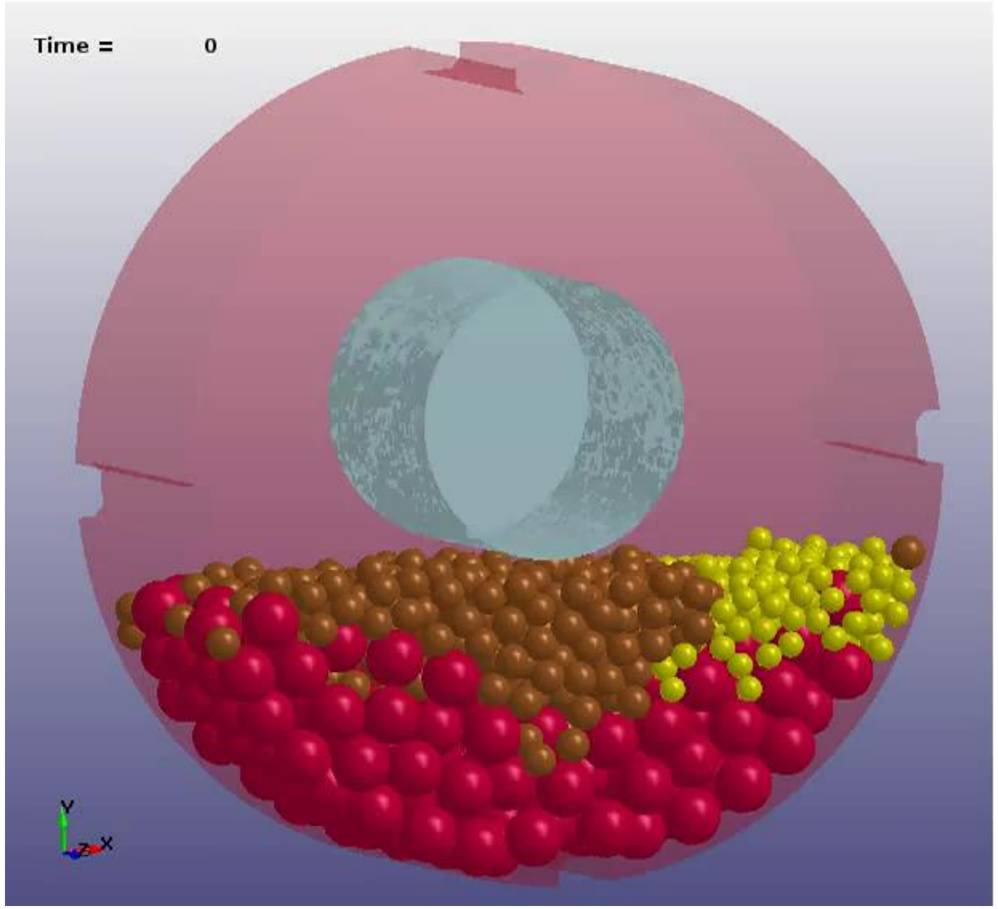
On the right total excitation forces for F_x and F_z. On the left FFT to identify frequency modes that could be used in a flatter prevention or noise analysis

DEM Coupling

- Two-way coupling
- Particles affect fluid volume
- Drag computation can use a constant Cd or Morrison's formula:

$$C_d = \frac{24.}{R_e} + \frac{2.6\left(\frac{R_e}{5.}\right)}{1+\left(\frac{R_e}{5.}\right)^{1.52}} + \frac{0.411\left(\frac{R_e}{2.63\times10^5}\right)^{-7.94}}{1+\left(\frac{R_e}{2.63\times10^5}\right)^{-8.00}}$$



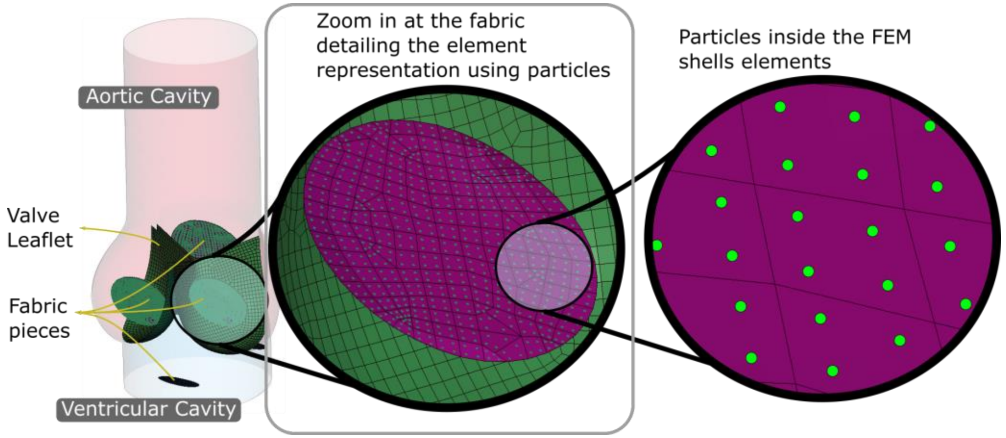


Courtesy of:
Samuel Hammarberg, doktorand.
Pär Jonsén, Professor.
Göran Lindkvist, PhD.
LULEÅ UNIVERSITY OF TECHNOLOGY

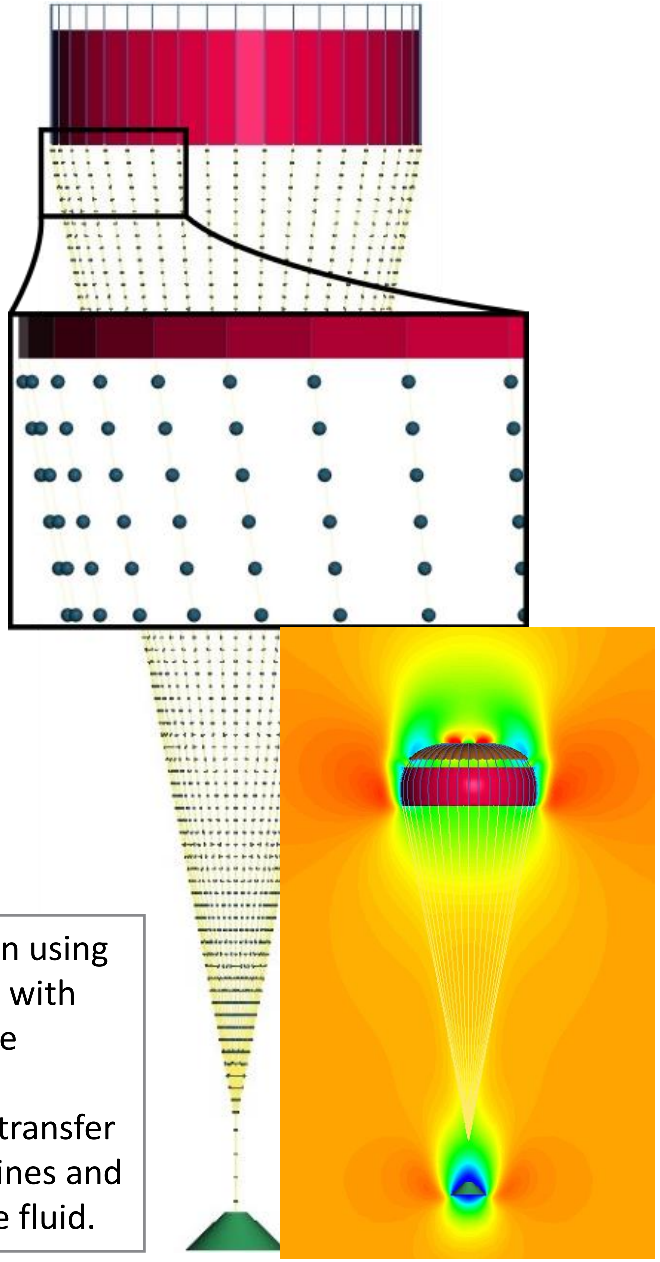
ICFD + DEM for Implicit FSI

- DEM particles in shells and beams provide an alternative FSI interface in some highly complex models.
- The FSI simulations can have a mixture of both body fitted and DEM interfaces even in implicit mechanics.
- A new coupling formulation has been added that uses the fluid pressure force instead of the drag force computed from the velocity field.
- The particle density is now considered for problems that involve buoyancy.

Prosthetic heart valve solved using body fitted implicit FSI is interacting with foreign bodies represented by shells and DEM particles.

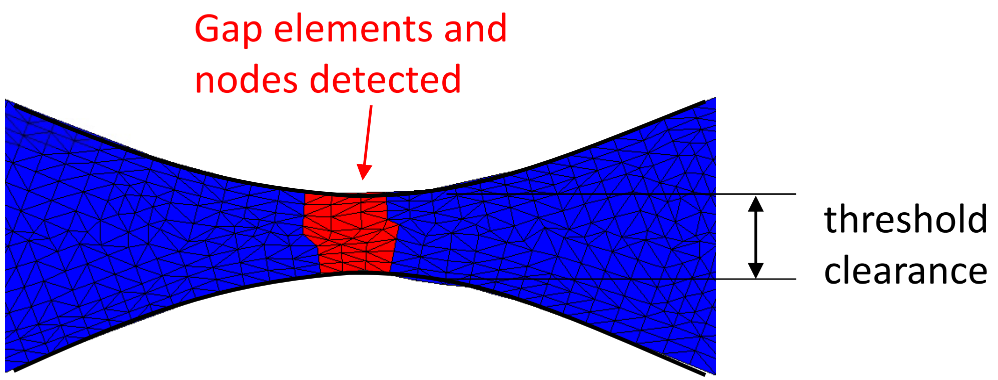


Parachute simulation using implicit FSI coupling with DEM particles on the beams representing suspension lines to transfer momentum to the lines and from the lines to the fluid.



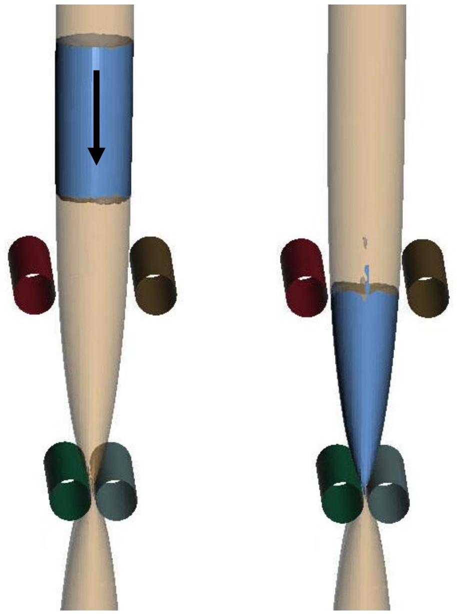
Gap Closure

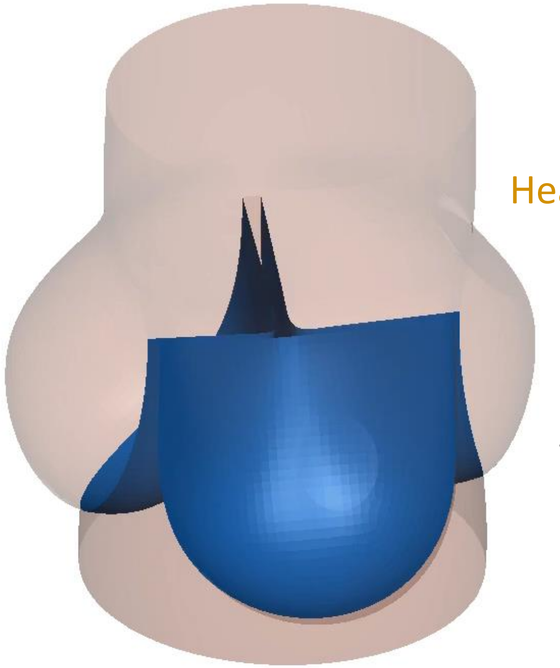
- If the distance between boundaries is less than a user-defined threshold value, the flow is blocked at this region.
- Use new keyword *ICFD_CONTROL_GAP to specify the threshold value and the surface IDs.



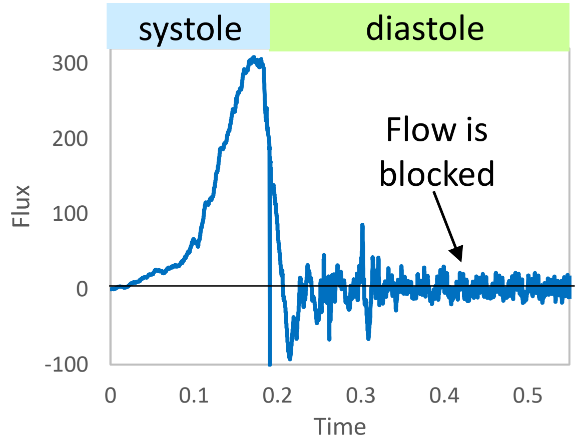
Applications

Filling Simulation



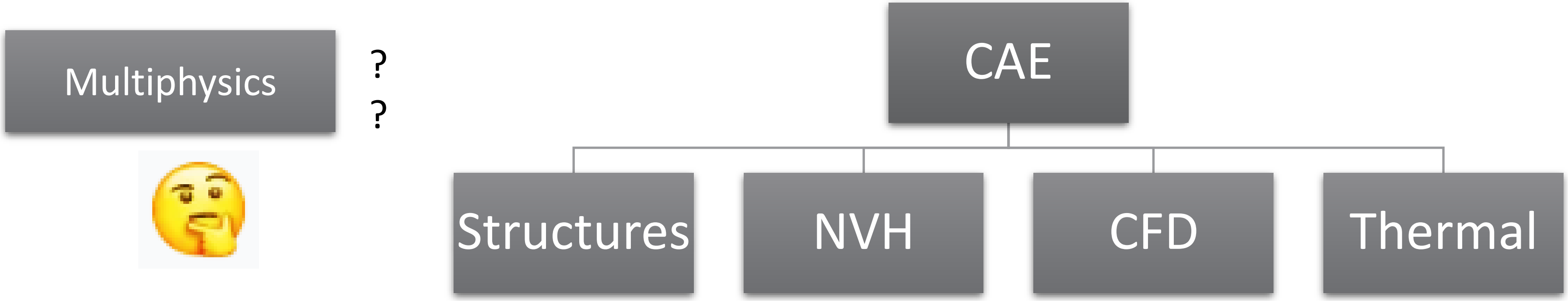


Heart valves



Conclusion and Observations

- LS-DYNA **Multiphysics will continue to push the boundaries of applications**, with a strong focus in the Healthcare sector.
- We need to help more traditional industries like automotive to find efficient workflows to apply Multiphysics. There is an increasing demand due to new technologies, but they are not yet structured in a way to fully embrace it. Historically R&D is divided in departments like Structures, CFD, Thermal and NVH leaving Multiphysics in nobody's land.



Ansys