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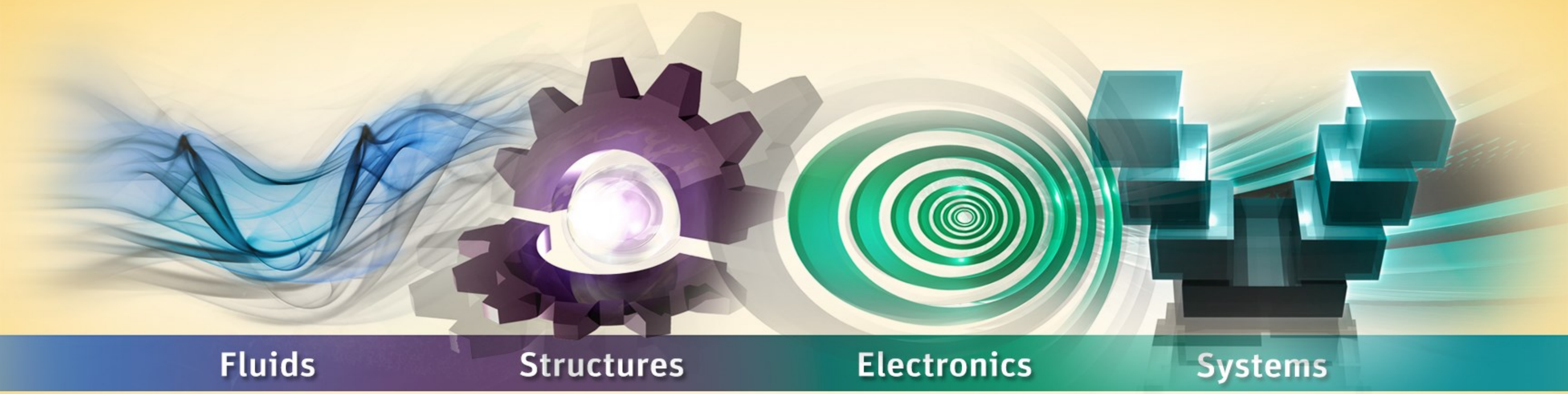
Advanced Simulations of Hypertrophic Obstructive Cardiomyopathy in Human Heart using ANSYS



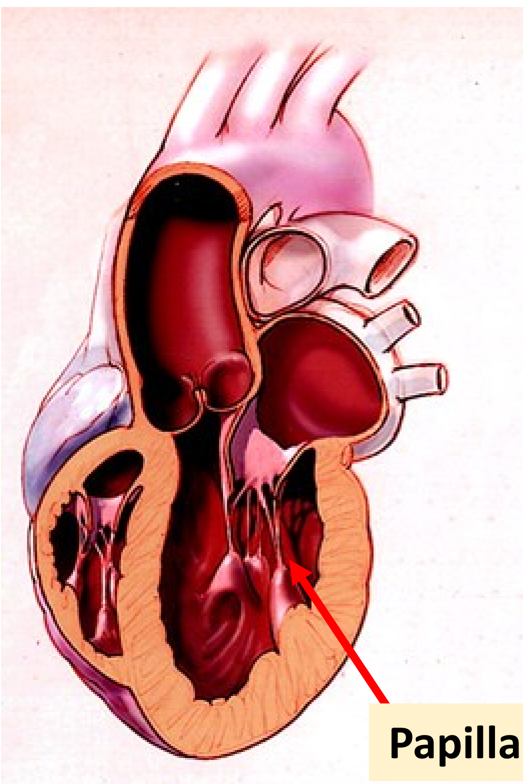
Can Ozcan, Vladimir Kudriavtsev, Metin Ozen

Outline

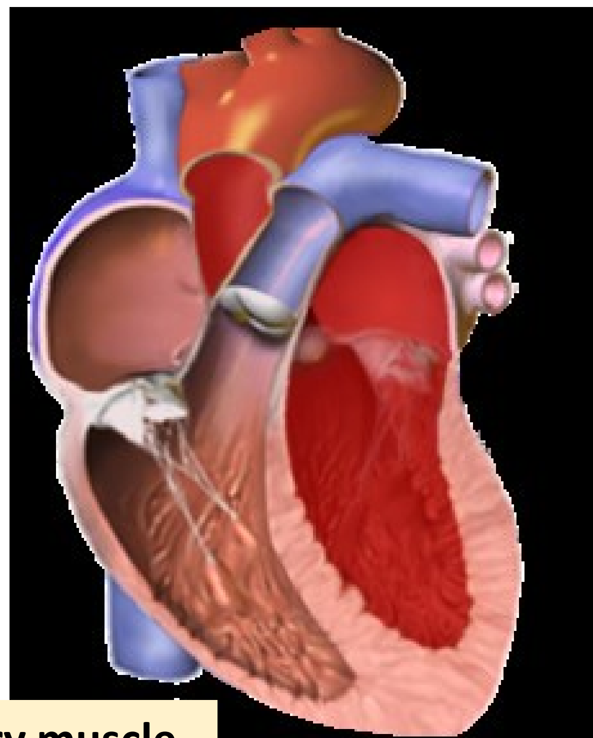
- Physiology and Pathology of Hypertrophic Obstructive Cardiomyopathy
- CFX vs Fluent for FSI Setup?
- Wall Motion in Fluent
- Setting up a 3D model
- Effect of Boundary Conditions
- Effect of Turbulence Modeling
- Effect of Coupling Relaxation Factors (Key Impactor for Convergence)
- How to setup the structural part of the FSI
- A case for CFX: Immersed Body approach

Human Heart Physiology (i.e. Normal Condition)

- Myocytes (contracting heart muscle cells) are at their normal size
- Ventricle volume is not squeezed from sides and allow normal out-flow into aorta



Papillary muscle



Animation
Normal_Echocardiogram.wmv

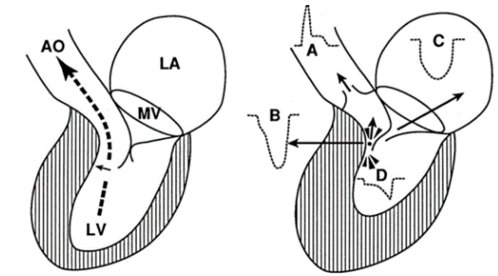
Definition of the Pathological Case

Cardio: Heart

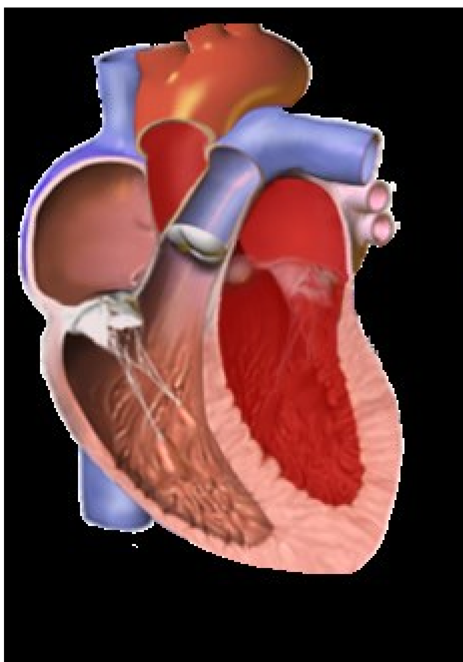
Myo: Muscle

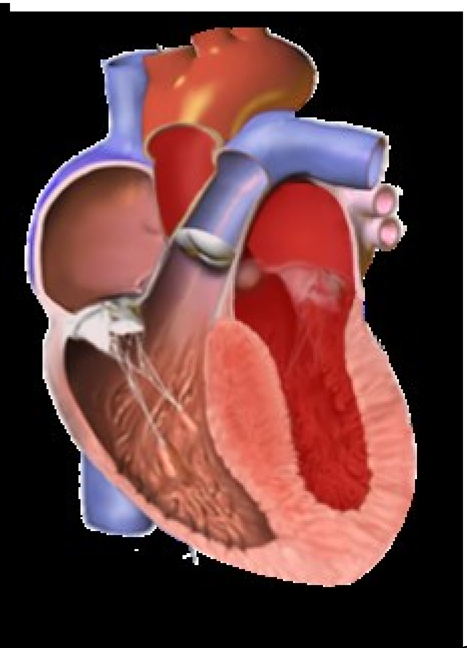
Pathy: Disease, suffering

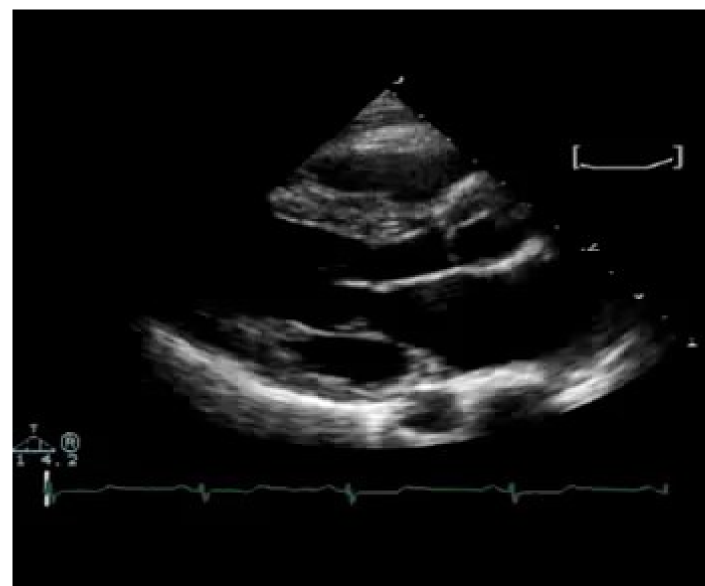
- **Mitral leaflets are large**
- **Papillary muscles are more anteriorly positioned**



Mechanism of dynamic outflow tract obstruction. The upper schematic shows a representation of the mitral leaflets. The elongated mitral leaflets that are drawn into the Left Ventricular Outflow Tract during early systole with midsystolic prolonged systolic anterior motion- septal contact, malcoaptation of the mitral leaflets, and the resultant posteriorly directed jet of mitral regurgitation.



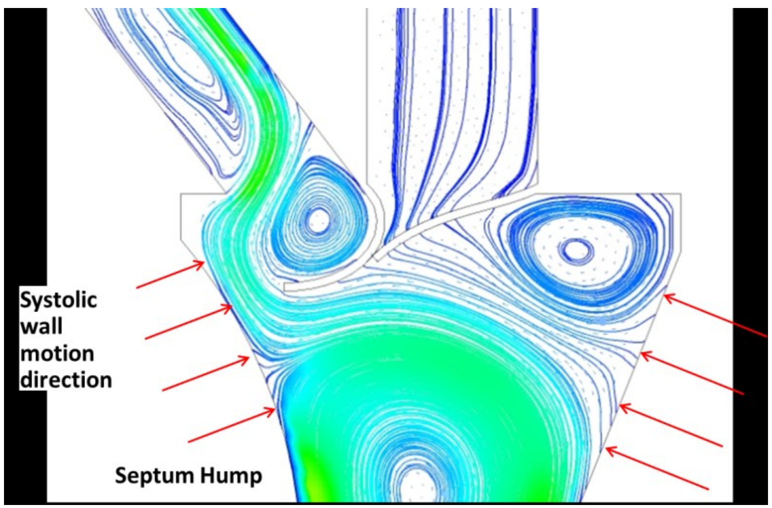


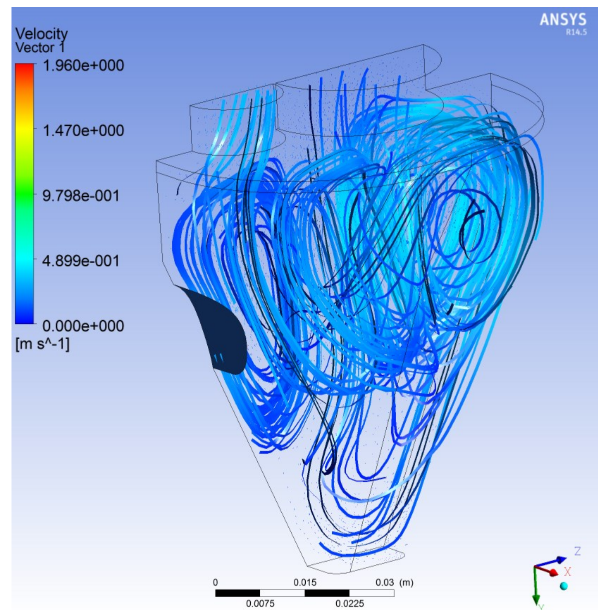


Motivation

2014 -> 2015

- **2014 User's Conference Presentation was performed with**
  - **Ideal 3D geometry -> updated to real 3D geometry**
  - **2D Ideal geometry with only mitral valve -> 2D realistic geometry with both mitral and aortic valve sets**
  - **Boundary conditions at inlet was specified with sinusoidal velocity -> Exponential wall motion definition with Inlet and Outlet vent definition (more realistic boundary conditions)**





CFX18

Why do we used Fluent and not CFX?

Main reason is the internal re-meshing capability

- **With CFX one can do re-meshing calls automatically, but this is not available for FSI setups yet**
  - **Fluent provides different re-meshing options like 2.5D extrusion mesh**
    - **Some tips about re-meshing:**
      - **Boundary layers in 2D does not work nicely**
      - **Use coarse elements near deforming regions as oscillations may result in negative volume errors**
      - **2.5D re-meshing is limited to “Spring” method**
      - **FSI surfaces are not re-meshed and keep original mesh elements (some kind of limitation here)**

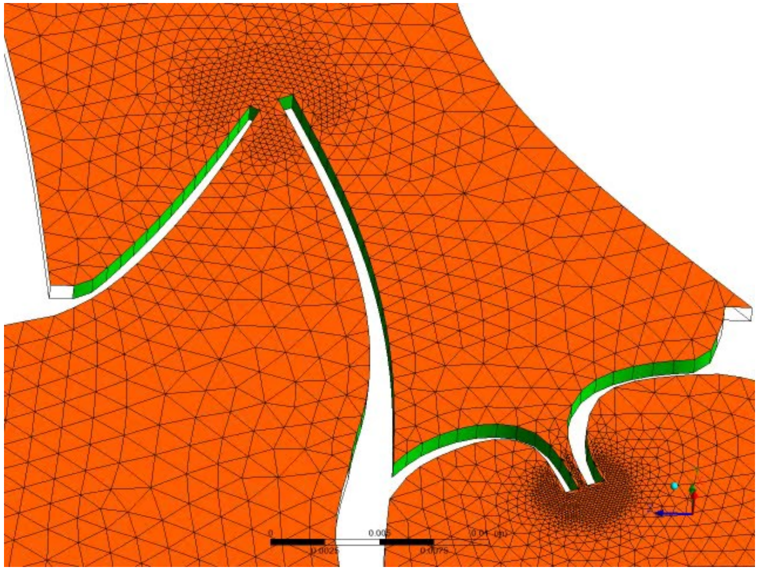
How to implement wall motion in Fluent?

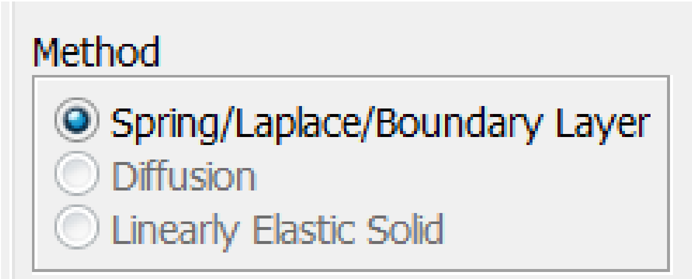
UDF in C language

- MACROS
  - Interpreted (does not need compiler; can be used for boundary condition)
  - Compiled (faster, but needs compiler; needed to define wall motion)
- Visual Studio Community Compiler is free
- When you switch versions of ANSYS (i.e. from R15 to R16) you need to re-compile the UDF libraries
- Compiling in different operating systems, require re-compilation and some syntax rules may change (like comments // does not work on some Linux cc compilers)

2D Analysis – 2.5D Analysis

- **For 2D problems, one can use 2.5D remeshing in Fluent (model a 3D slice to represent the problem in 2D)**
- **With 2.5D remeshing one can model 3D extruded geometry as well**
- **2.5D surface re-meshing method only applicable to along line extrusions**
- **Only triangular surfaces mesh is allowed (no mixed zones)**
- **Only Laplacian smoothing is available (kind of limitation for large wall deformations)**



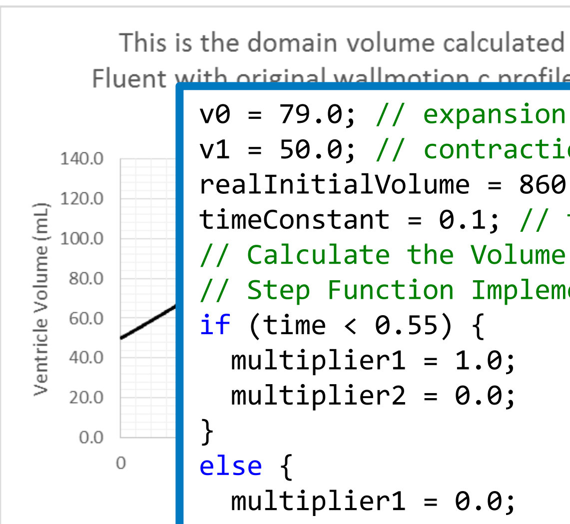


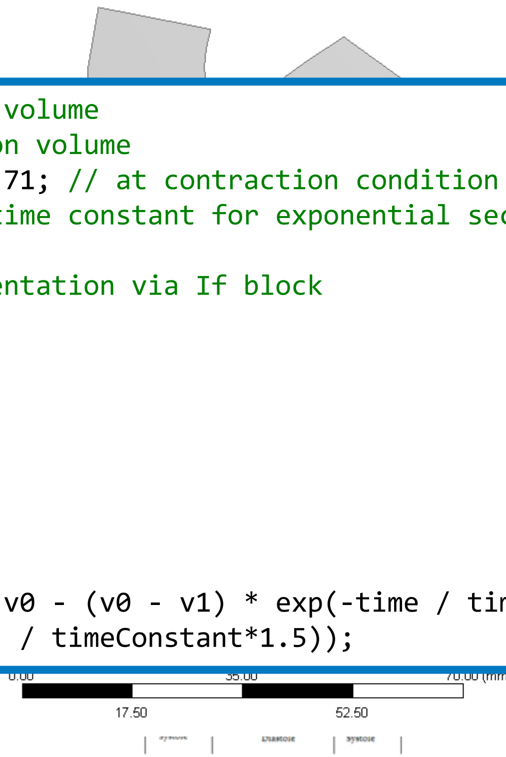
Effect of Boundary Conditions

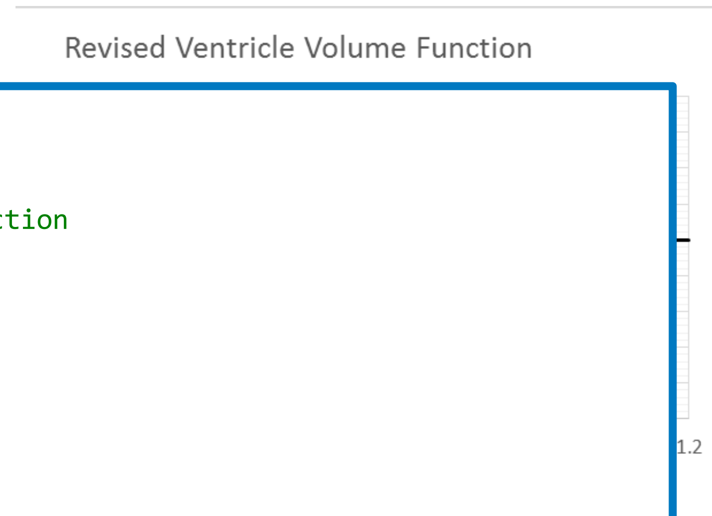
Last years 2D case was performed using sinusoidal wall motion as shown below

Physiological wall motion should be related to ventricle volume change

We switch to exponential function to define the wall motion to match the ventricle volume (this still miss complex ventricle contraction, but is closer to reality)








```
v0 = 79.0; // expansion volume
v1 = 50.0; // contraction volume
realInitialVolume = 860.71; // at contraction condition
timeConstant = 0.1; // time constant for exponential section
// Calculate the Volume
// Step Function Implementation via If block
if (time < 0.55) {
  multiplier1 = 1.0;
  multiplier2 = 0.0;
}
else {
  multiplier1 = 0.0;
  multiplier2 = 1.0;
}
volume = multiplier1 * (v0 - (v0 - v1) * exp(-time / timeConstant)) + multiplier2 * (v1 + (v0 -
v1) * exp(-(time - 0.55) / timeConstant*1.5));
```

…nsion:
130 mL; but remember this is 2D!

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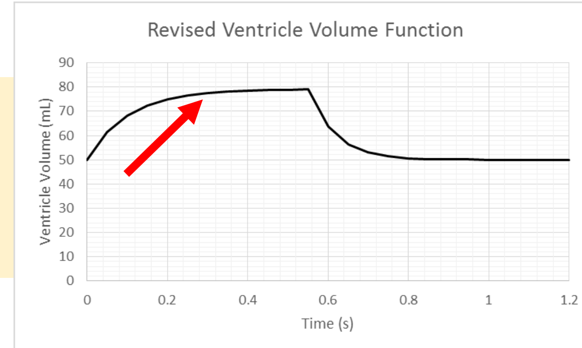
Effect of Boundary Conditions



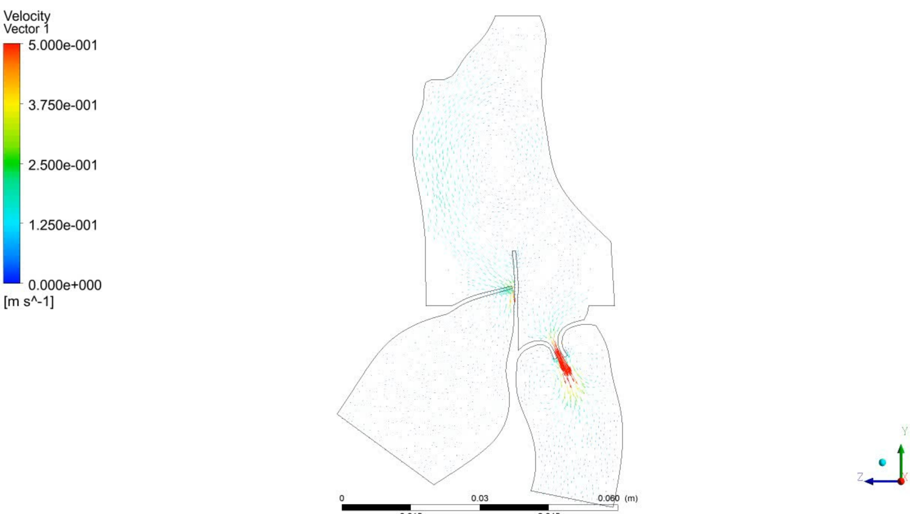
- Wall function is set to match volume change shown here
- Mass flow is set as derivative of volume change (rho*dV/dt)

Inlet velocity was specified

Opt-A: Inlet vent / Outlet vent

Opt-B: Inlet mass flow / Outlet pressure or vent

- **Mass flow is defined to match the ventricle volume change due to wall motion**

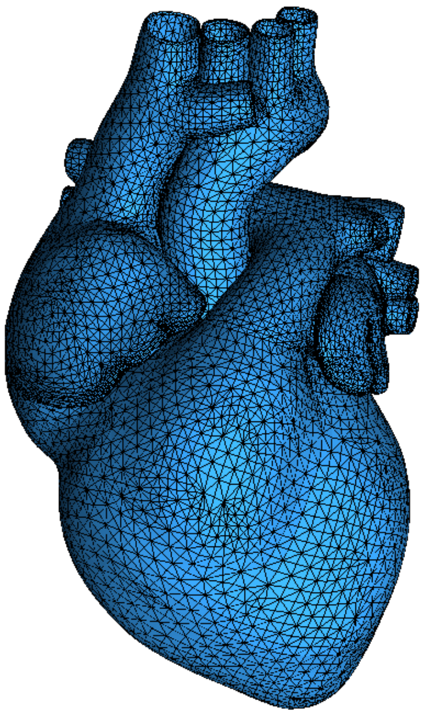


Option-A: Both Inlet and Outlet are defined as vent

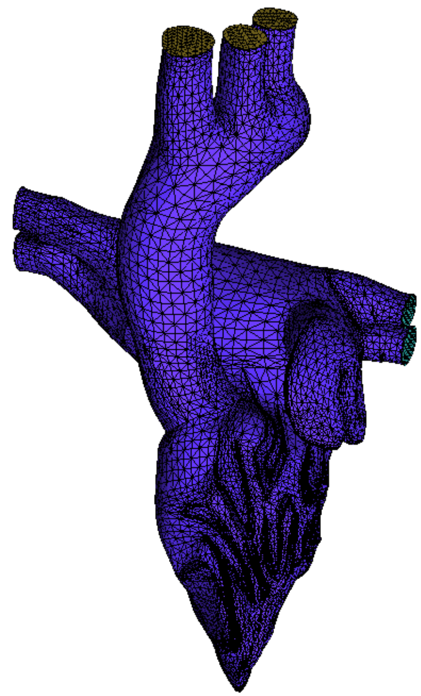
Option-B: Inlet mass flow Outlet is defined as vent

3D Real Heart Mesh

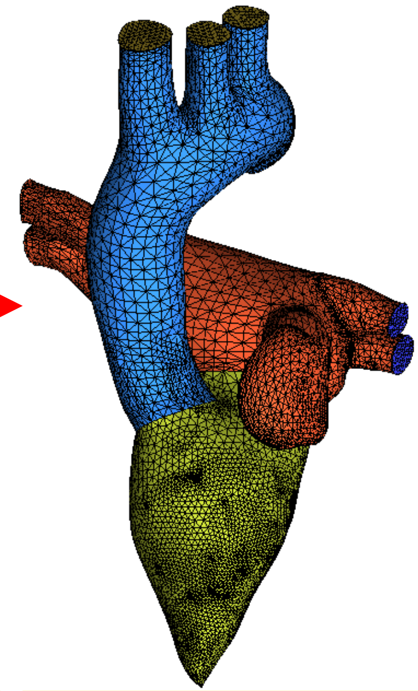
- Preparation of the geometry is performed in ICEM-CFD
- Wall motion definition required a new wallmotion3D.c
- Ventricle volume is expanded with respect to a center point located in between mitral and aortic valves



Original Full Heart Geometry



Left Ventricle and Atrium Extracted in ICEM

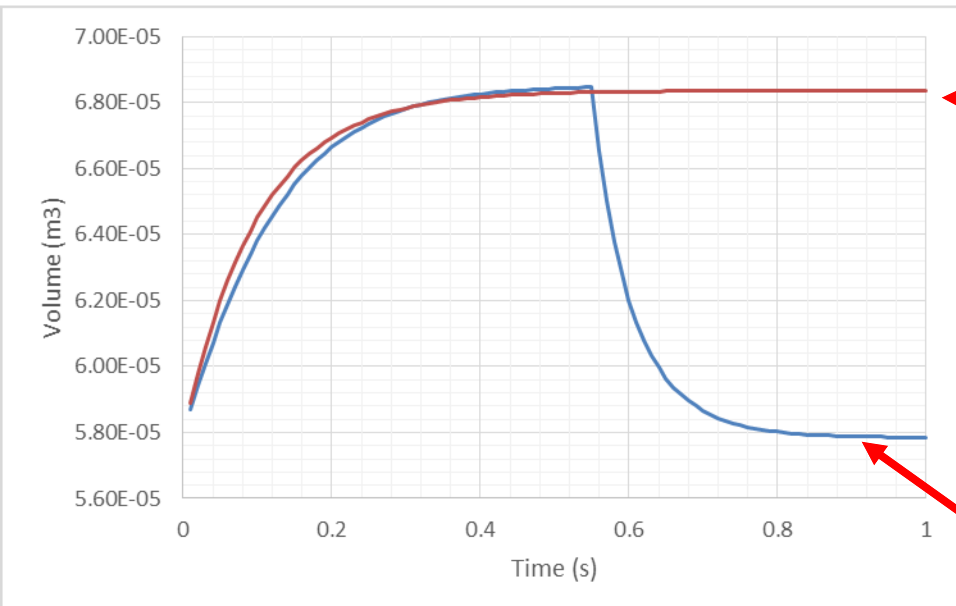


Smooth Mesh for Robust Wall Motion Definition

Model courtesy of Dr. Jingwen Hu, PhD
University of Michigan Transportation Research Institute

3D Case Boundary Conditions

- Outlet condition can be specified as vent(opening) or zero pressure condition
- Inlet mass flow rate is specified to match left-ventricle volume change
  - Mass flow rate is calculated according to equation: $\dot{m} = \rho \frac{\partial V}{\partial t}$

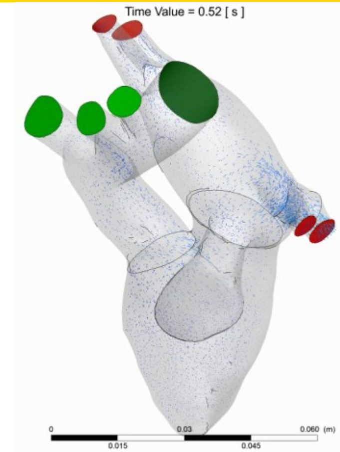


Mass Flow Rate equation is chosen to match the domain volume change

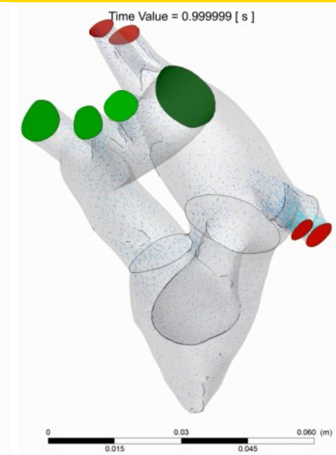
Modelled heart domain volume

3D Real Heart Model

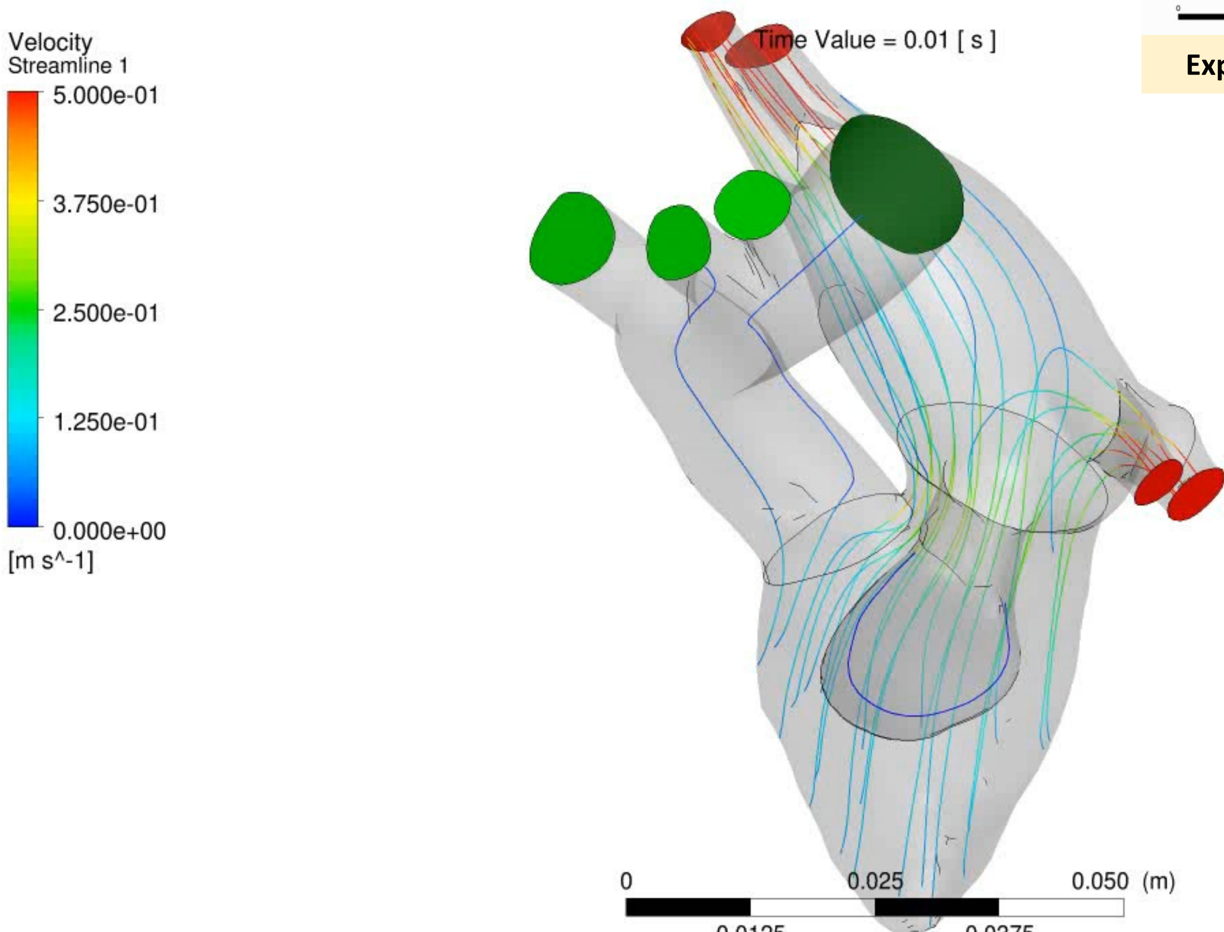
- **Animation. No valves modelled**
- **Outlet specified as vent/opening with inlet prescribed mass flow rate (see prev. slide)**

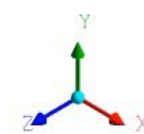


Expanded @0.55s



Contracted @1.0s





3D Real Heart Mesh – Solution in OzenCloud

- Technology by UberCloud
- Speed-up vs number of CPU's is analyzed with a small mesh (0.2M) and a large one (4.5M cells)
- **With Large Models One can appreciate speed up**

0.2M Cell Mesh

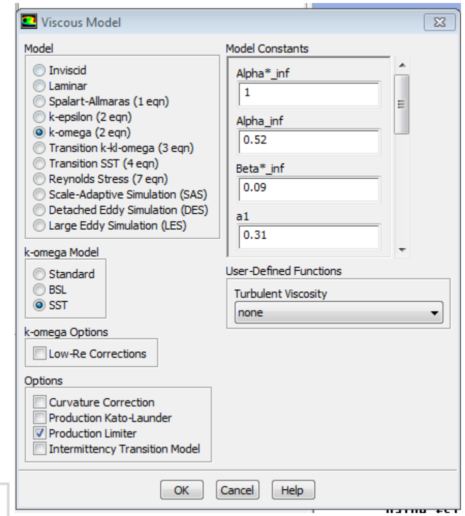
	Solve Time	Speed-Up
2 CPU	7090 sec	n/a
4 CPU	6360 sec	1.1X
8 CPU	6384 sec	1.0X
16 CPU		

4.5M Cell Mesh

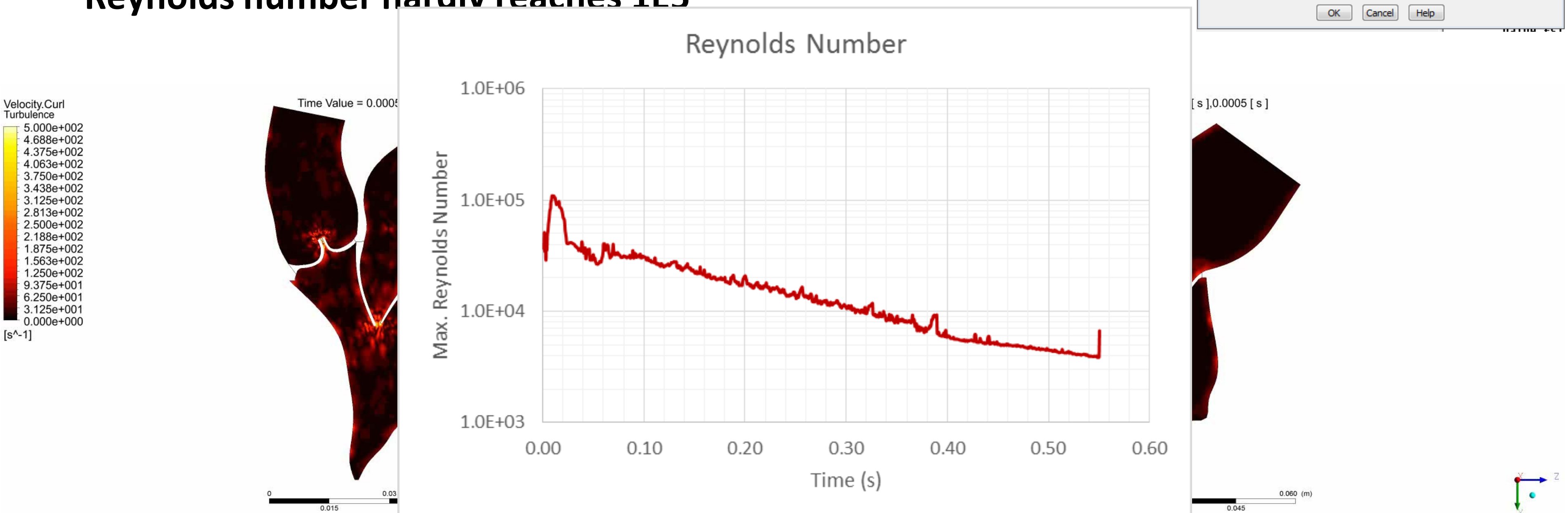
	Solve Time	Speed-Up
2 CPU		
4 CPU	81000 sec	n/a
8 CPU	45900 sec	**1.75X**
16 CPU		

This is mostly due to small mesh size and re-meshing taking relatively longer with respect to actual flow field solution

2D Effect of Turbulence Model



- **Laminar vs k-omega SST turbulence model differences over vorticity is provided below**
- **Inlet & Outlet condition with 5% Turbulent Intensity and 10 Viscosity Turbulent Viscosity Ratio**
- **Reynolds number hardly reaches 1E5**



Laminar **Turbulence**

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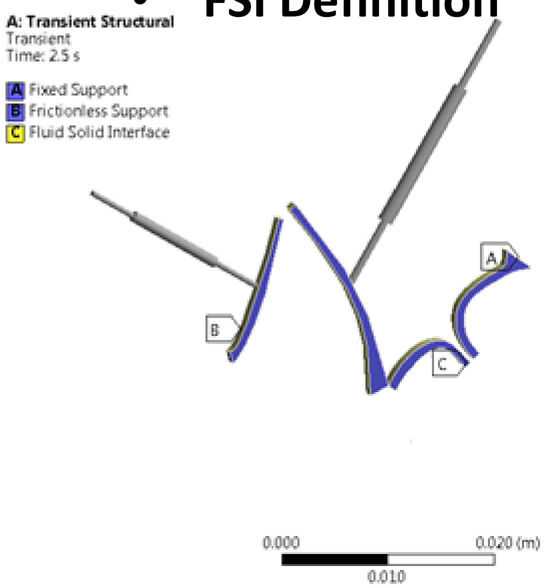
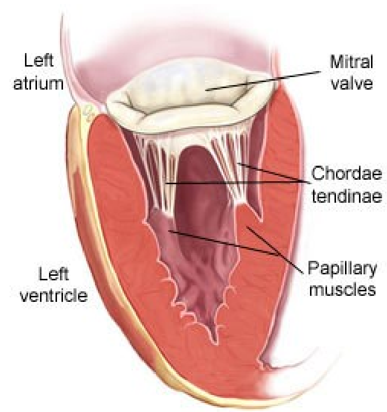
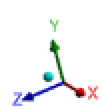
Structural Setup & Boundary Conditions

- No weak springs are used but damper/spring elements are added to mitral valve tips to mimic “Papillary Muscles”. In analysis this prevents collapse of mitral valve into left atrium.
- Large deflections should be turned ON (NLGEOM, ON)
- Structural boundary conditions
  - Fixed Surfaces
  - Symmetry (via frictionless support)
  - FSI Definition

Some cases may converge using “stabilization” but this usually results in unrealistic deformation and is an indication of unrealistic boundary conditions





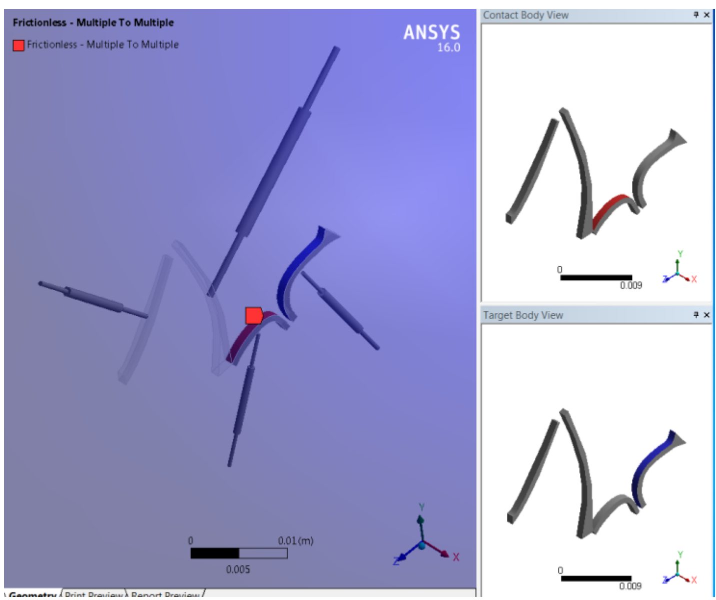


Details of "Analysis Settings"

Step Controls	
Solver Controls	
Solver Type	Program Controlled
Weak Springs	Off
Large Deflection	On
Restart Controls	
Nonlinear Controls	
Newton-Raphson Option	Program Controlled
Force Convergence	Program Controlled
Moment Convergence	Program Controlled
Displacement Convergence	Program Controlled
Rotation Convergence	Program Controlled
Line Search	Program Controlled
Stabilization	Reduce
--Method	Damping
--Damping Factor	5.e+008
--Activation For First Substep	Yes
--Stabilization Force Limit	0.2
Output Controls	
Damping Controls	

Structural Setup Details (Contacts)

- **Contact definitions are critical to achieve robust solution in FSI setup**
- **Contact conditions with offset to prevent fluid elements collapsing in CFD side**
- **In addition to surface-to-surface contact, one should make use of edge-to-surface contacts to prevent penetration problems in valve-to-valve contact**
- **Stiffness factor can be decreased up to 0.01 for better convergence**



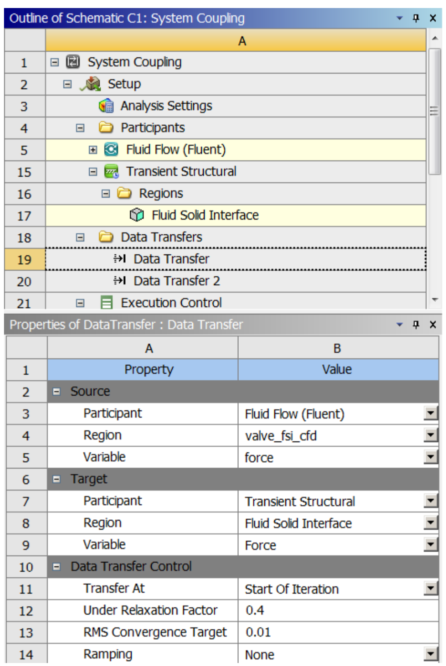
ANSYS R16 Contact View

Advanced	
Formulation	Pure Penalty
Detection Method	Program Controlled
Penetration Tolerance	Program Controlled
Normal Stiffness	Manual
Normal Stiffness Factor	1.e-002
Update Stiffness	Program Controlled
Stabilization Damping Factor	0.
Pinball Region	Radius
Pinball Radius	5.e-002 m
Time Step Controls	None
Geometric Modification	
Interface Treatment	Add Offset, No Ramping
Offset	5.e-004 m
Contact Geometry Correction	None
Target Geometry Correction	None

Contact Definition

Effect of Coupling Relaxation Factors

- **Force and displacement "under relaxation factor" values limits potential large variations which may result in divergence**
- **Maximum number of coupling iterations should be set to allow complete convergence within each coupling step**



$$\phi_{\mathrm{Relaxed}} = \phi_{\mathrm{Reference}} + \omega\left(\phi_{\mathrm{Raw}} - \phi_{\mathrm{Reference}}\right)$$

Under relaxation factor

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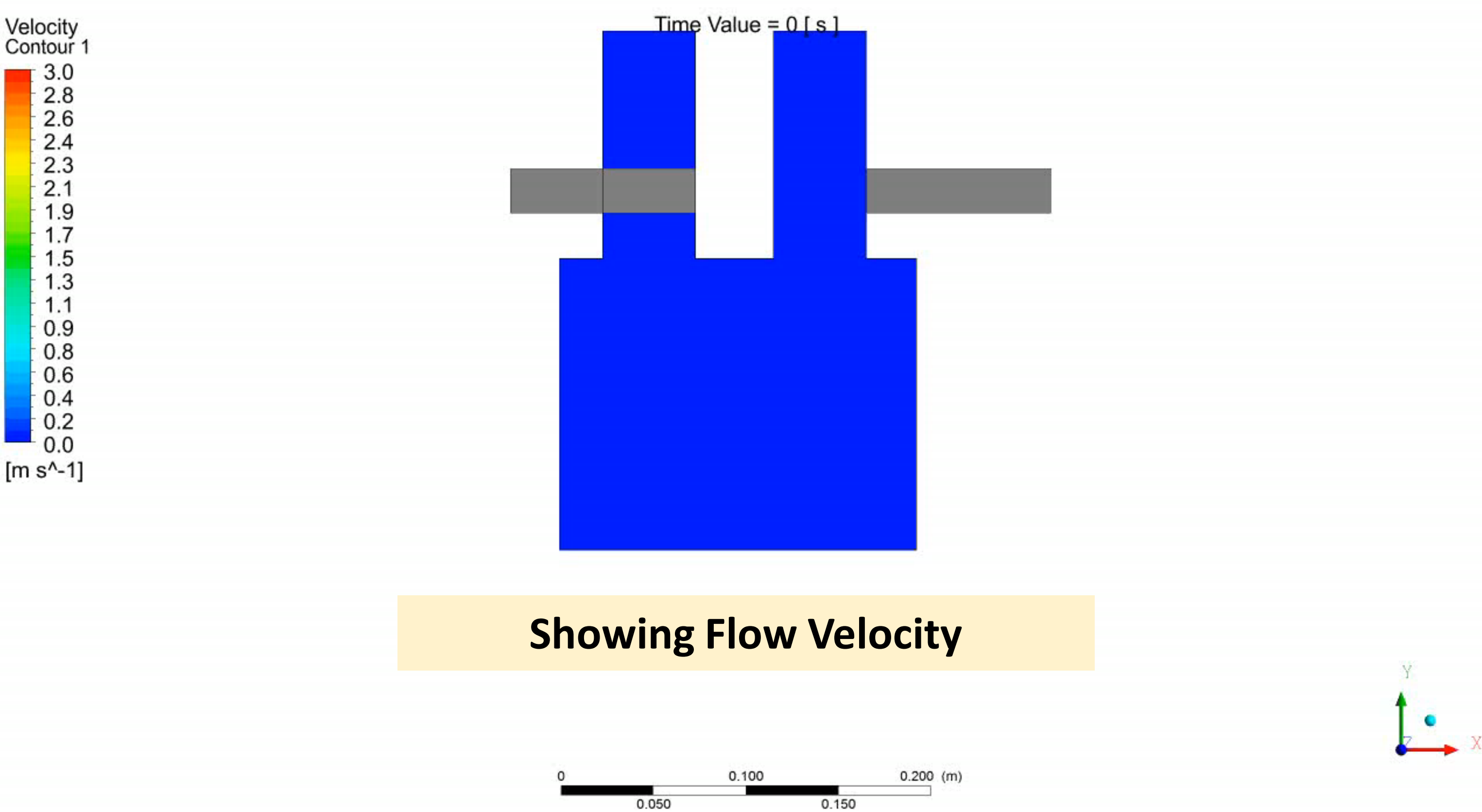
3D CFX using immersed boundary method

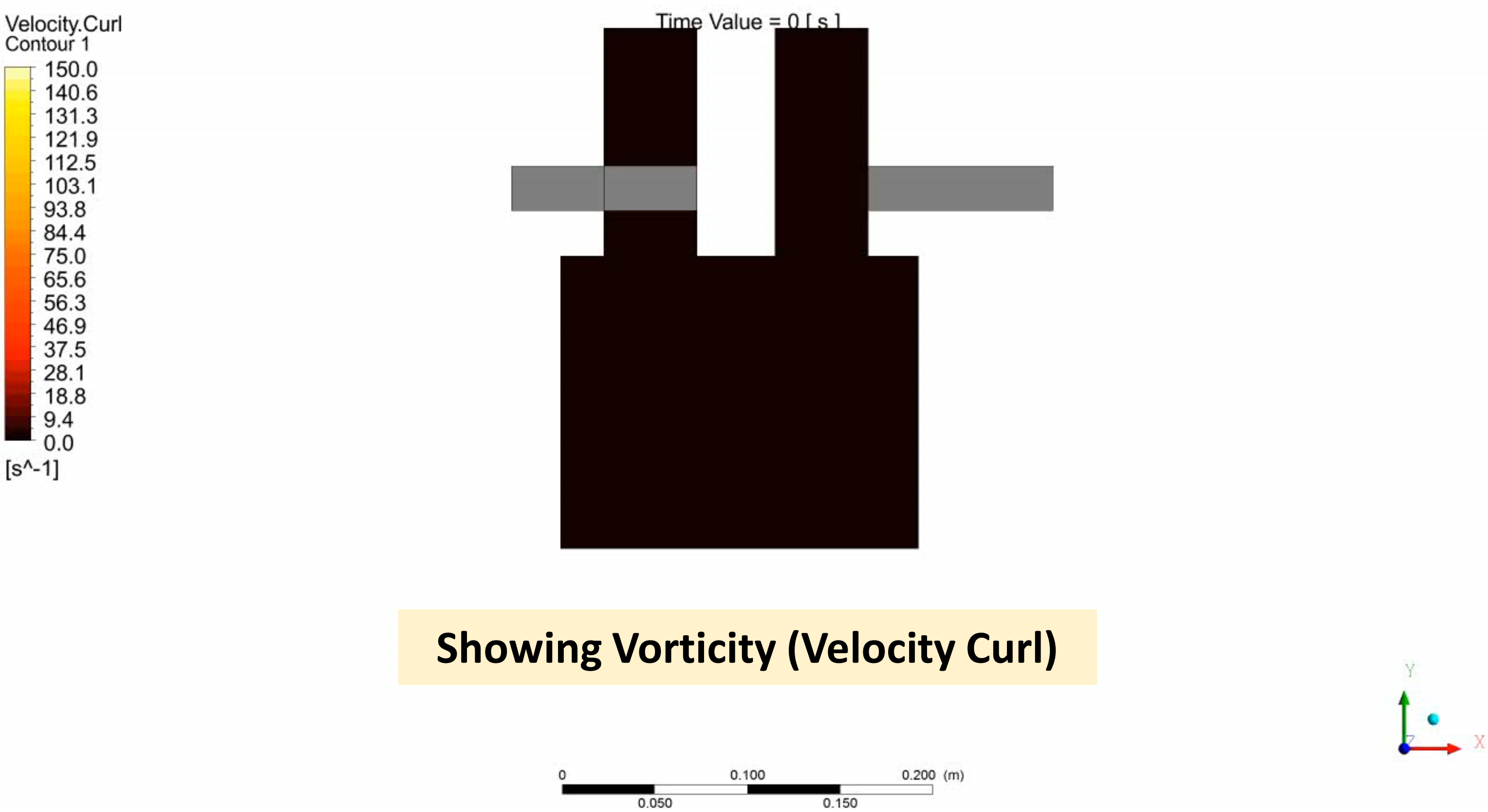
- Can be used to model physiological case (i.e. normal condition)
- Valve deformation cannot be captured, so not useful for modelling hypertrophic cardiomyopathy



Showing Flow Velocity

3D CFX using immersed boundary method

- **Can be used to model physiological case (i.e. normal condition)**
- **Valve deformation cannot be captured, so not useful for modelling hypertrophic cardiomyopathy**



Showing Vorticity (Velocity Curl)

Next Steps

- **3D valve with re-meshing in Fluent can be implemented**
- **Realistic valve contraction input can be obtained from Cardiac MRI and applied using Fluent UDF(user defined functions)**