II

Immersed Boundary Method and Investigation of Some Fundamental Questions Regarding the "Design" of the Heart

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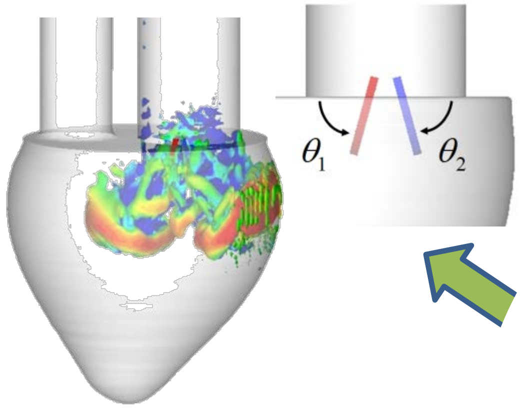
Mechanical Engineering

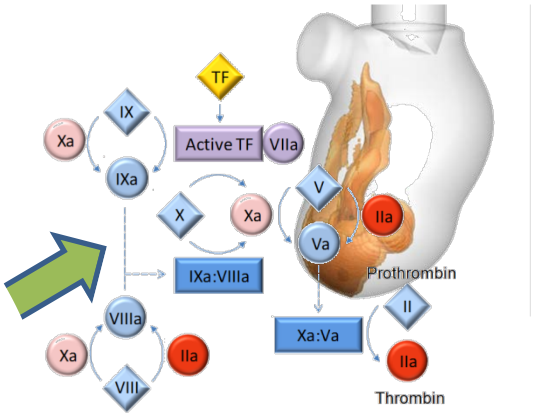
Theodore Abraham, Albert Lardo and Richard T. George
Cardiology

Multi-Capability Tool Required

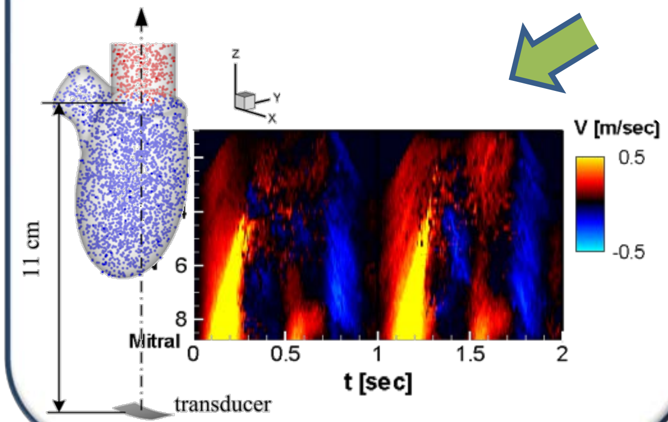
Flow-Structure Interaction



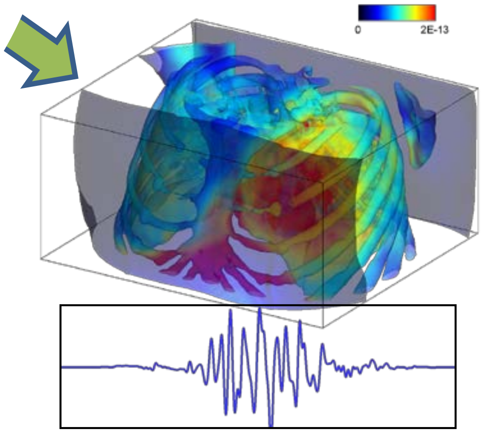
Biochemical Reactions



Virtual Cardiography

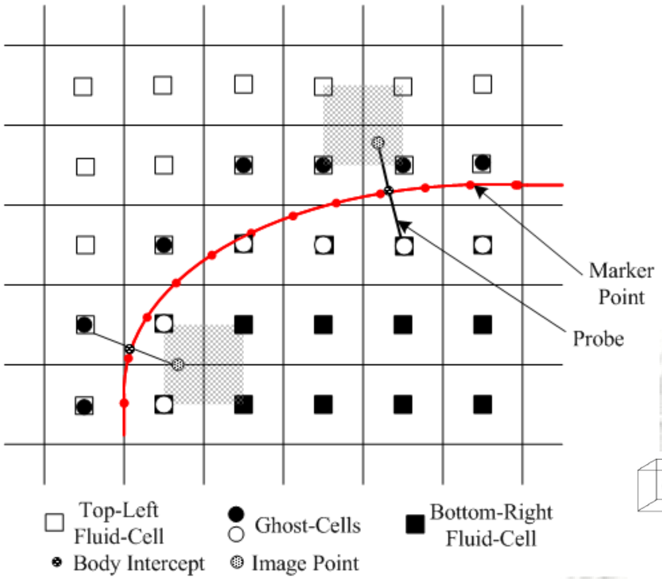


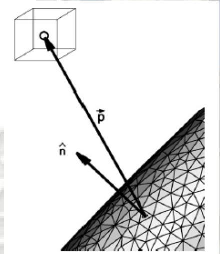
Hemoacoustics



ViCar3D — Viscous Cartesian Grid Solver for 3D Immersed Boundaries

- Simulations on non-conforming Cartesian Grids
  - Stationary/moving boundaries
  - Solids/membranes
- Sharp Interface IBM method
  - No boundary forcing (Peskin et al)
  - 3D ghost-cell methodology
- 2nd Order Fractional Step Scheme
- 2nd Order non-dissipative central difference scheme
  - IBM treatment also 2nd order accurate
- Global Dynamic Coeff SGS Model (Vreman)

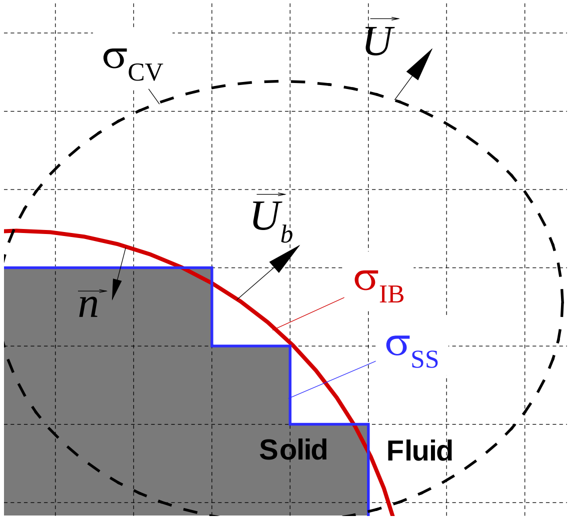




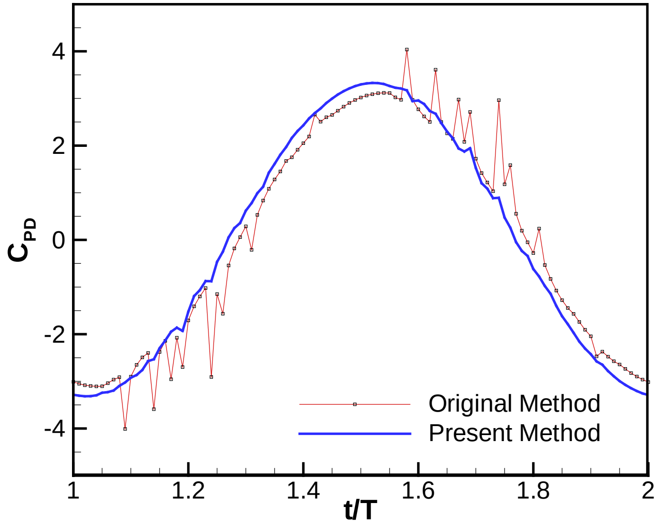
Immersed Boundary Methods
Mittal & Iaccarino,
Ann. Rev Fluid Mech. 2005

ViCar3D: Improved Conservation

- For finite-difference based IBM, boundary motion leads to violation of geometric conservation law
  - Loss of strict local mass conservation
  - Spurious pressure oscillations
  - Bad for FSI and sound prediction

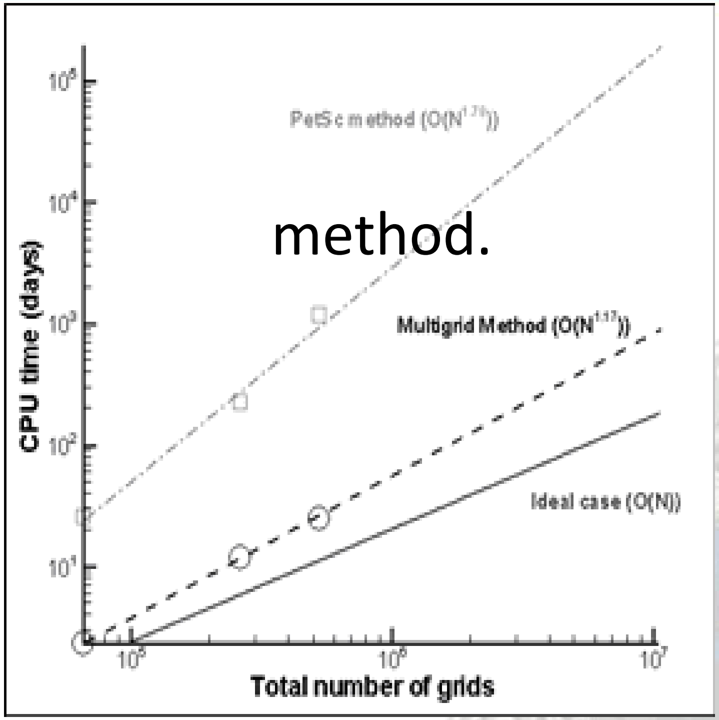


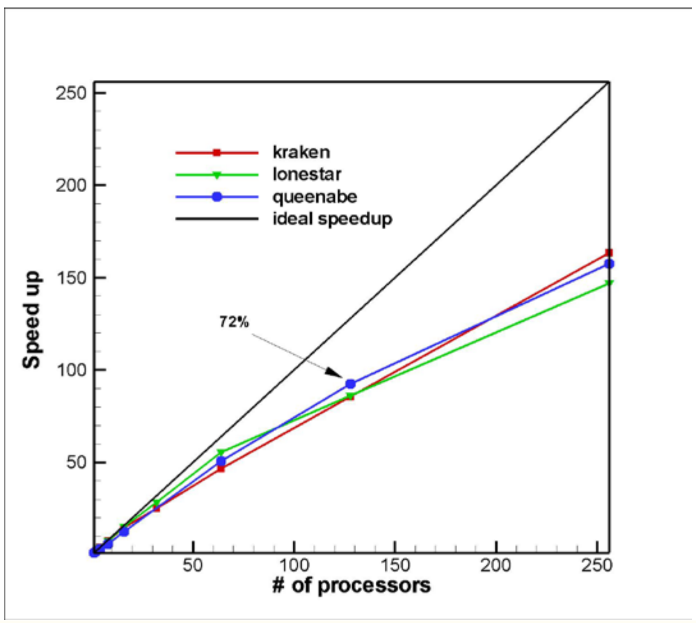
- Have devised a method that ensures "regional" mass conservation
  - Finite-difference for momentum
  - Finite-volume for mass



ViCar3D: Performance

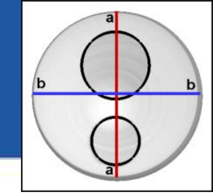
- Pressure Poisson
  - > 80% of CPU time
  - Geometric multigrid
  - Semi-coarsening + LSOR
  - Approx. reconstruction of IB on coarse levels.





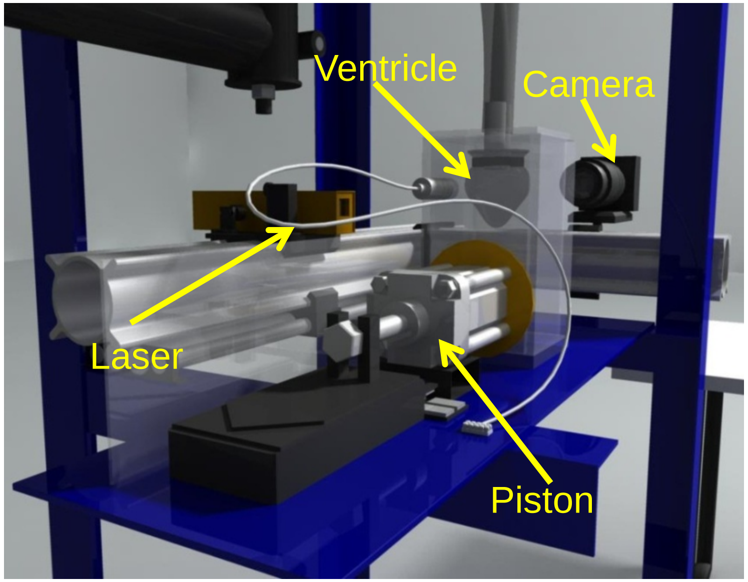
- **MPI based parallelization**
  - **2D domain decomposition**

Experimental Validation: Simplified LV

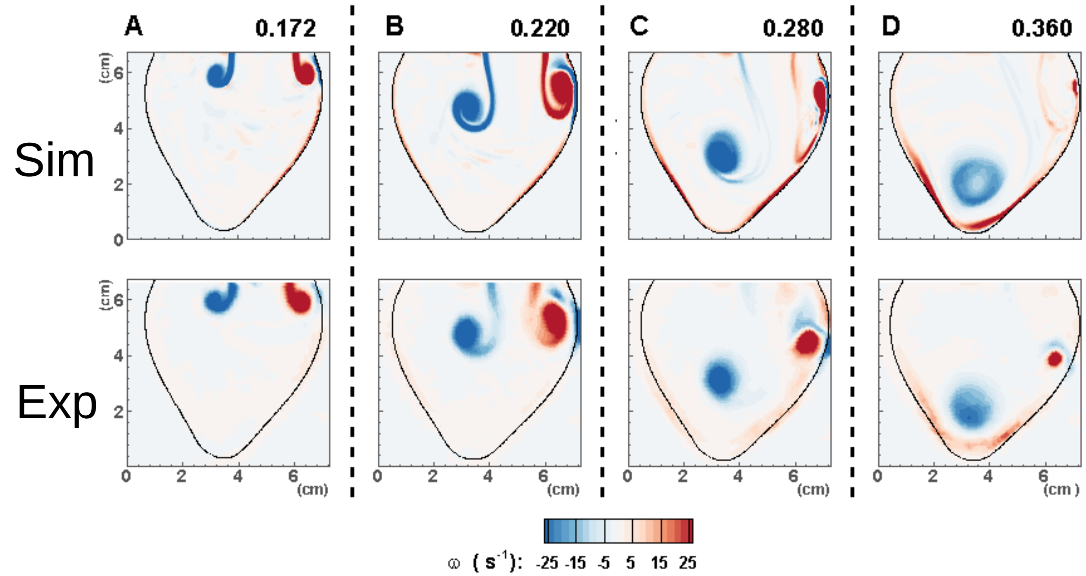


Top View

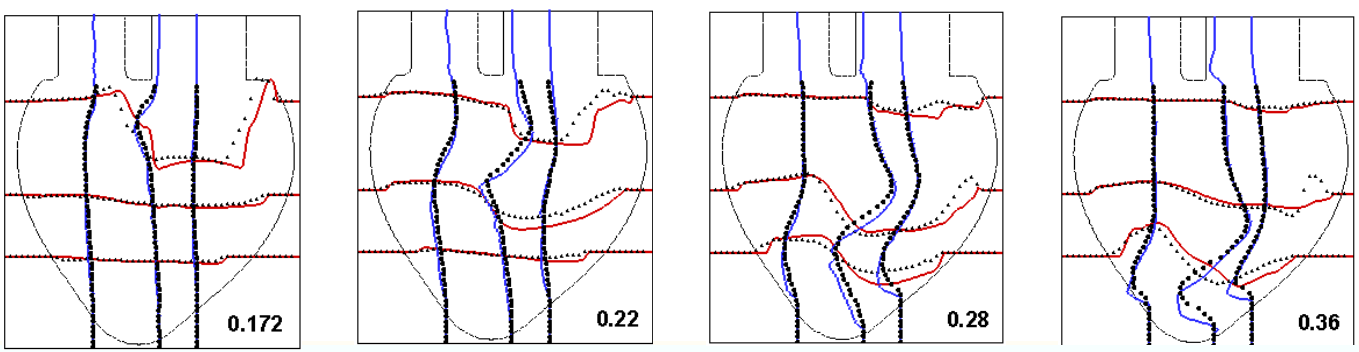
Vedula et al. *Theo. Comput. Fluid Dyn.* 2014, vol. 28(6)
Fortini et al., *Exp. Fluids.*, 2013, vol. 54(11)

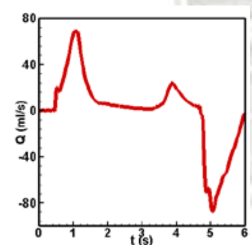


Vorticity Field Comparison



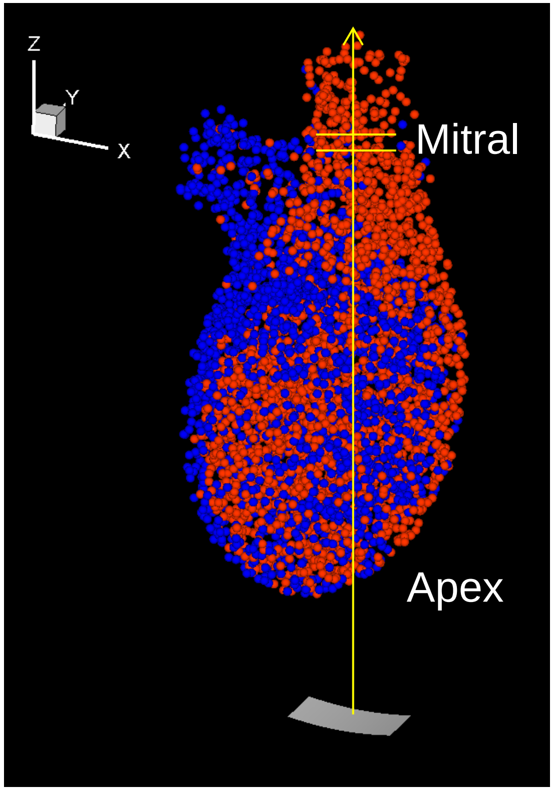
Velocity Profiles Comparison



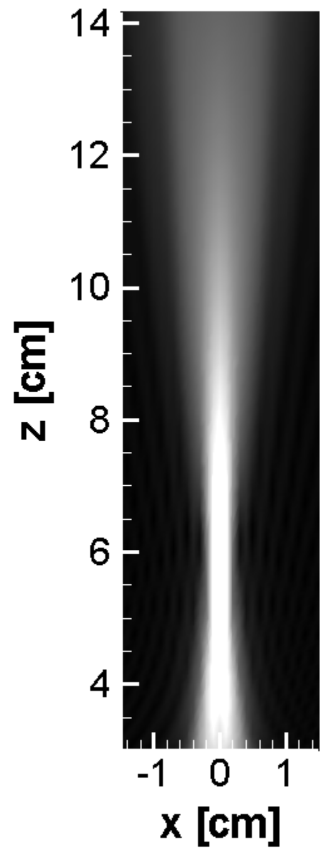


Re: 3475
Wo: 9.7
SV: 60 ml
EF: 40%

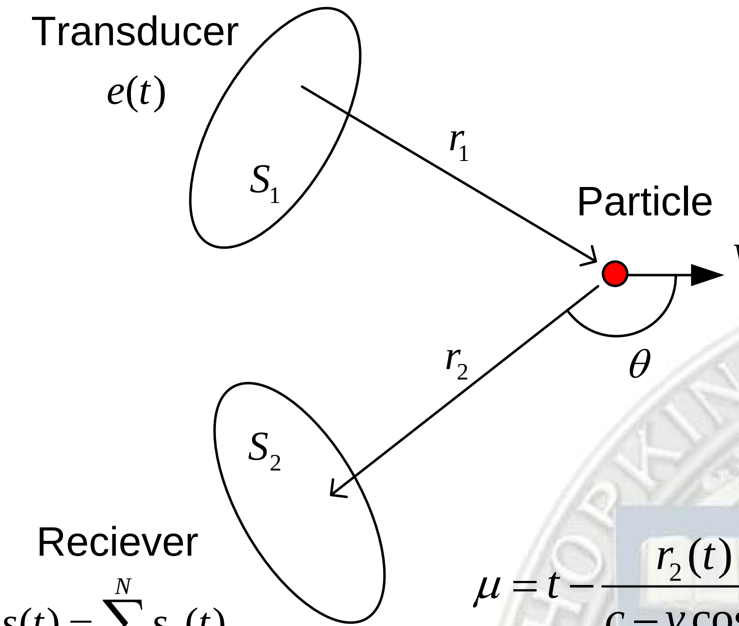
Diagnosis: Virtual Doppler Ultrasound



Parabolic transducer
Size: 2 cm, pulsed wave
f_0= 2 MHz, T_p=1 μsec



Ultrasound wave intensity



$$s(t) = \sum_{n=1}^{N} s_n(t)$$

$$\mu = t - \frac{r_2(t)}{c - v\cos\theta}$$

$$\frac{v\cos\theta}{c} = \frac{\Delta f}{2 f_0}$$

f_0: driving frequency
Δf: frequency shifting in $s(t)$
c: speed of sound

Scattered signal by single particle $$s_n(t) = \frac{1}{(2\pi)^2} \int_{S_2} \int_{S_1} \frac{1}{r_2(\mu)} \frac{1}{r_1(\mu)} e(\mu - r_1(\mu)/c)\, dS_1\, dS_2$$

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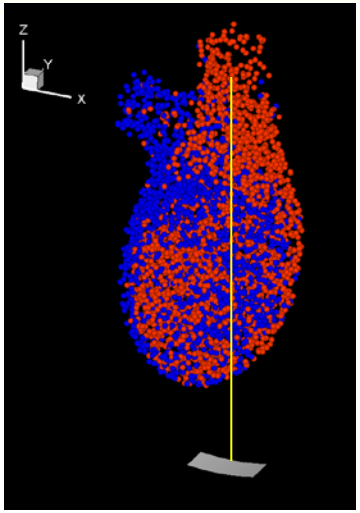
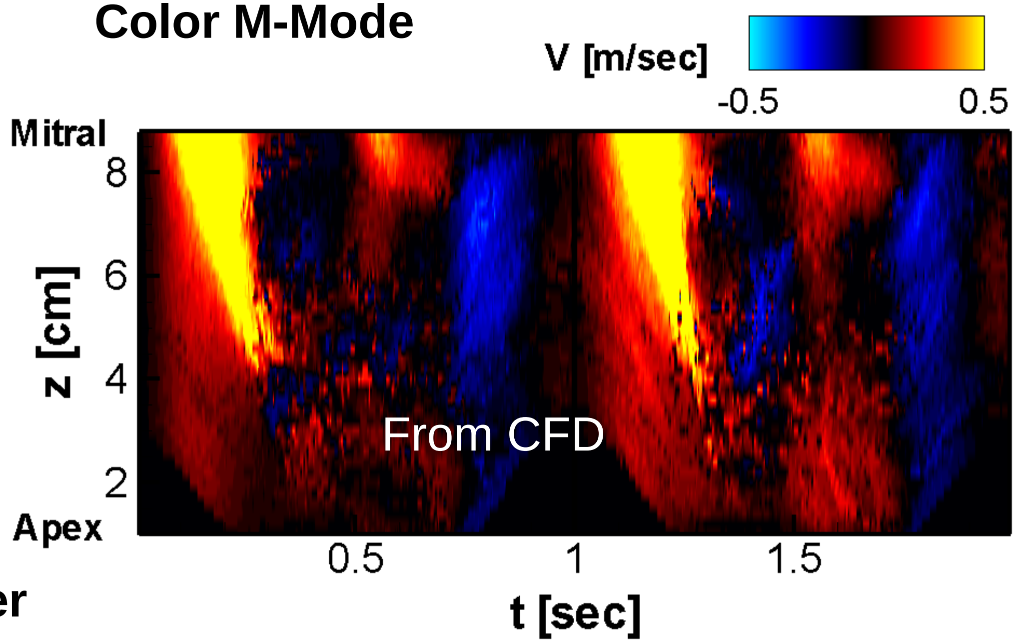
Virtual Doppler Echocardiography

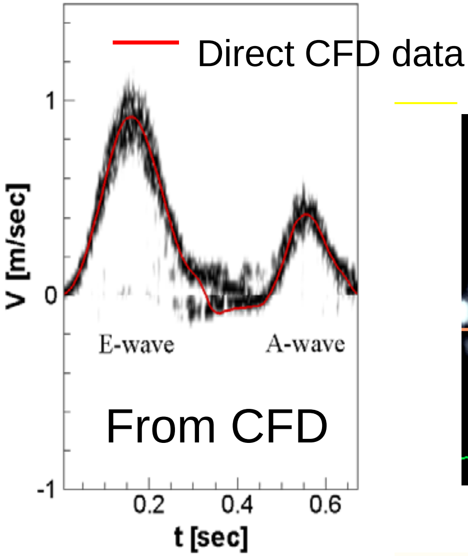


Parabolic transducer
Size: 2 cm, pulsed wave
f_0= 2 MHz, T_p=1 μsec

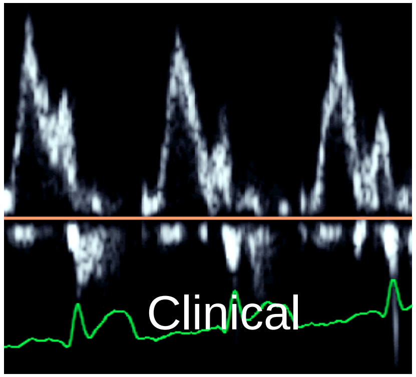
Virtual mitral inflow diagram

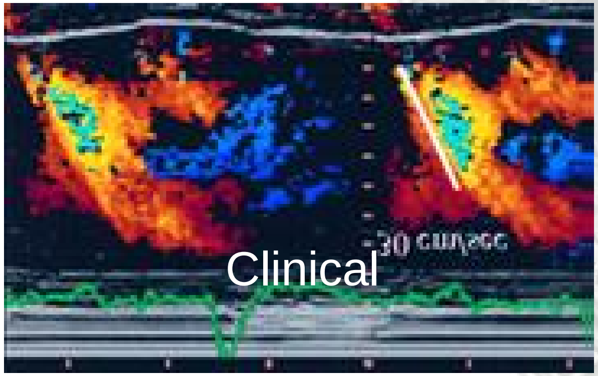
Color M-Mode



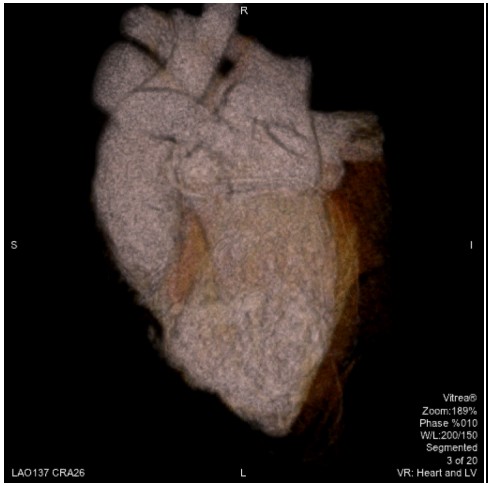


Pulsed Doppler Mode

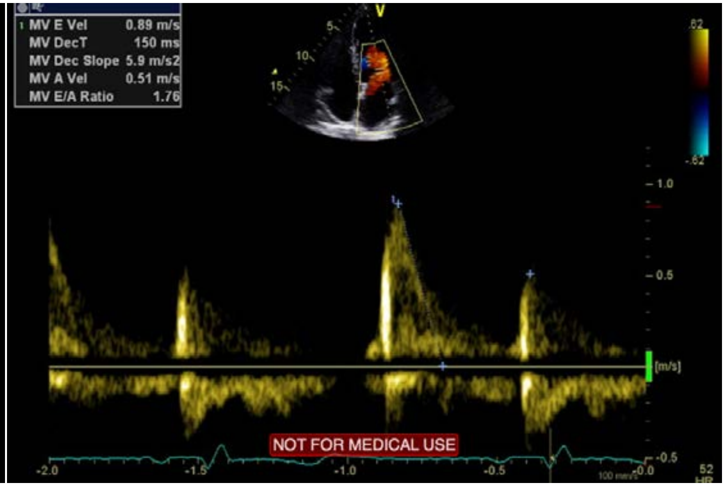




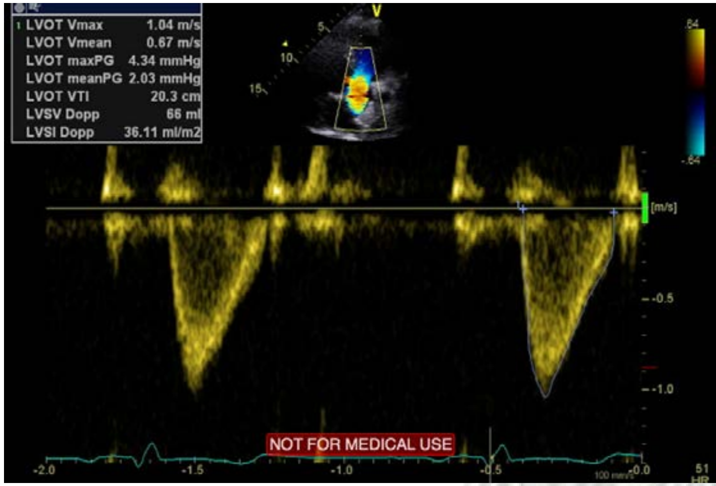
Multi-Modality Segmentation & Registration



Dynamic 4D CT scan

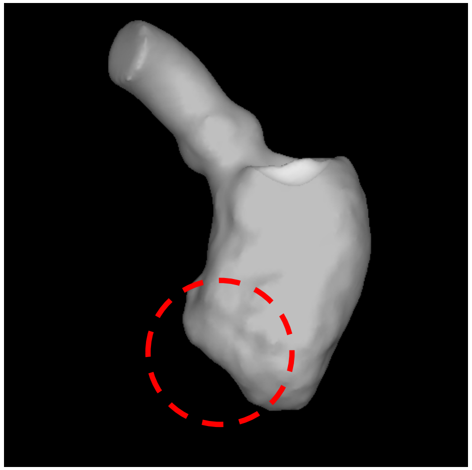


Mitral inflow Doppler

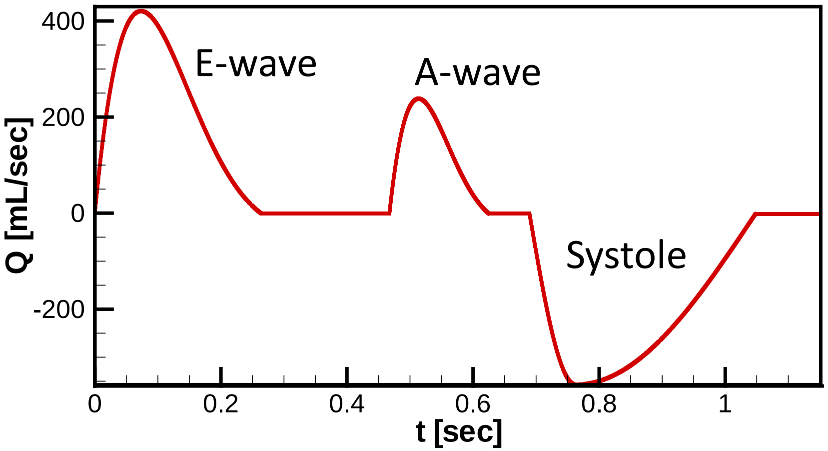


Outflow tract Doppler

Patient:
SV=84 mL, EF=47%
Apical Aneurysm
Apical Akinesia

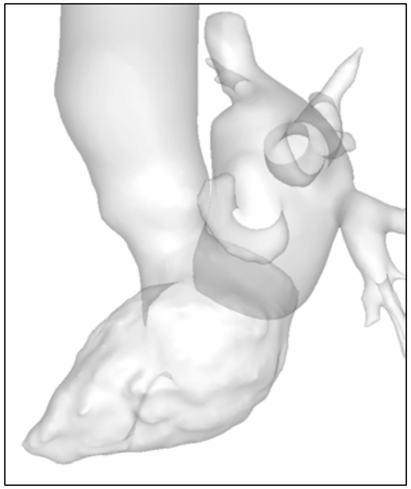


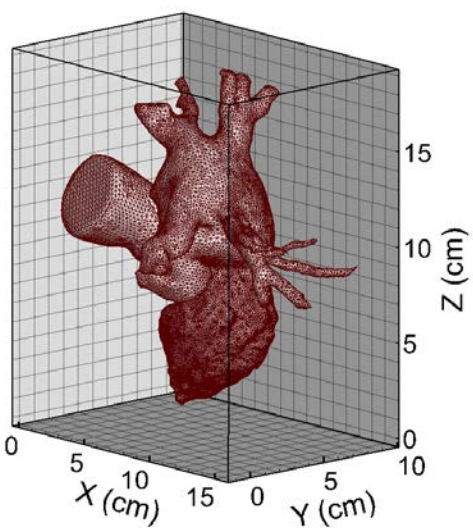
Segmented/Reconstructed Model



Reconstructed LV Flow Profile

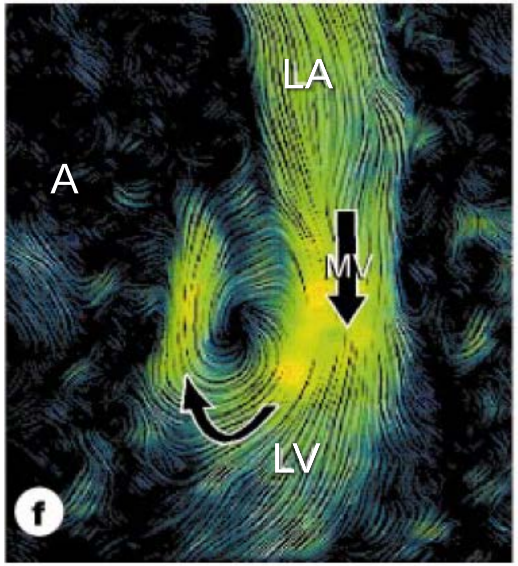
Patient-Specific Left Heart Model



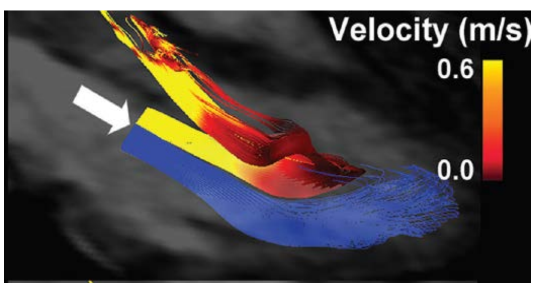


Now to some fundamental questions….

Significance of Ventrical Flow Patterns?



Kilner et al, Nature letter, 2000



Bolger et al., JCMR, 2007

Effect of hemodynamics on the ventricular function ?

- Intraventricualr flow "*efficiently* redirects" blood stream to the aorta.
- No clear, quantitative evidence

1. "Mechanical Efficiency" of the ventricle

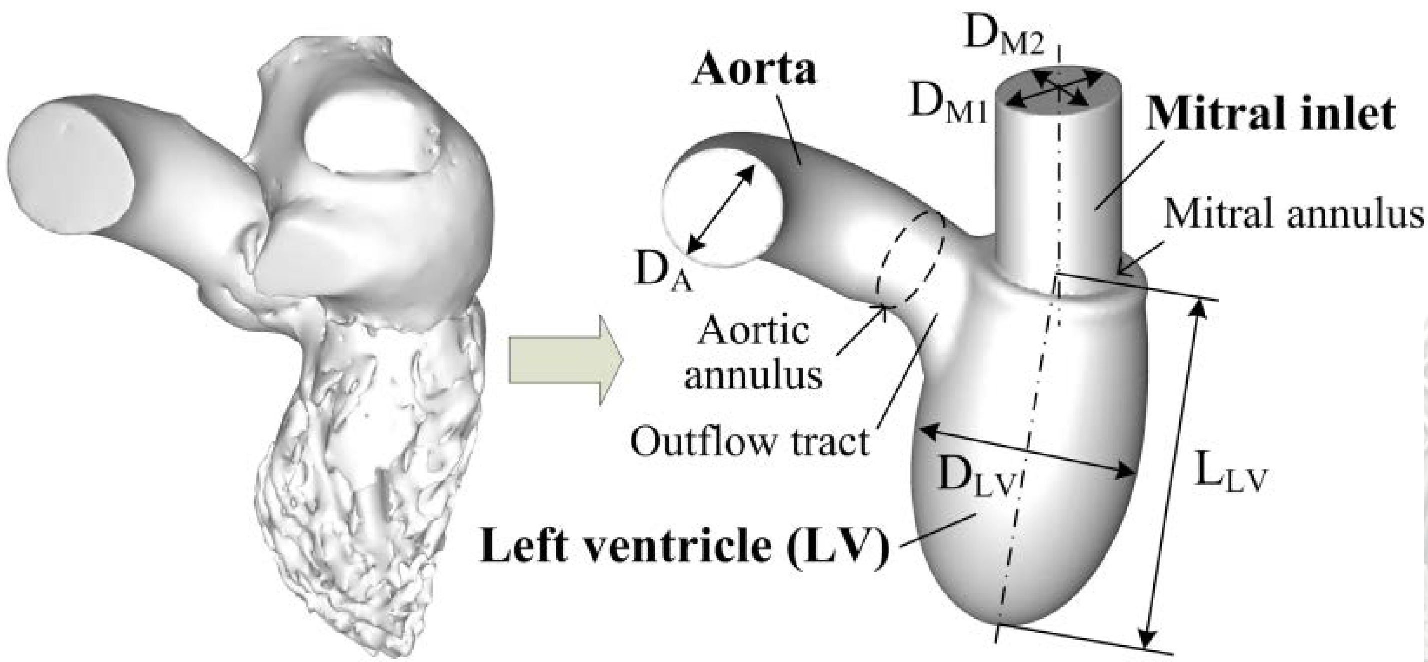
- Reduction of the work required to eject blood flow
- Minimize the energy loss (energy dissipation)

2. Blood Transport and Mixing

- Mixing of freshly oxygenated and residual bloods
- Blood residence time in the ventricle

⇒ ***Quantitative analysis using CFD***

Simplified Left Ventricle (LV) Model

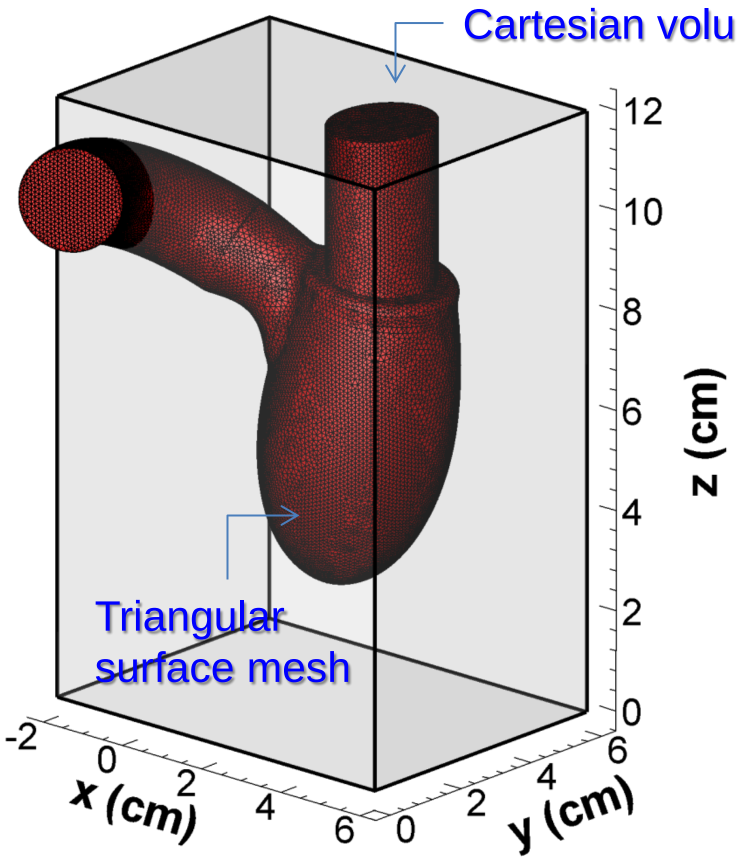


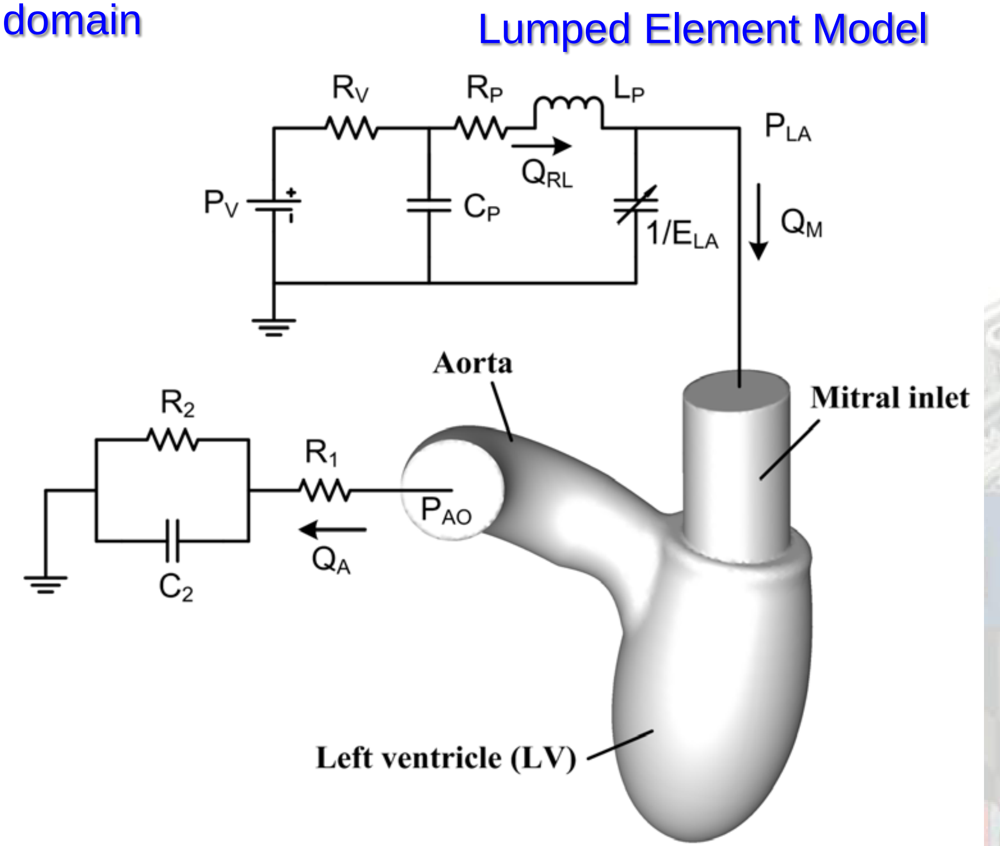
3D model constructed from the contrast CT-scan data*

Simplified model for the computational analysis

* CT-scan data provided by Dr. Albert C. Lardo, JHU

Computational Methods

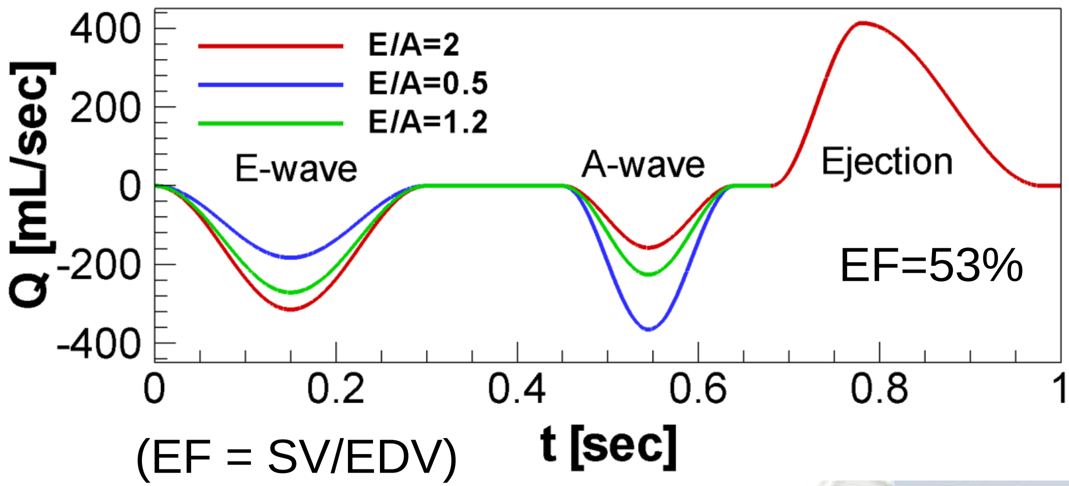




- LV motion is prescribed on the surface mesh
- Incompressible Navier-Stokes equations with the immersed boundary method
- Coupled with LEM to model pre/after loads

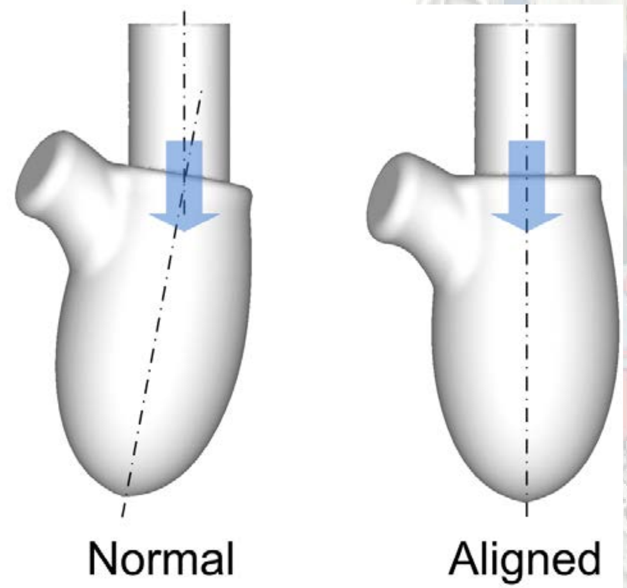
E/A ratio, Geometric Variations

- E/A ratio and geometric variations are considered for different intravnetricular blood flow patterns



(EF = SV/EDV)

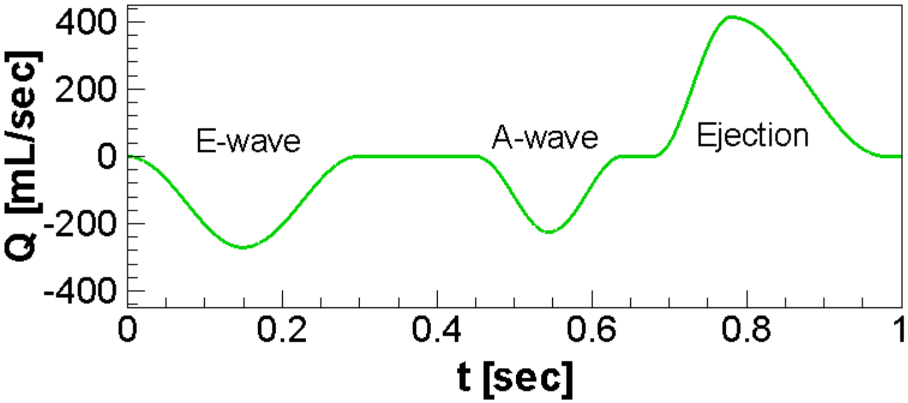
Case	E/A ratio	Geometry
A	1.2	Normal
B	0.5	Normal
C	2	Normal
D	2	Aligned

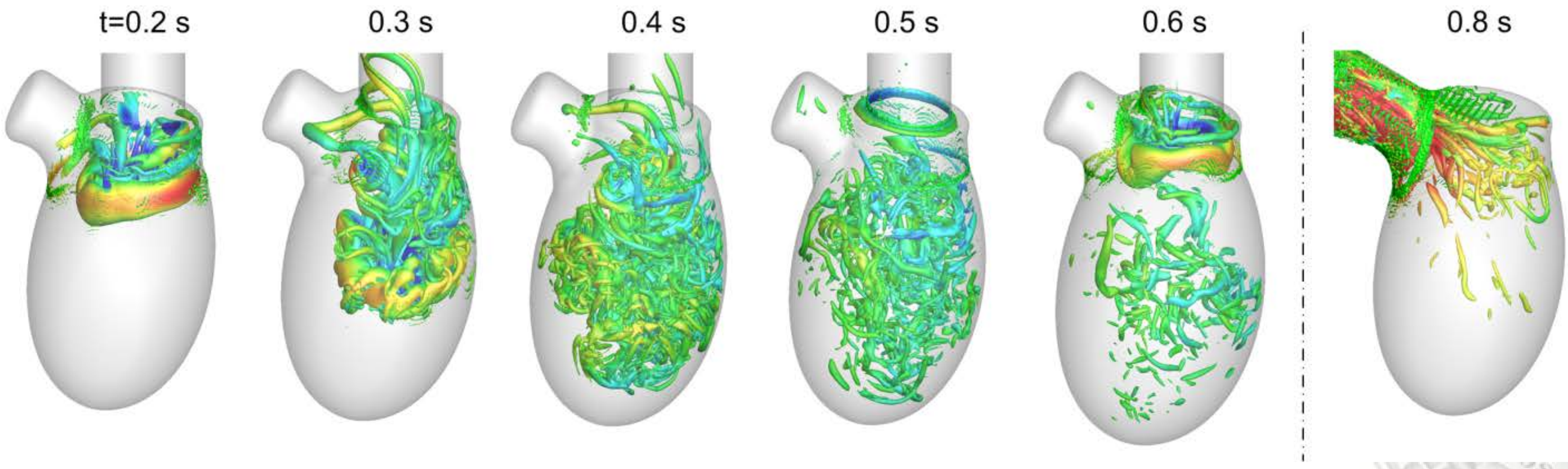


Vortical Structure (Case A)

Normal, **E/A=1.2**
(256x256x384, 25M)

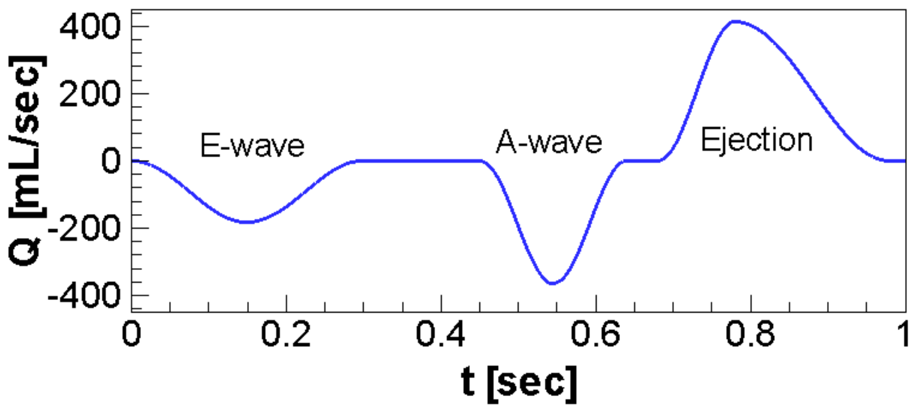
Highly resolved, grid indep.
Dissipation.

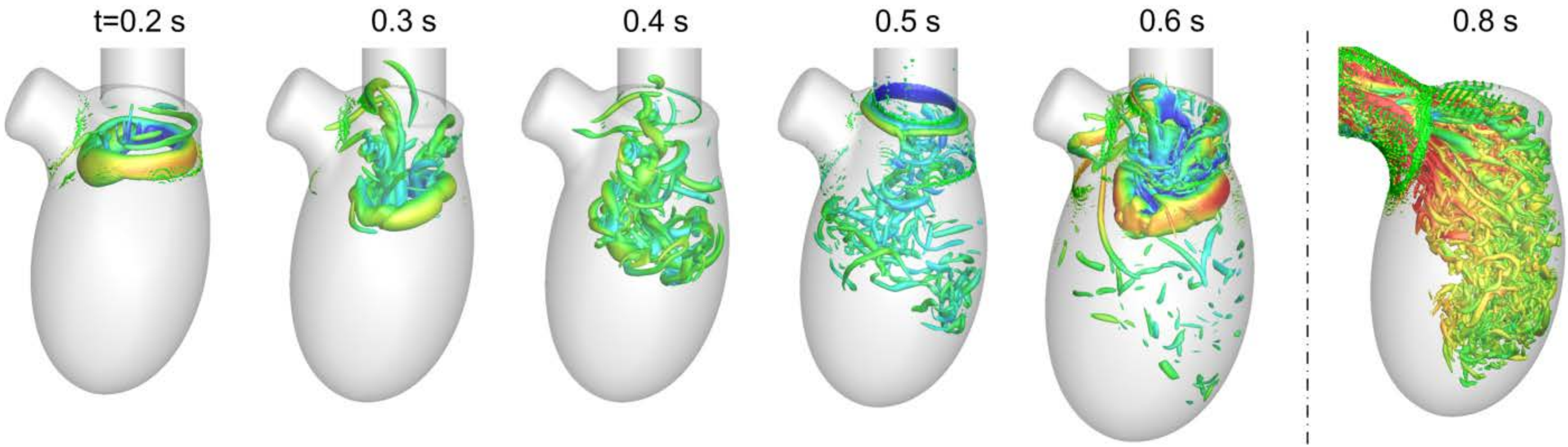




Vortical Structure (Case B)

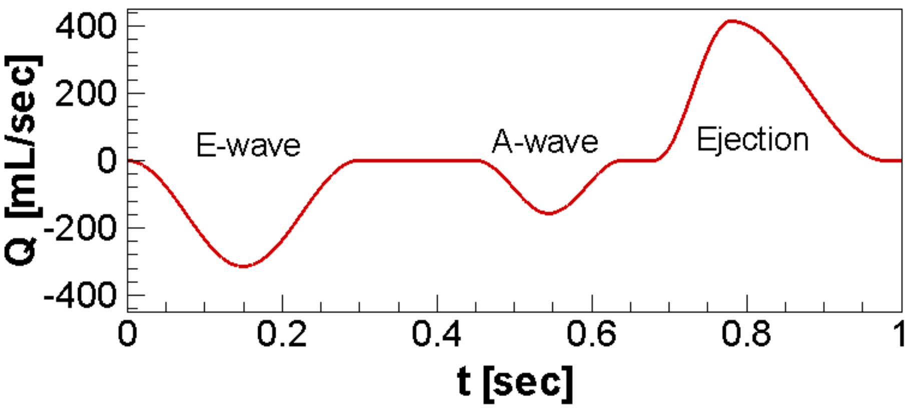
Normal, **E/A=0.5**
(256x256x384)

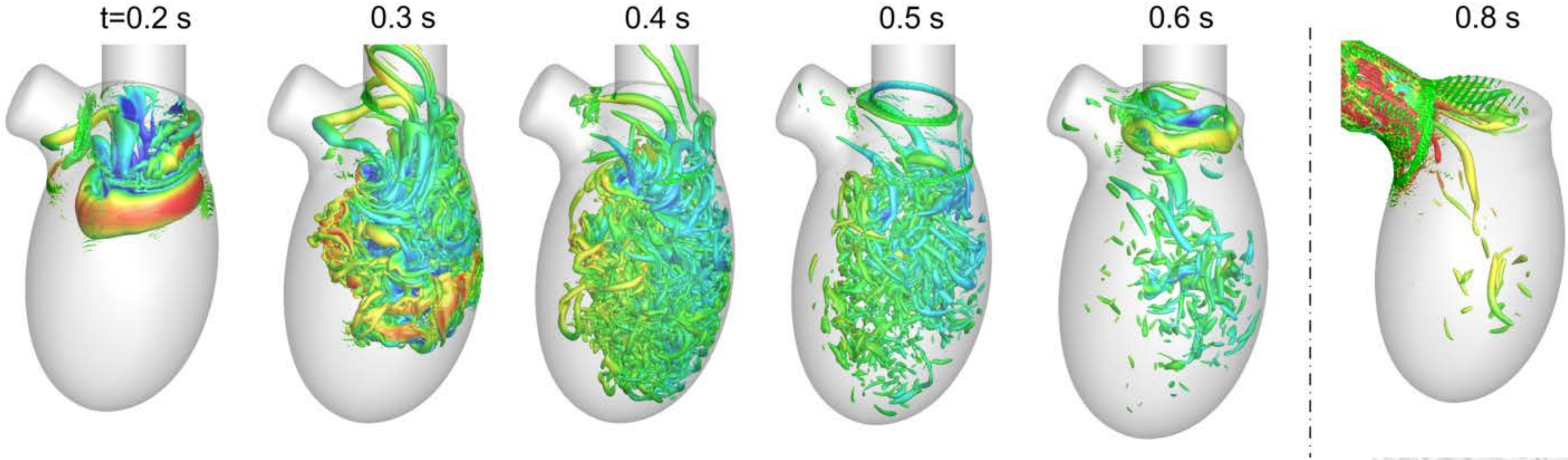




Vortical Structure (Case C)

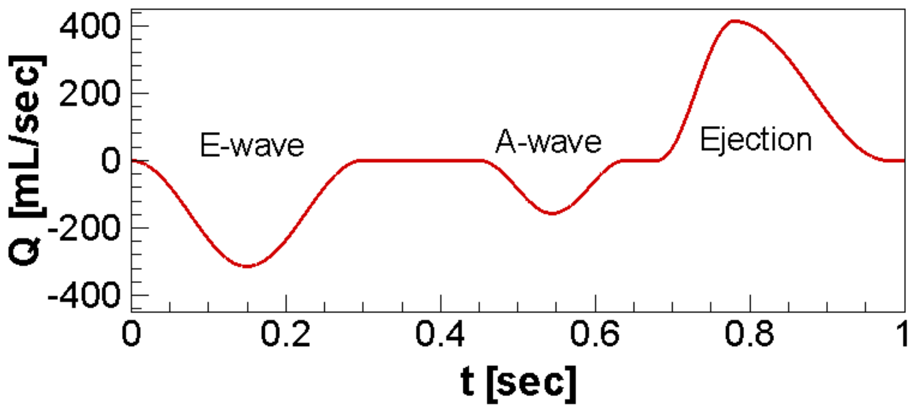
Normal, **E/A=2**
(256x256x384)

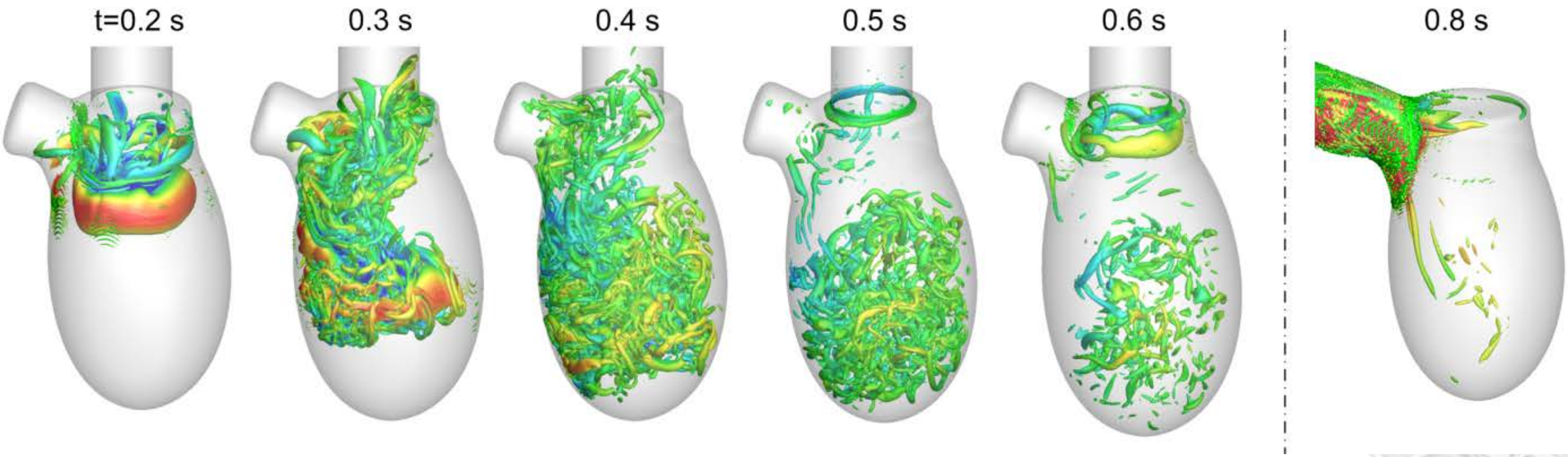




Vortical Structure (Case D)

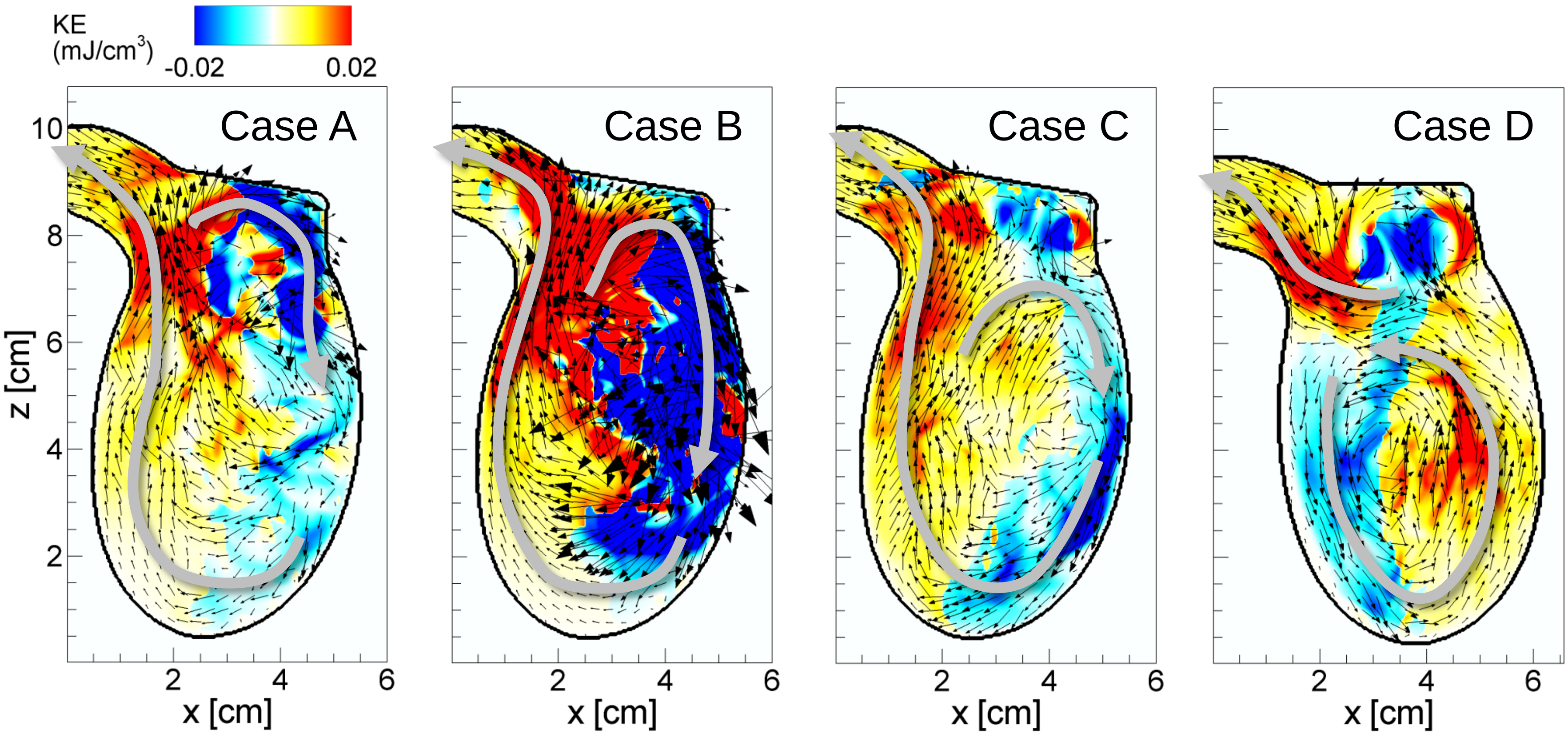
Aligned, **E/A=2**
(256x256x384)





Redirection of Kinetic Energy

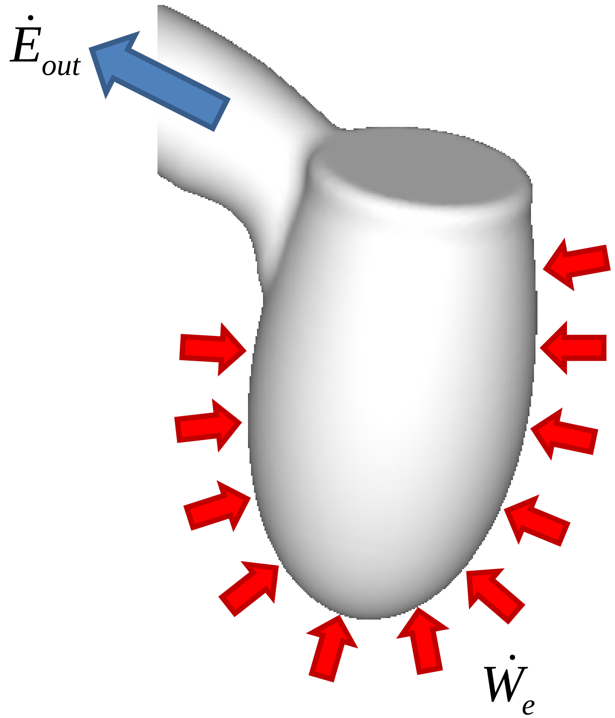
Flow Pattern and Kinetic Energy at Early Systole



E/A=1.2 | E/A=0.5 | E/A=2.0 | E/A=2.0, Alinged

Pumping Efficiency

Total Energy output



Work done by heart muscle

	Work [mJ]	E_{out} [mJ]	η
E/A=1.2	688	674	0.980
E/A=0.5	687	672	0.978
E/A=2	688	674	0.980
Aligned, E/A=2	687	673	0.980

Negligible Differences

$$\eta = \frac{\int \dot{E}_{out} dt}{\int \dot{W}_e dt}$$

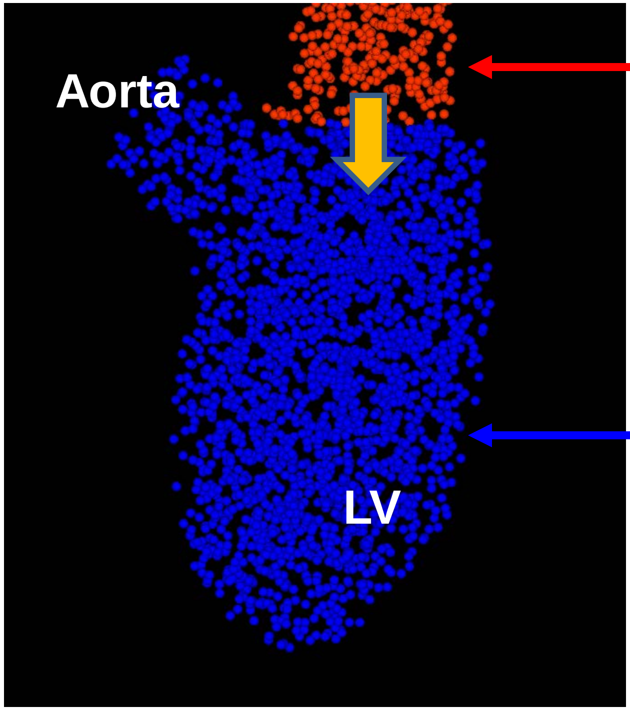
Overall ***pumping efficiency***

Reason:
(*Energy required to overcome peripheral resistance*) **>>**
(*Kinetic energy of blood flow at end diastole*)

Blood Transport and Mixing

Red Blood Cell Motion:
Lagrangian particle tracking

$$\vec{x}_p(t+\Delta t) = \vec{x}_p(t) + \int_t^{t+\Delta t} \vec{U}(\vec{x}_p)\, dt$$

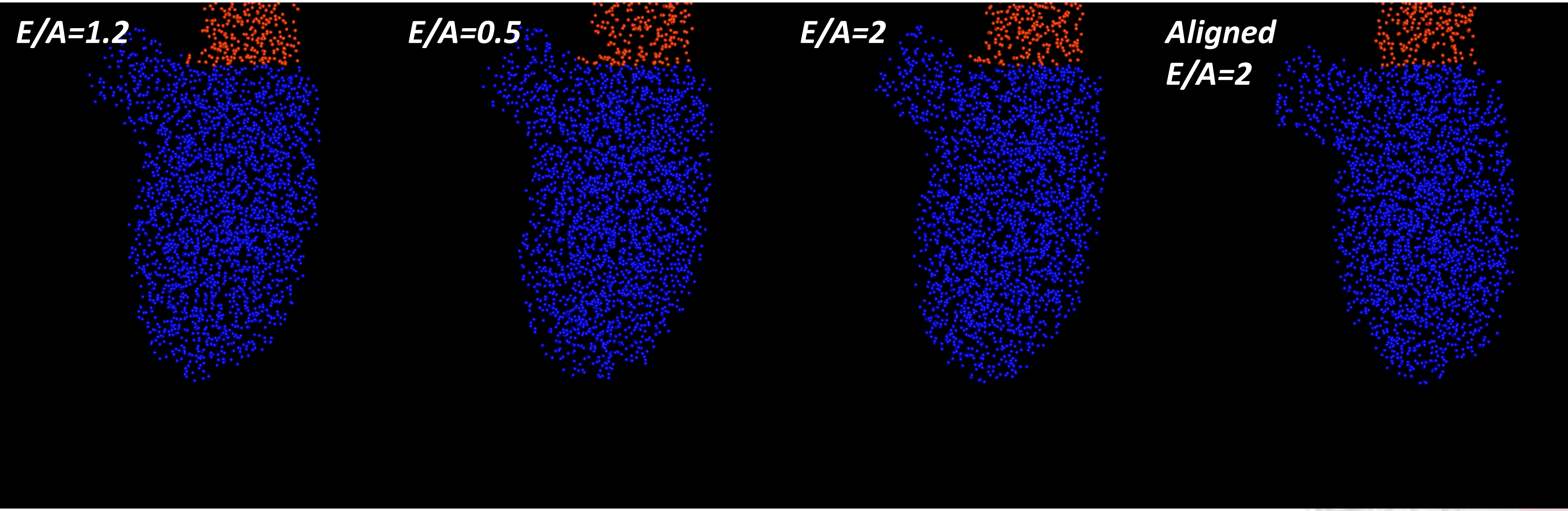


(freshly oxygenated) Atrial blood cells

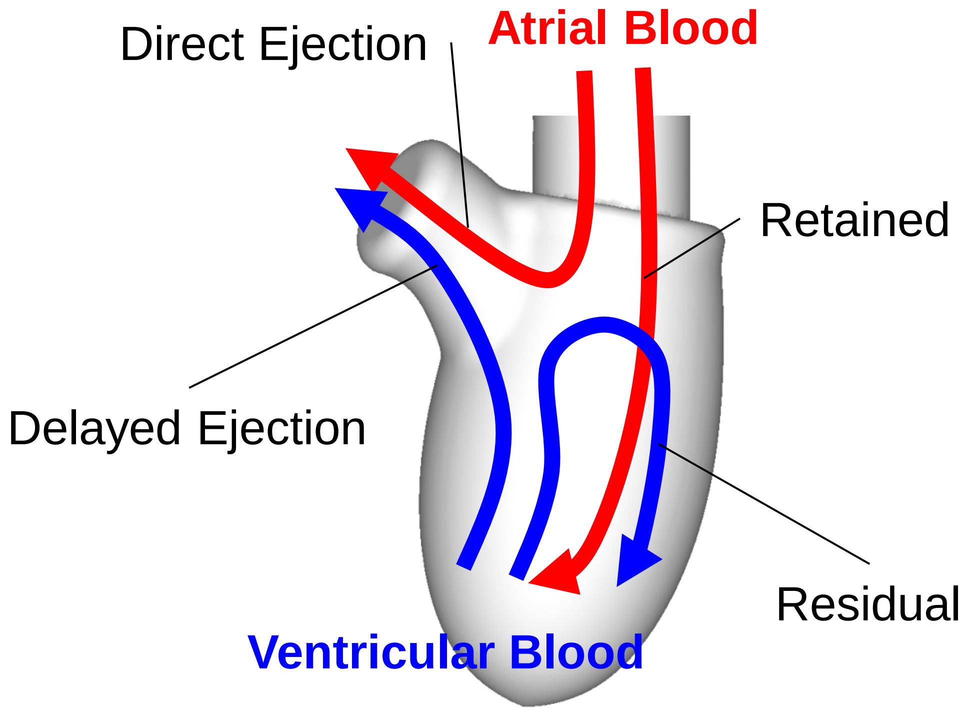
Ventricular blood cells of previous cycles

Blood Cell Motions

Red Blood Cell Motion:
Lagrangian particle tracking



Blood Transport and Washout



***Washout*:**
Fraction of Ejected Ventricular Blood Volume
=(Delayed Ejection)
/(Total ventricular blood volume)

Remaining Fraction of original Ventricular Blood Volume after *n* cycles
$=(1-\mathit{Washout})^n$

Perfect mixing: Washout = EF

Lower Washout: longer blood residence time

Blood Transport Metrics

Average for 4 cycles

EF=53%	*M*	*Washout*	$n_{1\%}$
E/A=1.2	0.82	0.584	5.25
E/A=0.5	0.78	0.681	4.03
E/A=2	0.87	0.523	6.22
E/A=2, Aligned	0.88	0.489	6.86

Mixing quality, ***M***
0: not mixed
1: perfect mixing

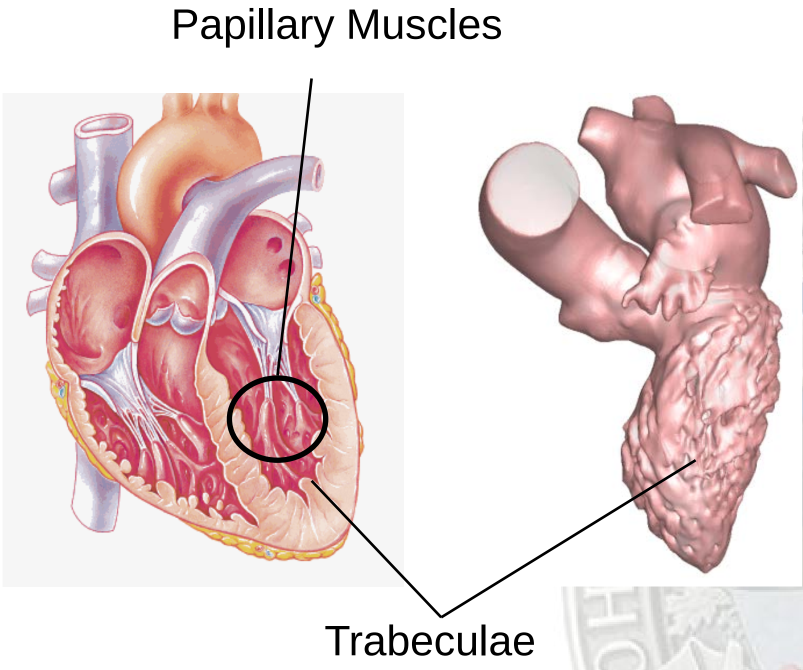
$n_{1\%}$: Time (cardiac cycle) required to reduce initial ventricular blood to 1%

- Up to ~25% differences in ***Washout*** due to the different flow patterns
- Lower ***Washout*** causes longer residence time of RBC in the ventricle: more conducive to *clot formation (thrombogenesis)*

Conclusion – Flow patterns primarily thrombo-protective!
Effect on efficiency is very small.

Effect of Trabeculae and Papillary Muscles on LV Hemodynamics

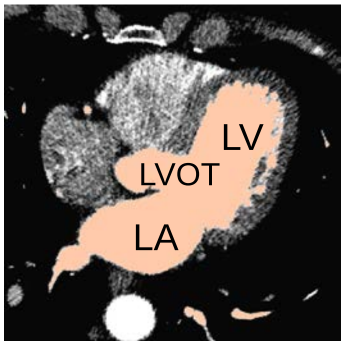
- Why is the LV trabeculated?
- Does this not compromise the hydrodynamic of the LV?
- Does it not create locations for thrombogenesis?
- How significant is the effect?
- Can we ignore the trabeculae in computational models?



Computational Model

Ranganathan et al., *Circ.*, 1970, vol. 41
Seo et al., *Phys. Fluids*, 2014, vol. 26

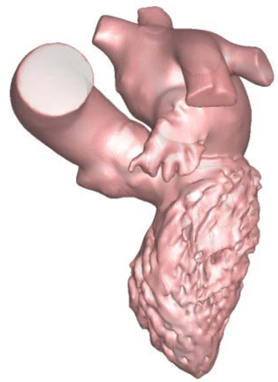
CT based model

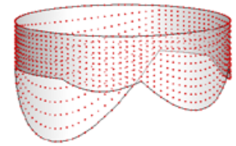


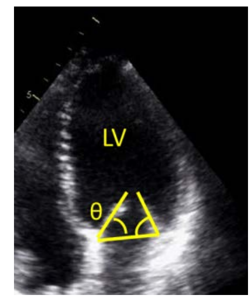
0.3x0.3x0.5mm^3 (512^3)

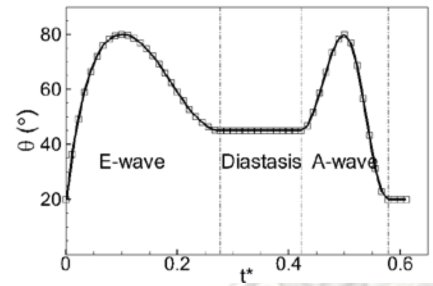
Region Growing

Materialise
innovators you can count on



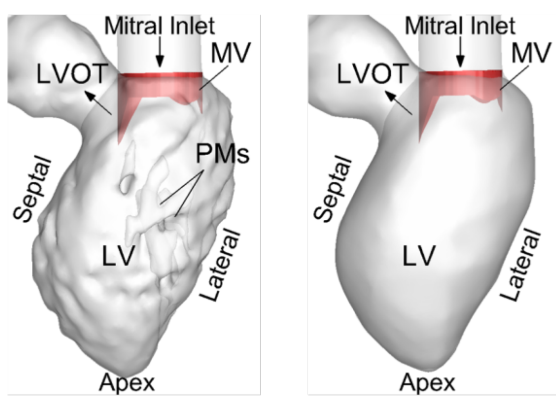






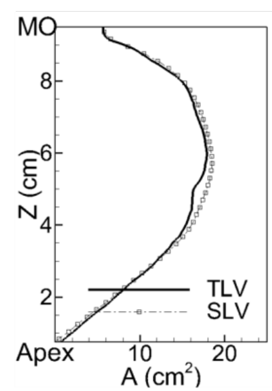
TLV: Trabeculated LV
SLV: Smooth LV

SD: Smallest Detail
CD: Closing Distance



SD=0.8mm, CD=0.8mm

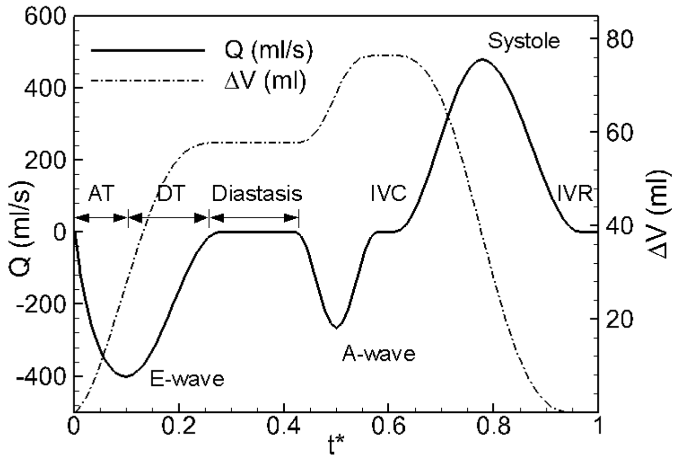
SD=3.0mm, CD=3.0mm



Max. Area Diff
~ 10%

Computational Model

Flow Waveform Model



Relevant Parameters

E/A Ratio	1.5
Stroke Volume (SV)	76 ml
Ejection Fraction	0.61
Heart Rate (HR)	67 bpm
Reynolds No. (Re)	5630
Womersley No. (Wo)	15.7

CFD-Ready Model

Duration of various phases

AT	DT	Diastasis	A-wave	IVC	Systole	IVR	Total
90	160	130	140	30	320	30	900

Kovacs et al., *Am. J. Physiol. Heart Circ. Physiol.*, 1987 (252)
McGuire et al., *Am. J. Physiol. Heart Circ. Physiol.*, 1997(272)
Chung et al., *Am. J. Physiol. Heart Circ. Physiol.*, 2004 (287)
Nagueh et al., *J. Am. Soc. Echocardio.*, 2009 (22)
Seo & Mittal, *Phys. Fluids*, 2013 (25)
Vedula et al., *Theo. Comput. Fluid Dyn. (SI)*, 2015 (submitted)

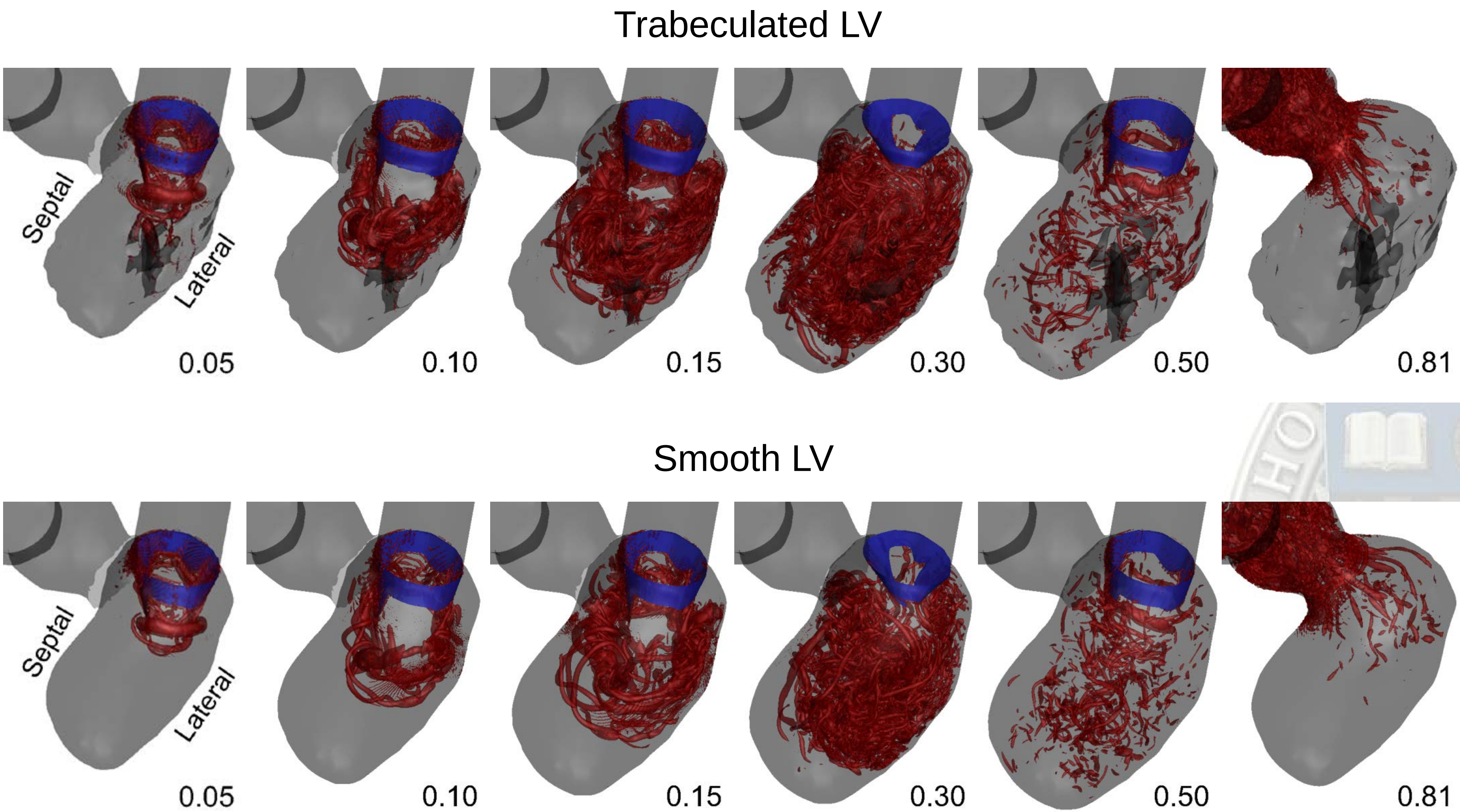
3D Vortex Structures

- 3D vortex structures, λ_{ci} criterion[†]
- Cartesian grid size:
  - 256x256x512 (≈33 million)
- 512 processors on XSEDE Stampede high performance cluster
- 1 days per cardiac cycle

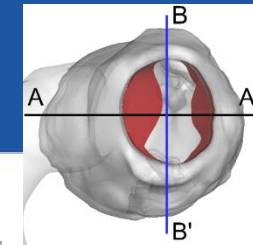
Trabeculated Model

Isosurfaces of λ_{ci}=133.3 s^{-1}

3D Vortex Structures



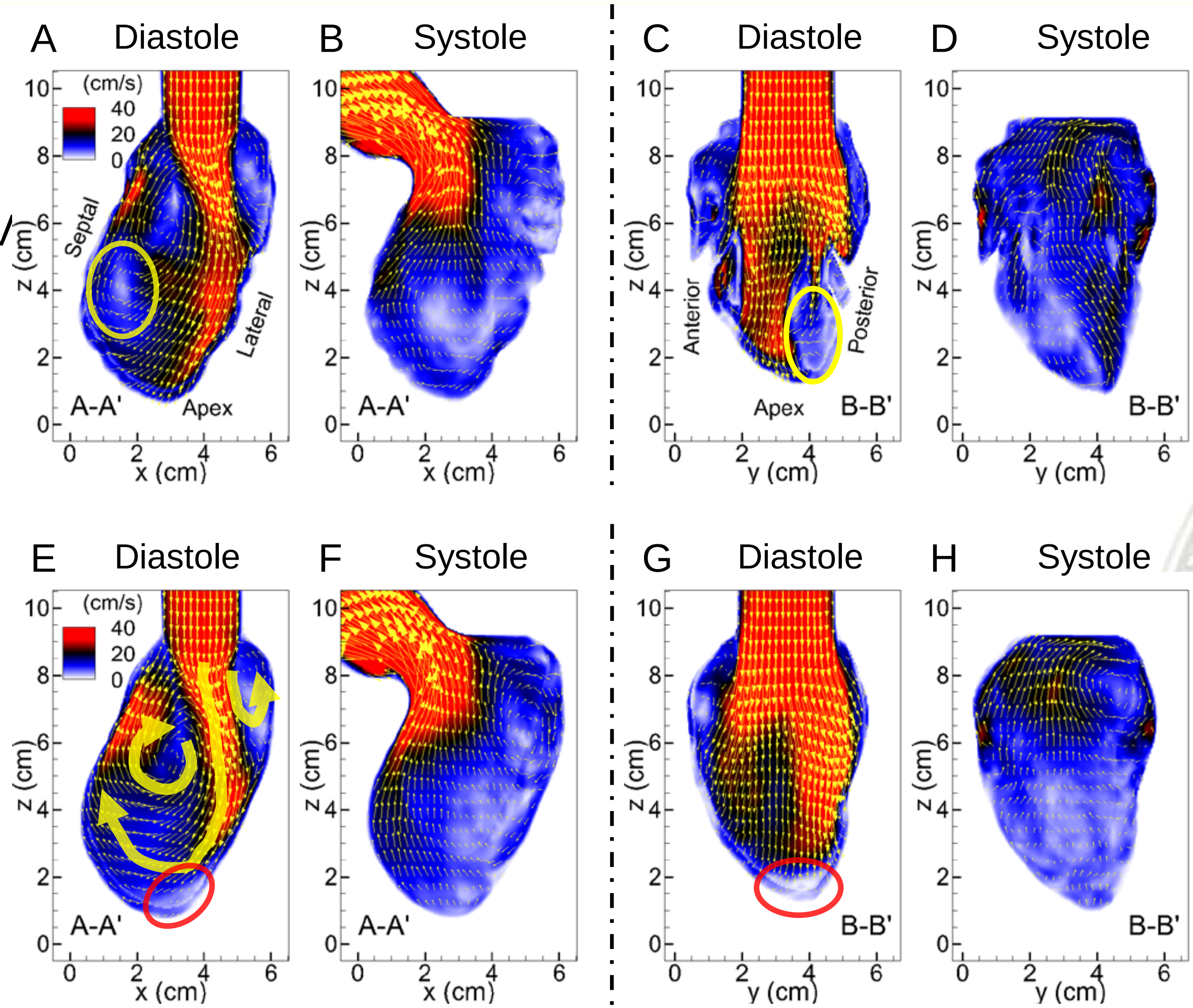
Phase-Time Averaged Flow



Top View

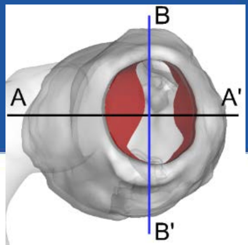
Trabeculated LV

Smooth LV



Phase averaging performed over 3 cardiac cycles

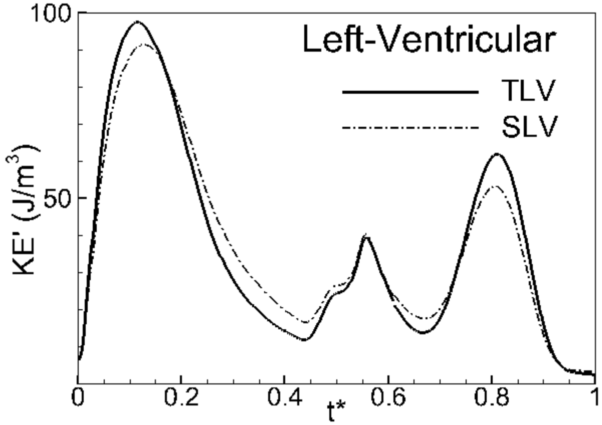
Kinetic Energy and Dissipation

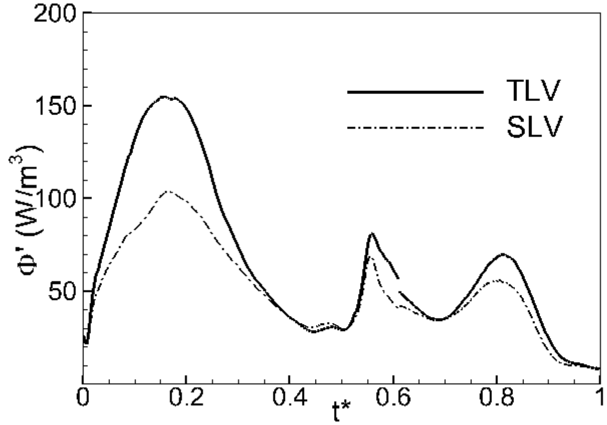


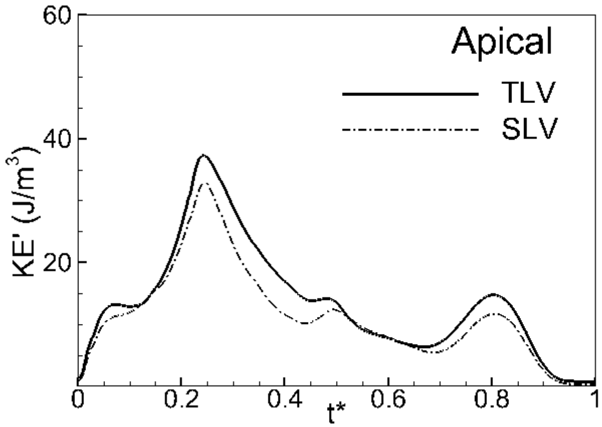
Top View

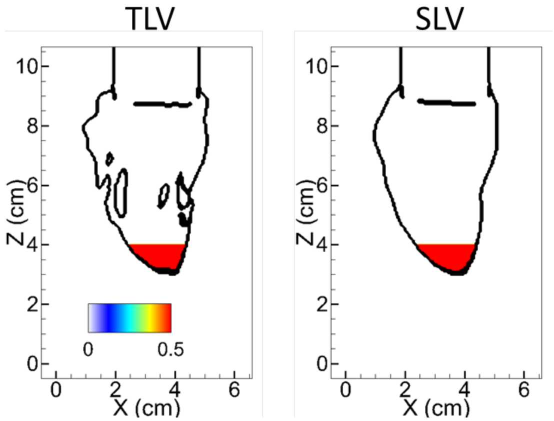
$$KE'_{LV} = \frac{1}{2V_{LV}} \iiint \rho u^2 dV$$

$$\Phi'_{LV} = \frac{1}{V_{LV}} \iiint 2\mu\varepsilon : \varepsilon dV$$







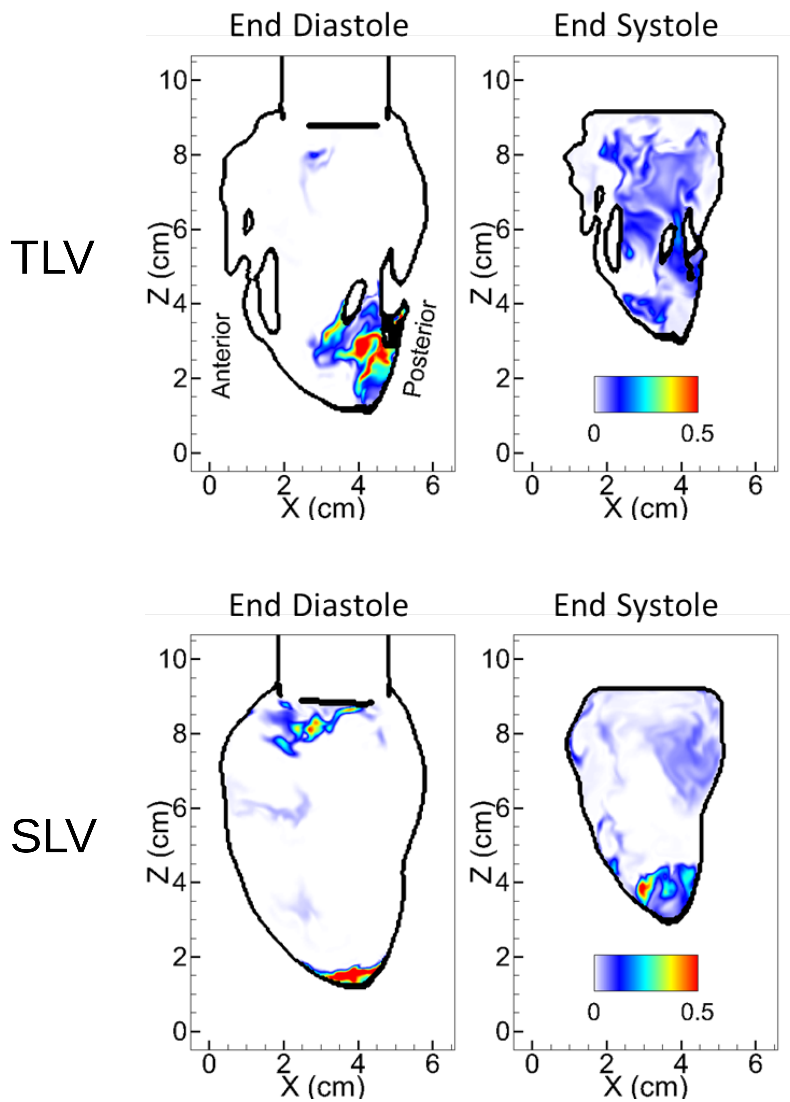


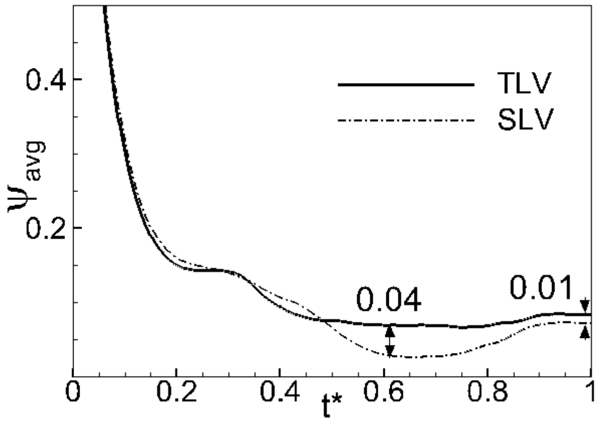
$$\frac{\partial \psi}{\partial t} + \vec{u}.\nabla \psi = D\nabla^2 \psi$$

at t=0, $\psi = 1$

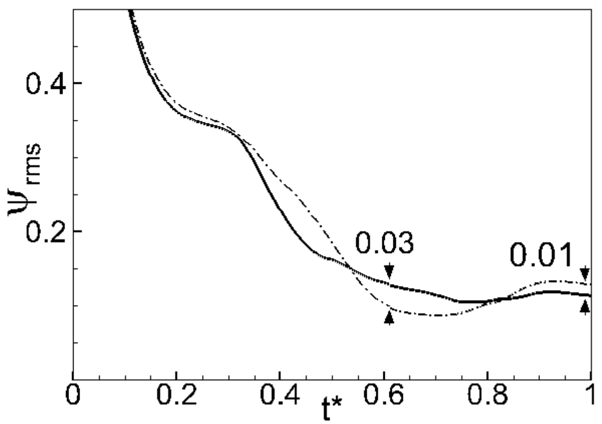
Apical volume: Z ≤ 4 cm

“Virtual” Ventriculography





$$\frac{\partial \psi}{\partial t} + \vec{u}.\nabla \psi = D\nabla^2 \psi$$



Summary

- **No measureable impact on hydrodynamic efficiency**
  - Significant increase in viscous dissipation (55%)
  - Negligible compared to systolic pressure work (6mJ vs. 0.8 J)
- **Deeper penetration of inflow jet and energized apical region**
  - Despite only 10% blockage due to PMs
  - Additional blockage due to multiple boundary layers and recirculating flow
- **Trabeculae is at least as effective as smooth wall in minimizing apical flow residence time. But, arguably, trabeculae might marginally reduce the risk of thrombogenesis**
  - Similar mean and RMS profiles
  - Slightly lower end-systolic RMS value for TLV
  - Higher apical flow energy

Note: Model missing realistic squeezing of the trabeculae.

Might further increase benefit o trabeculae.

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