IV
Modeling and Analysis of Heart Murmurs

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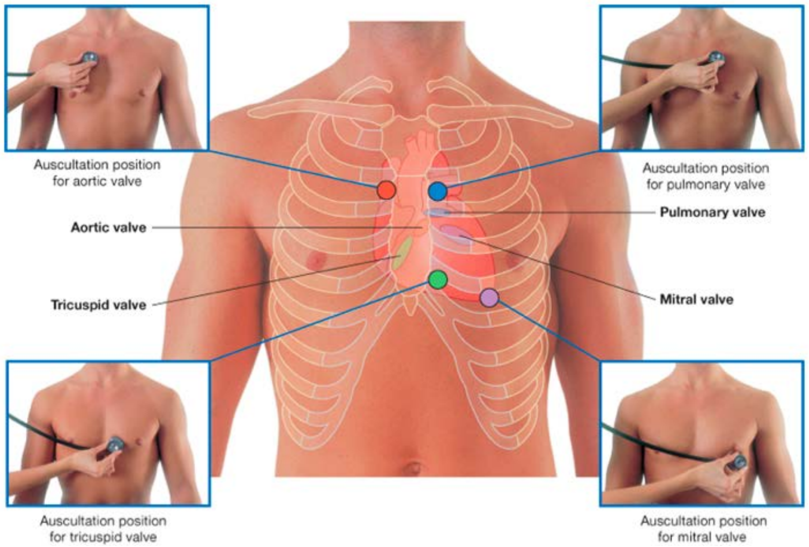
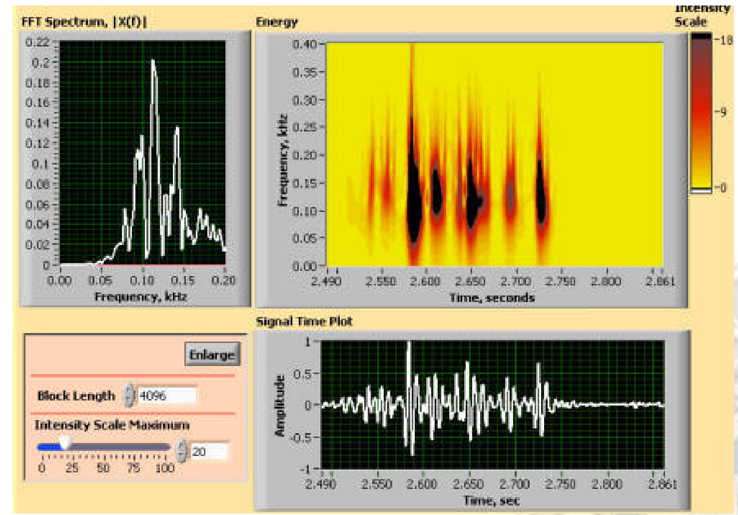
Cardiac Auscultation



Digital Stethoscope



BioSignetic Corporation

Murmur Scores	
Intensity	157.40
Duration	94.38
Frequency	118.43
Half Bandwidth	21.53
Murmur Grade	5

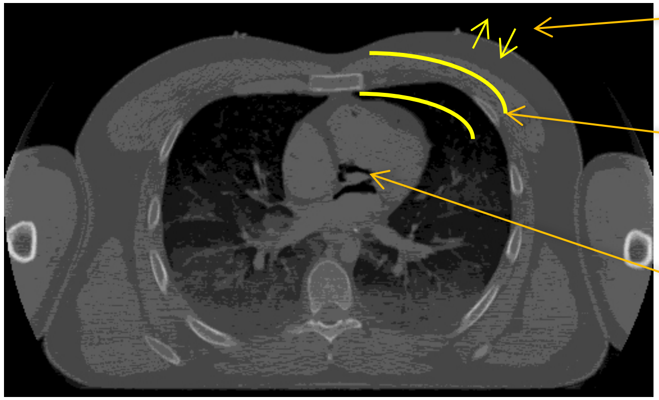
- 3000 year old technique
- Cheap
- Non-invasive, high sensitivity
- Good as a screening tool

But…

- Low specificity (high false positives) → *60% of all pediatric murmurs leading to referral are "innocent"*
- Diagnosis is based on the empirical/statistical correlation
- Source mechanism of murmurs is poorly understood
- No modality provides simultaneous assessment of source and measurement

Computational Hemo-acoustics

Can computational modeling provide the missing link between cause (pathology) and effect (sound)?



Computational Hemo-acoustics (CHA) *directly simulate the above procedure:*

- Prediction of murmur generation/propagation
- Source mechanism of murmurs
- Better Disease - Hemodynamics - Sound (Auscultation) relation

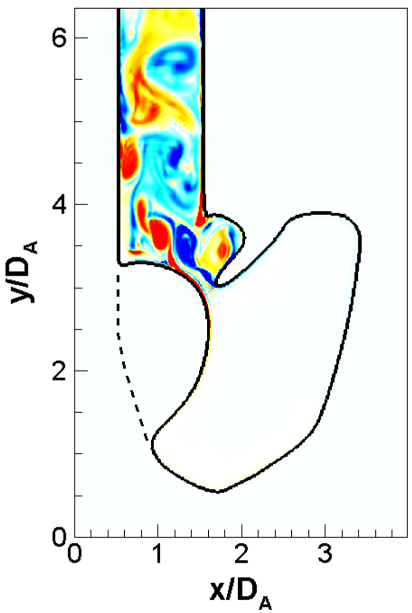
Present Approach:

-**Immersed Boundary Method based Hybrid Approach**

- **Blood Flow -** *IBM Incompressible Navier-Stokes solver*
- **Flow induced sound** - *Linearized Perturbed Compressible Equations (LPCE)*
- **Sound Propagation in tissue** – *Linear wave equation*

Computational Hemoacoustics

Hemodynamics



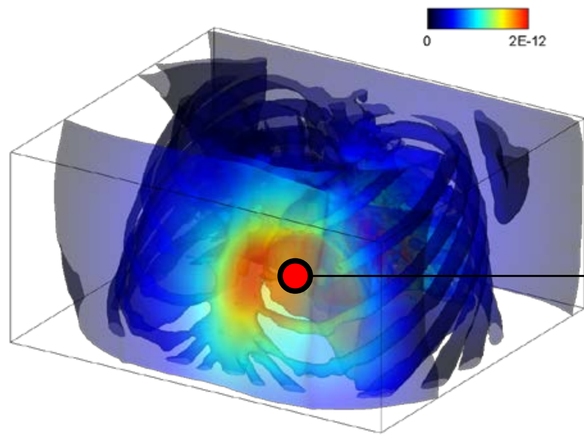
Incompressible N-S Eqns.

$$\nabla \cdot \vec{U} = 0, \quad \frac{D\vec{U}}{Dt} + \frac{1}{\rho_0}\nabla P = \nu_0 \nabla^2 \vec{U}$$

$P(\vec{x}, t)$

Hemodynamic Sound Source

Wave Propagation

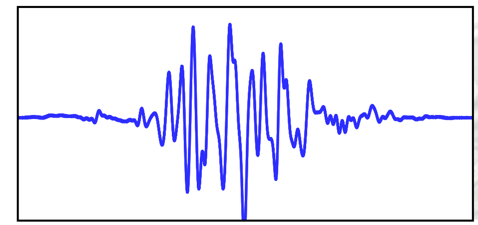


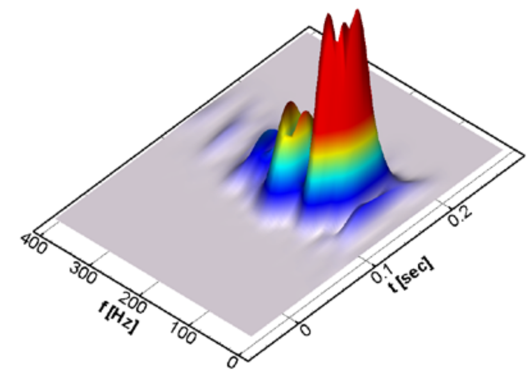
Structural wave Eqns.

$$\frac{\partial p_{ij}}{\partial t} + \lambda \frac{\partial u_k}{\partial x_k}\delta_{ij} + \mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) = S_p$$

$$\frac{\partial u_i}{\partial t} + \frac{1}{\rho}\frac{\partial p_{ij}}{\partial x_j} = \frac{\eta}{\rho}\frac{\partial}{\partial x_j}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) + S_{u,i}$$

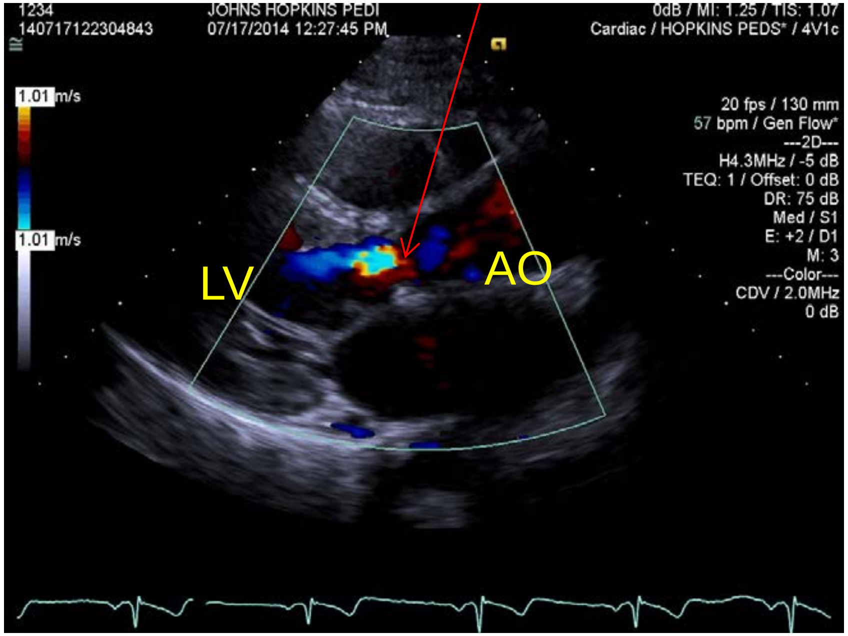
Sound Signal

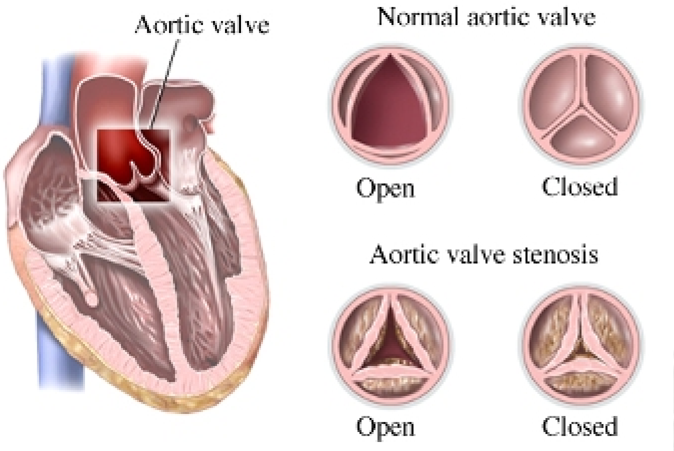




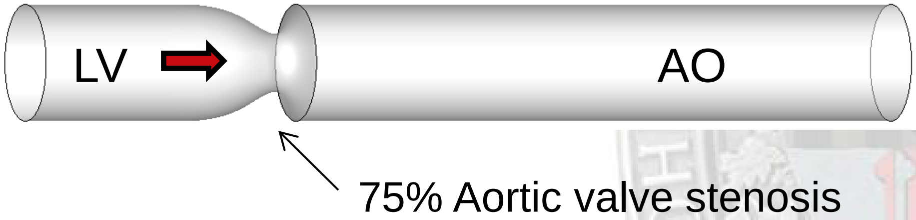
Murmur Associated with Aortic Stenosis

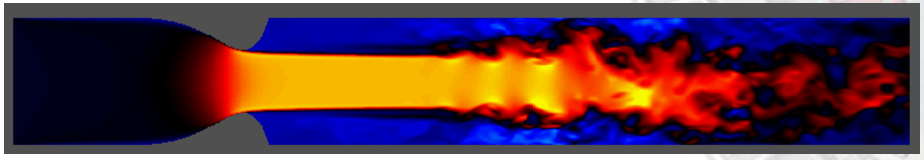
Aortic Valve Stenosis



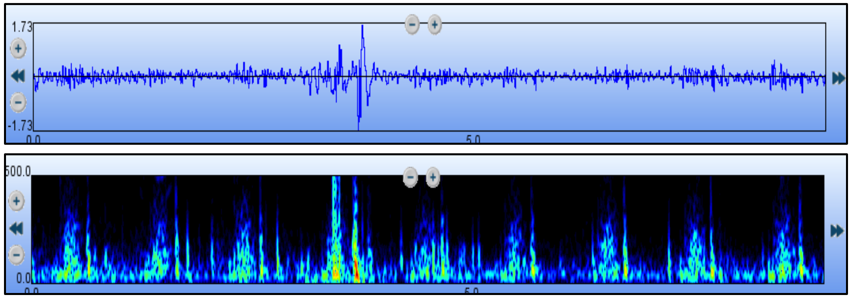


Simplified Hemodynamic Modeling

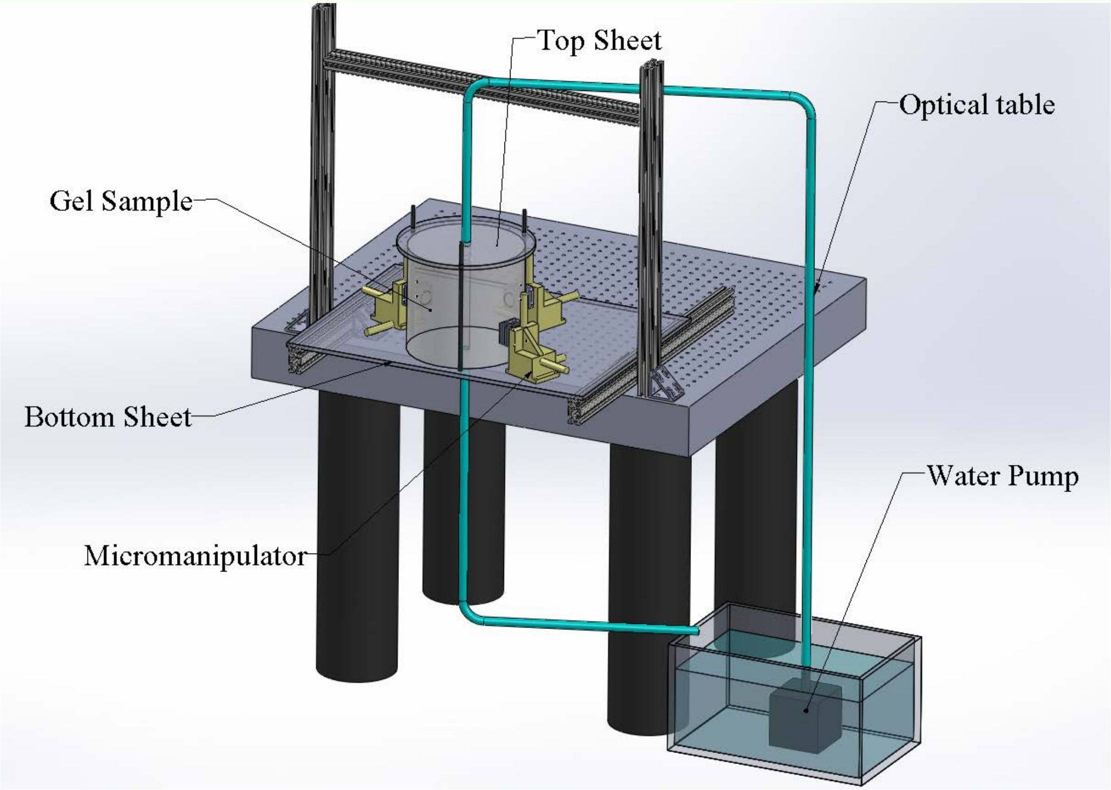


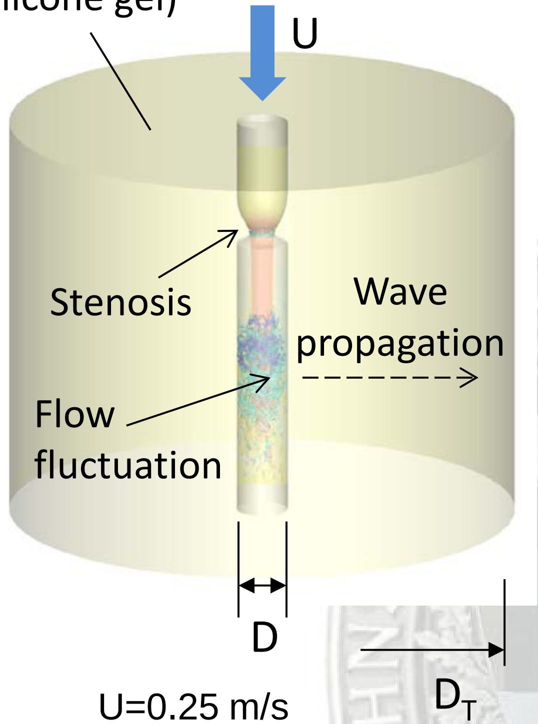


Aortic Stenosis Murmur



Cardio-Thoracic Phantom Studies





Material: EcoFlex-10

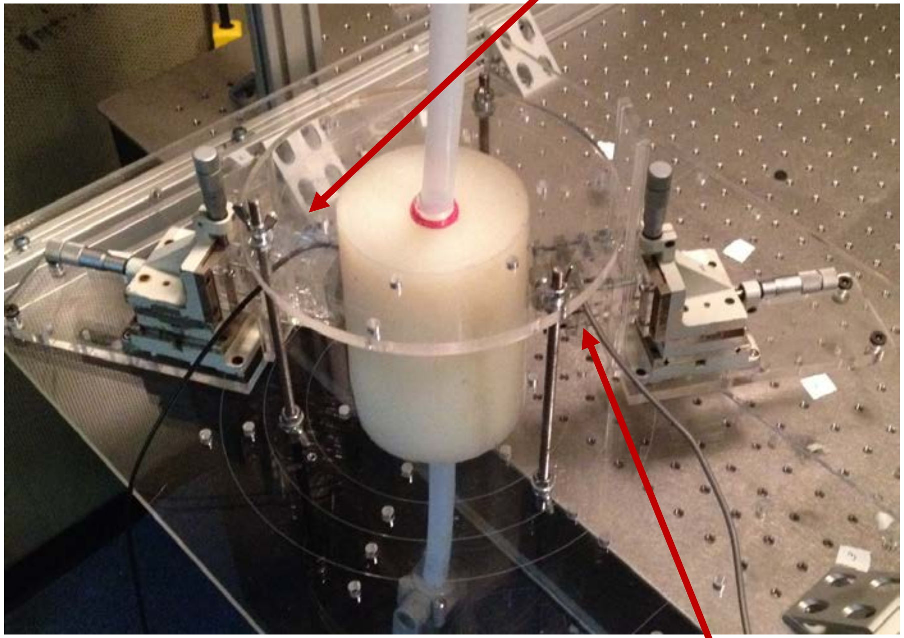
ρ=1040 kg/m^3
E=55.16 kPa
K=91.3 Mpa (c_b=297.3 m/s)
G=18.39 kPa (c_s=4.2 m/s)
μ=14 Pa s

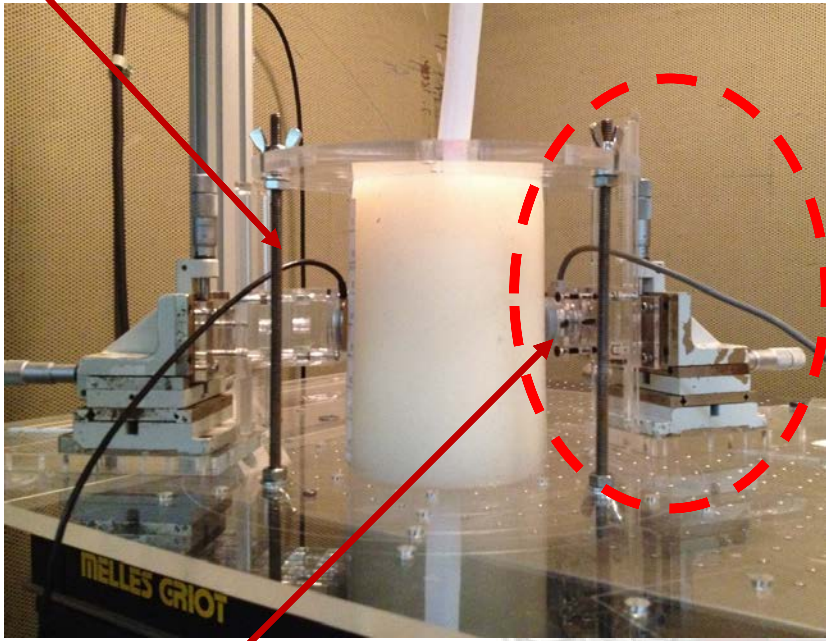
U=0.25 m/s
D=1.5875 cm
D_T=9.84 cm

$Re=UD/\nu=4000$
$St=fD/U$

Acoustic Sensors

Biopac sensor attached to the Micromanipulator



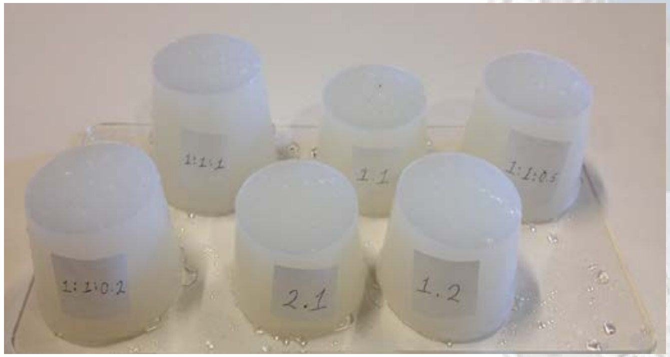


HP sensor attached to the Micromanipulator

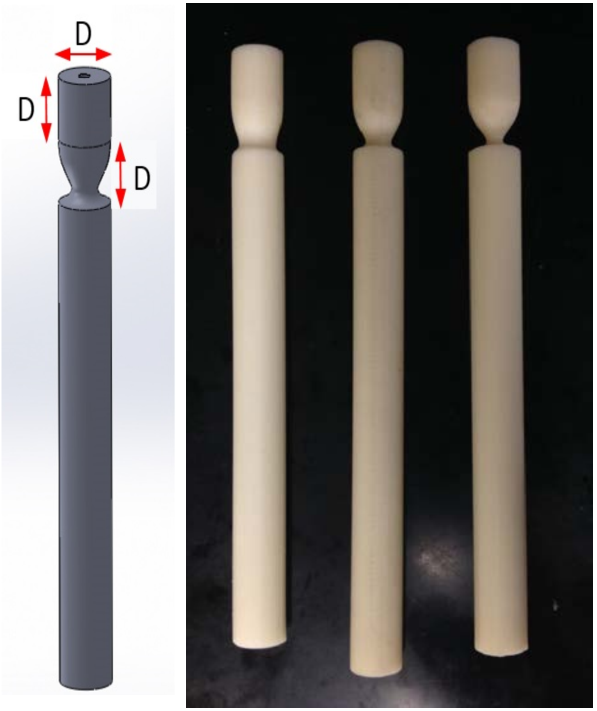
Silicone Rubber- Tissue Mimicking Material

- Silicone rubber, Ecoflex 010 (Smooth-on)
  - Easy to produce
  - Extremely stable
  - Non-toxic and
  - Negligible shrinkage

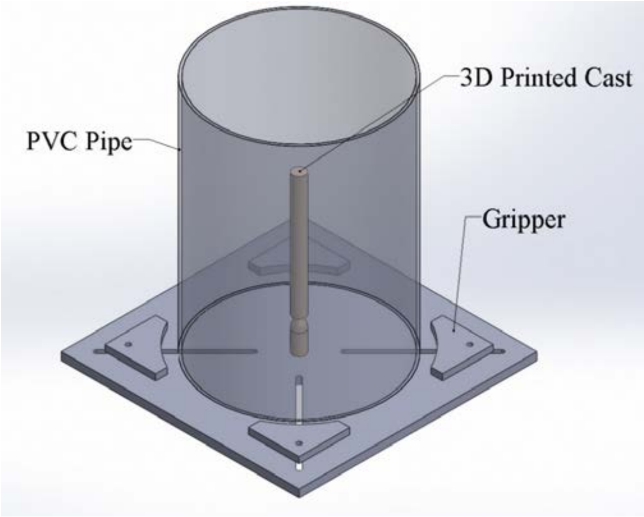
- Procedure to make→
  - Mixing Part A part B,
  - Adding Silicon thinner,
  - Degassing for 3-4 min in (-29 in Hg) to remove air bubbles

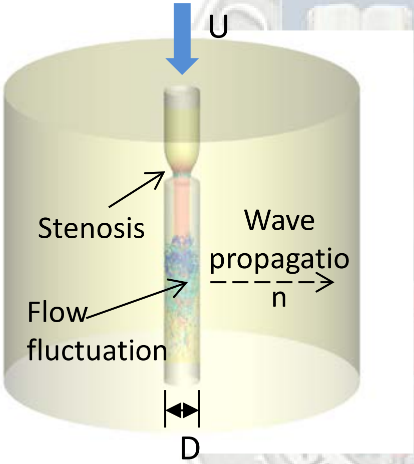


Murmur Generating

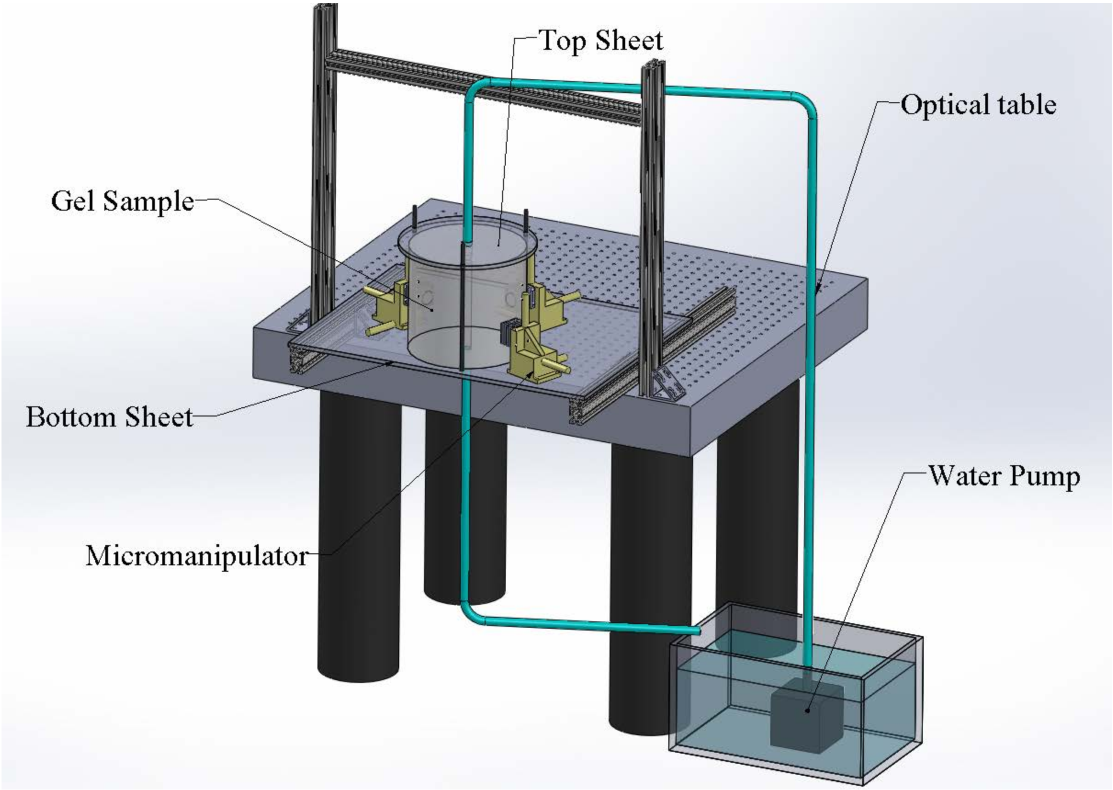


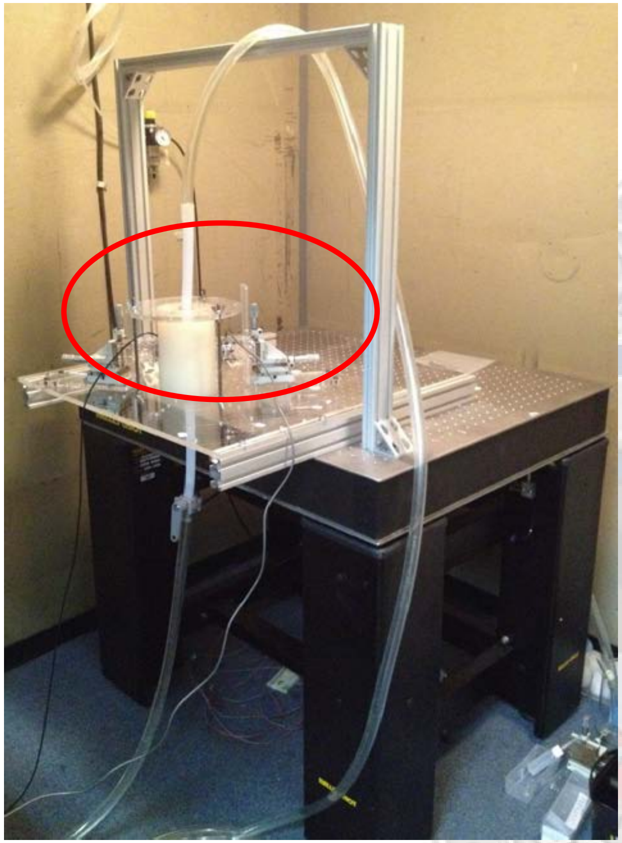
3D printed
Casts



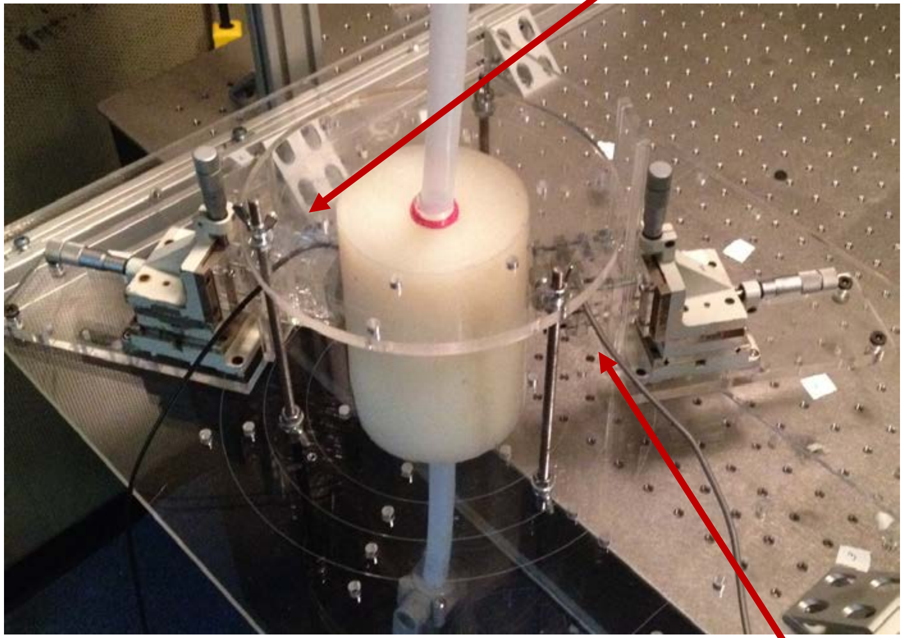


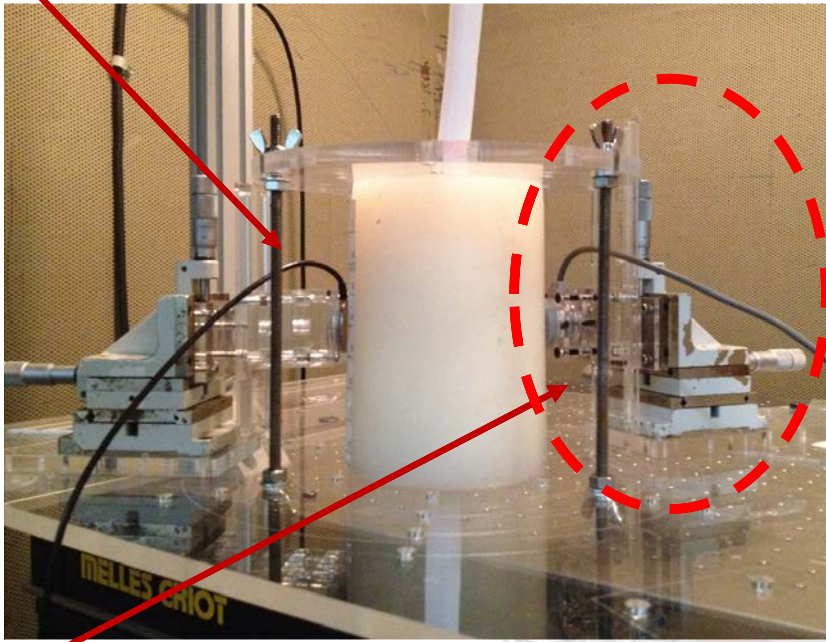
Fluid Flow Circuit





Biopac sensor attached to the Micromanipulator

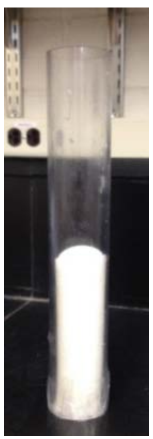


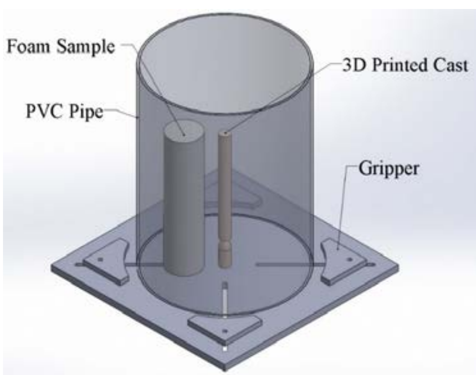


HP sensor attached to the Micromanipulator

Cardiothoracic Phantom-2nd generation

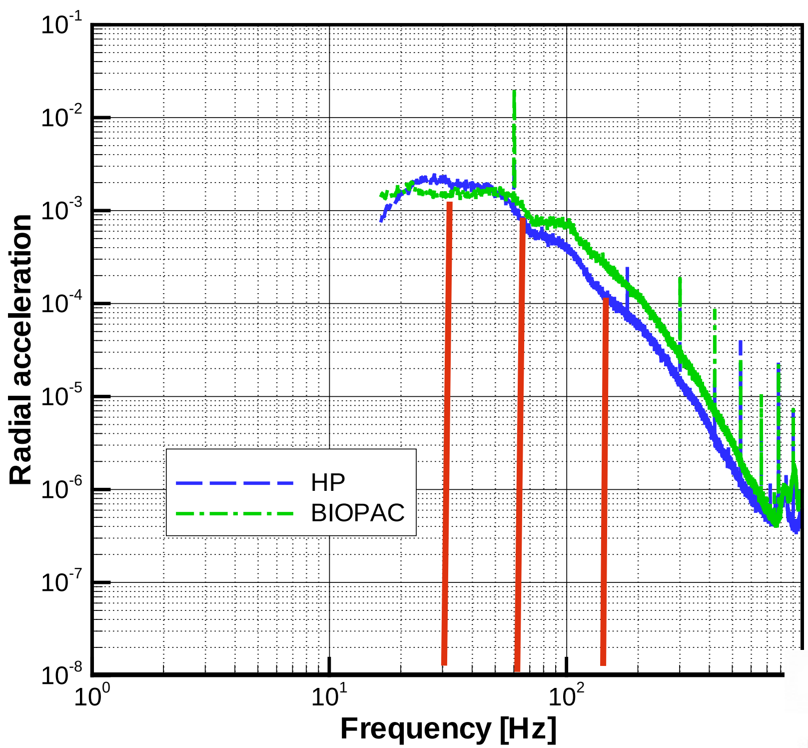
- Adding lung to the phantom
- Foam is used to model the lung
- Non-axisymmetric model

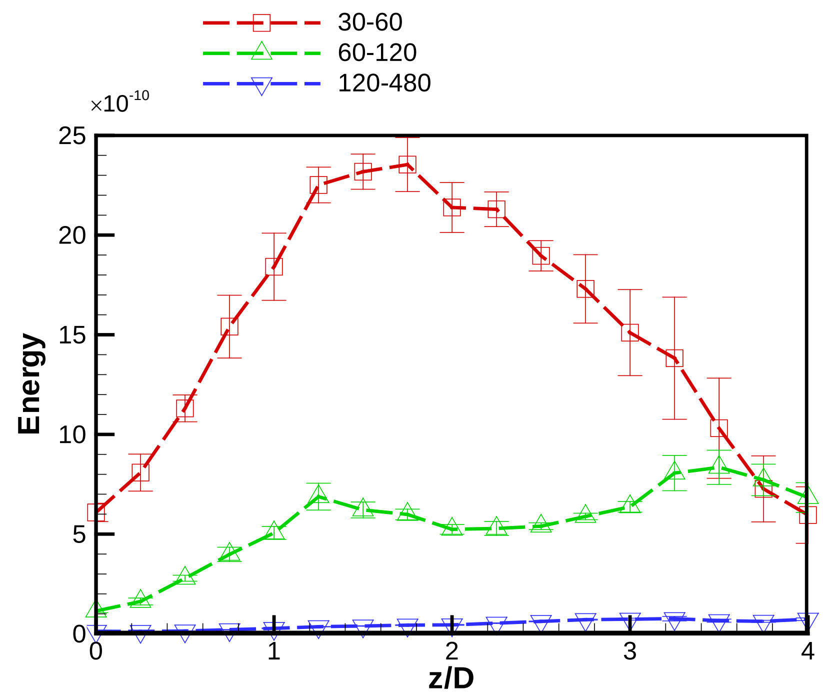




Experimental Measurements

Outer-surface radial accelerations



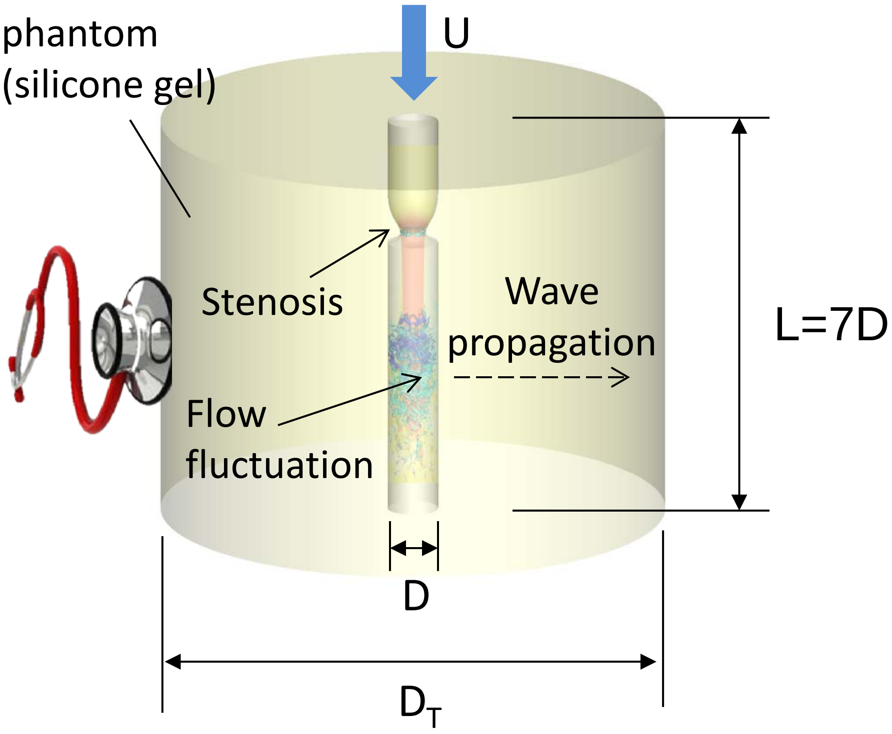


Frequency spectrum

Energy mapping

Computational/Experimental Studies

Simple model for the aortic stenosis murmur



Re=UD/ν=4000

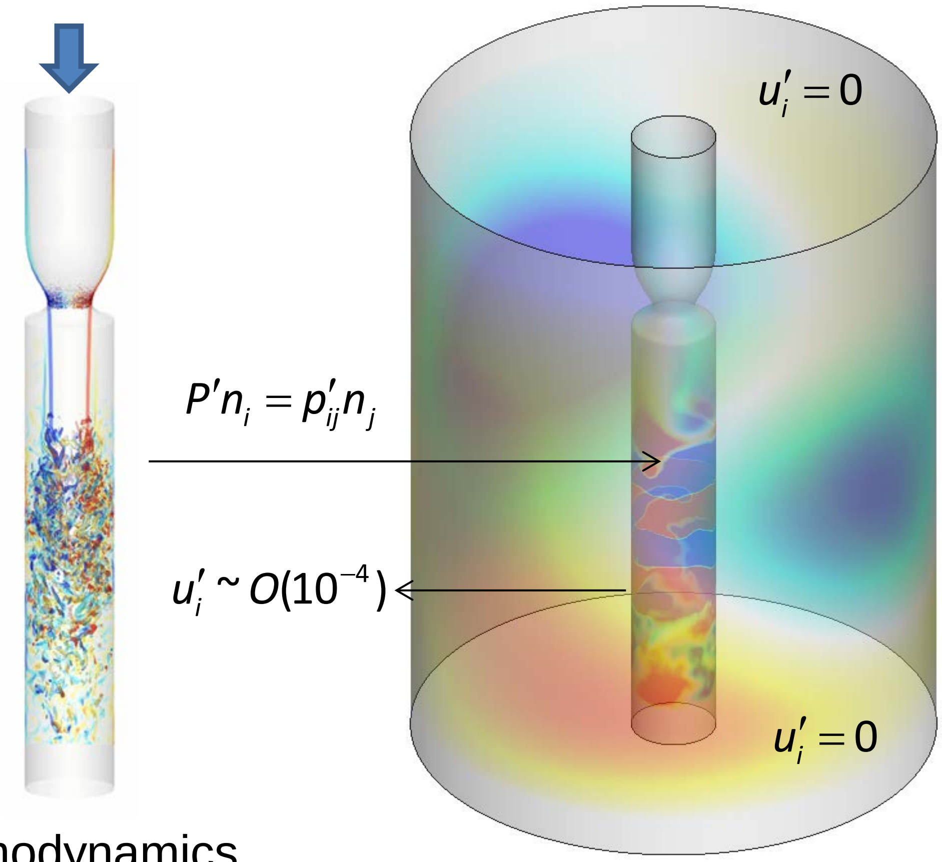
Material properties:
Tissue mimicking,
viscoelastic gel (EcoFlex-10)

ρ=1040 kg/m^3
K=1.04 GPa (c$_b$=1000.0 m/s)
G=18.39 kPa (c$_s$=4.2 m/s)
μ=14 Pa s

Other parameters:
U=0.25 m/s
D=1.5875 cm
D_T=9.84 cm (gelA), 16.51 cm (gelB)

c.f.
Biological soft tissue:
K=2.25 GPa (c$_b$=1500 m/s)
G=0.1 MPa (c$_s$=10 m/s)
μ=0.5 Pa s

Computational Modeling



Hemodynamics
IBM, Incompressible N-S

$$\nabla \cdot \vec{U} = 0, \ \frac{\partial \vec{U}}{\partial t} + (\vec{U} \cdot \nabla)\vec{U} + \frac{1}{\rho}\nabla P = \nu \nabla^2 \vec{U}$$

Elastic wave eq.
for viscoelastic material

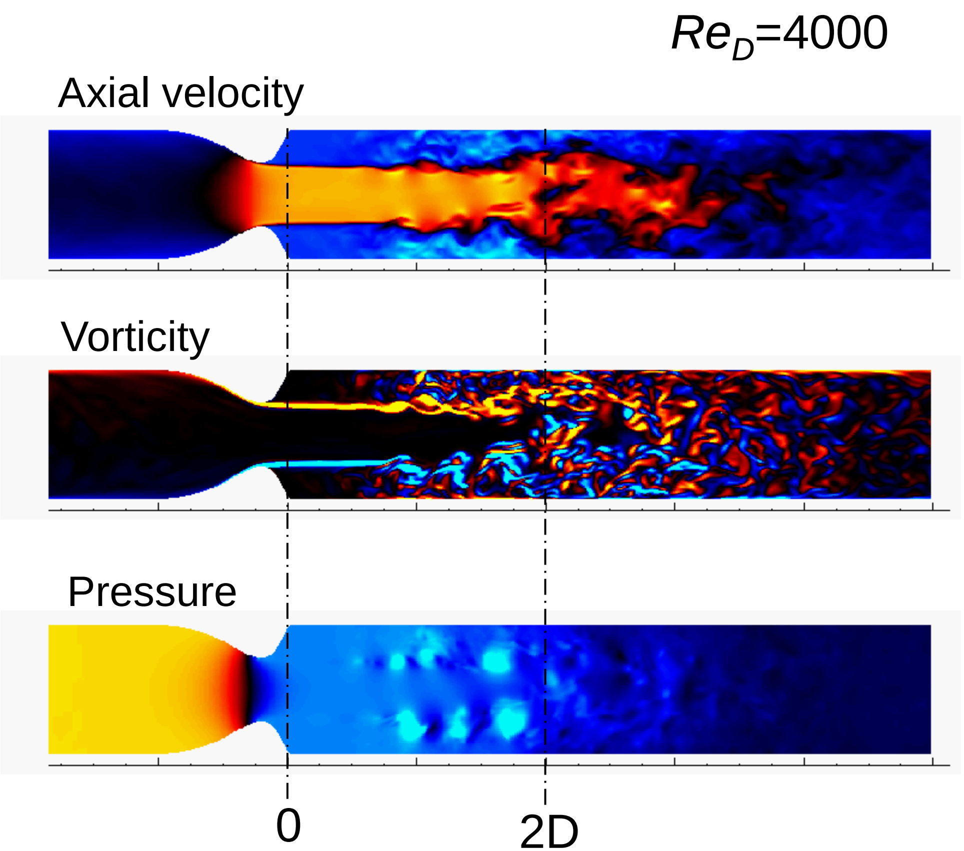
Generalized Hooke's law
Kelvin-Voigt model

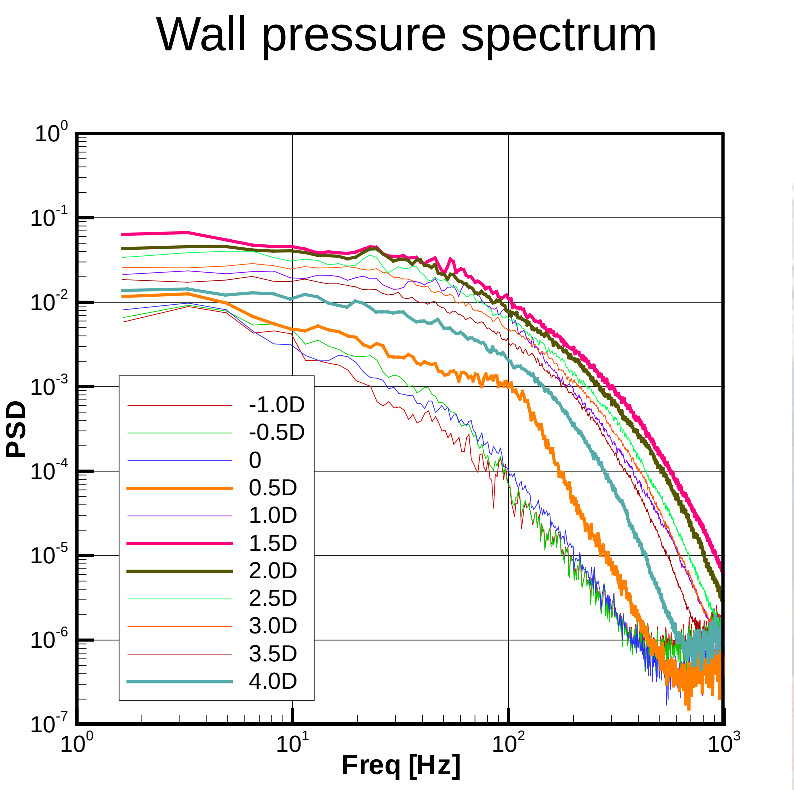
$$\frac{\partial p_{ij}'}{\partial t} + \lambda \frac{\partial u_k'}{\partial x_k}\delta_{ij} + \mu\left(\frac{\partial u_i'}{\partial x_j} + \frac{\partial u_j'}{\partial x_i}\right) = 0$$

$$\frac{\partial u_i'}{\partial t} + \frac{1}{\rho}\frac{\partial p_{ij}'}{\partial x_j} = \frac{\eta}{\rho}\frac{\partial}{\partial x_j}\left(\frac{\partial u_i'}{\partial x_j} + \frac{\partial u_j'}{\partial x_i}\right)$$

High-order IBM,
6th order Compact Finite Difference Scheme,
4 stage Runge-Kutta method

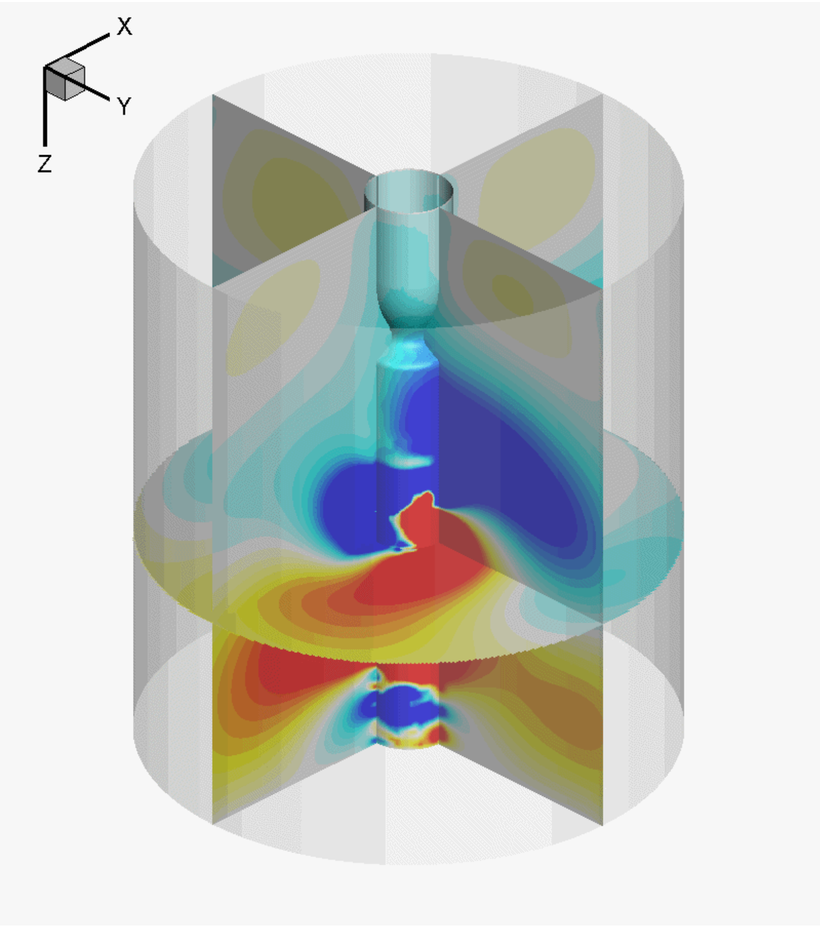
Flow Simulation

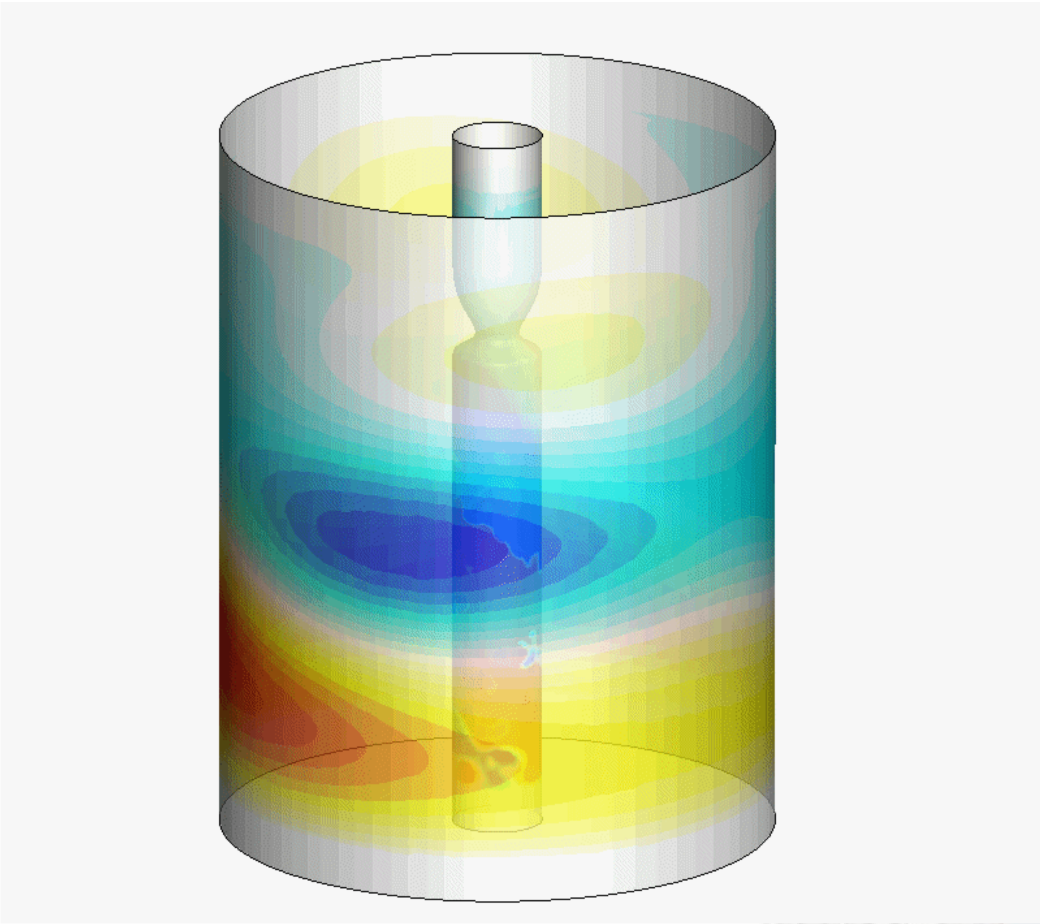




3D Elastic Wave Simulation

Radial velocity fluctuation contours

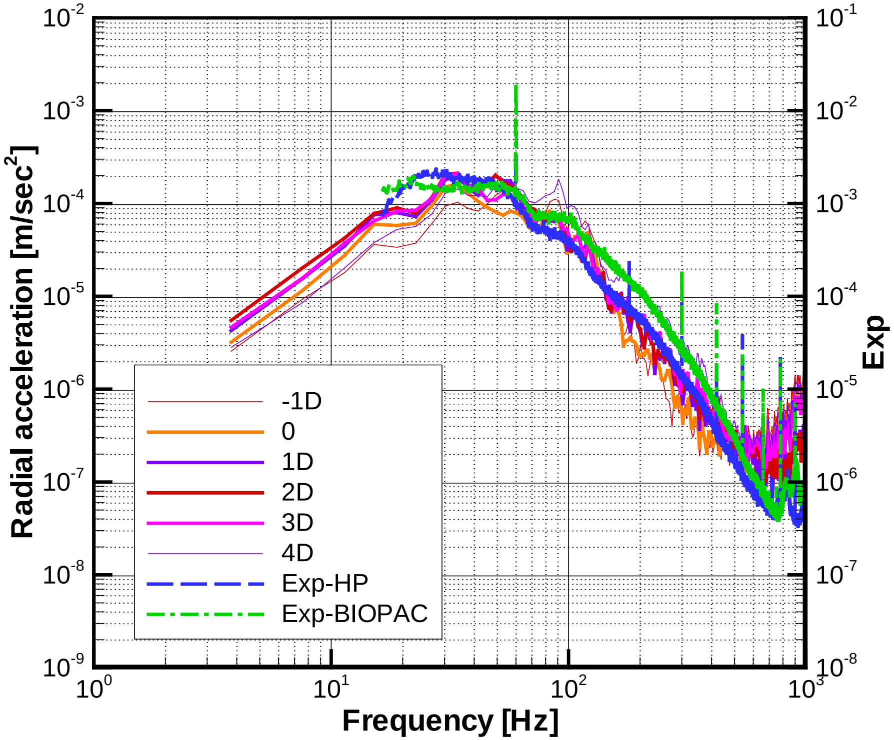




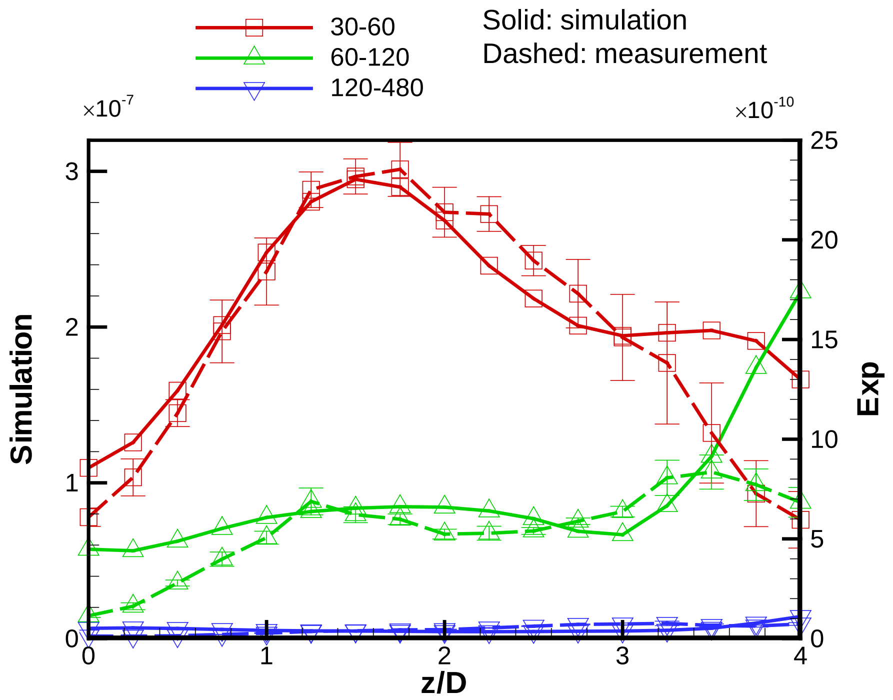
- 200x200x320 (12.8 M), about 60 hrs with 1024 cores for real time 0.8 sec

Comparison with Experimental Measurements

Outer-surface radial accelerations



Frequency spectrum



Energy mapping

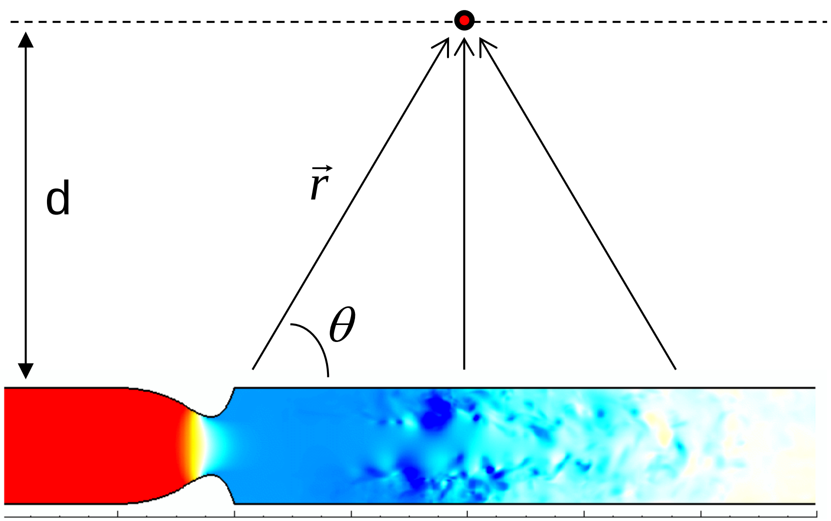
Free-Space Green's Tensor

Analytical estimation of elastic wave solution
(no geometrical effects)

$$\rho \frac{\partial^2 u_i}{\partial t^2} - \left(\lambda \delta_{ij}\delta_{kl} + \mu(\delta_{ik}\delta_{jl} + \delta_{il}\delta_{jk})\right)\frac{\partial^2 u_l}{\partial x_j \partial x_k} = f_i(t)\delta(\vec{r})$$

$$u_i(t) = \frac{1}{2\pi}\int U_i(\omega)e^{-i\omega t}d\omega$$

$$f_i(t) = \frac{1}{2\pi}\int F_i(\omega)e^{-i\omega t}d\omega$$



$$U_i(\vec{r},\omega) = G_{ij}(\vec{r},\omega)F_j(\omega)$$

Green's tensor (Ben-Menahem & Singh,1981)

$$G_{ij}(\vec{r},\omega) = \frac{ik_p}{12\pi(\lambda+2\mu)}\left(\delta_{ij}h_0^{(1)}(k_p r) + (\delta_{ij} - 3\frac{x_i x_j}{r^2})h_2^{(1)}(k_p r)\right)$$

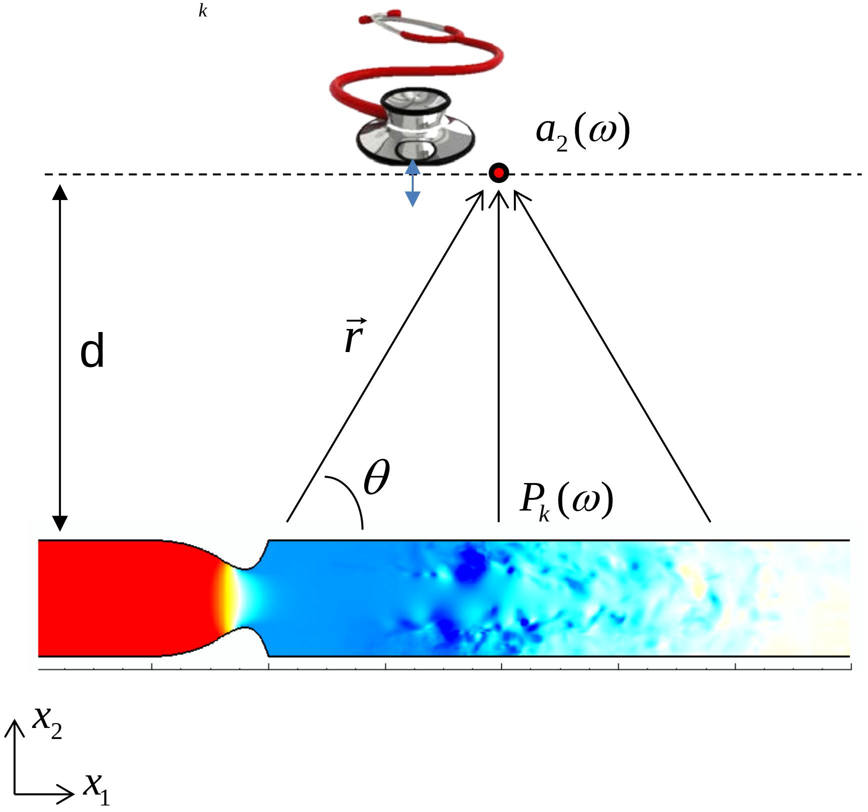
$$-\frac{ik_s}{12\pi\mu}\left(-2\delta_{ij}h_0^{(1)}(k_s r) + (\delta_{ij} - 3\frac{x_i x_j}{r^2})h_2^{(1)}(k_s r)\right)$$

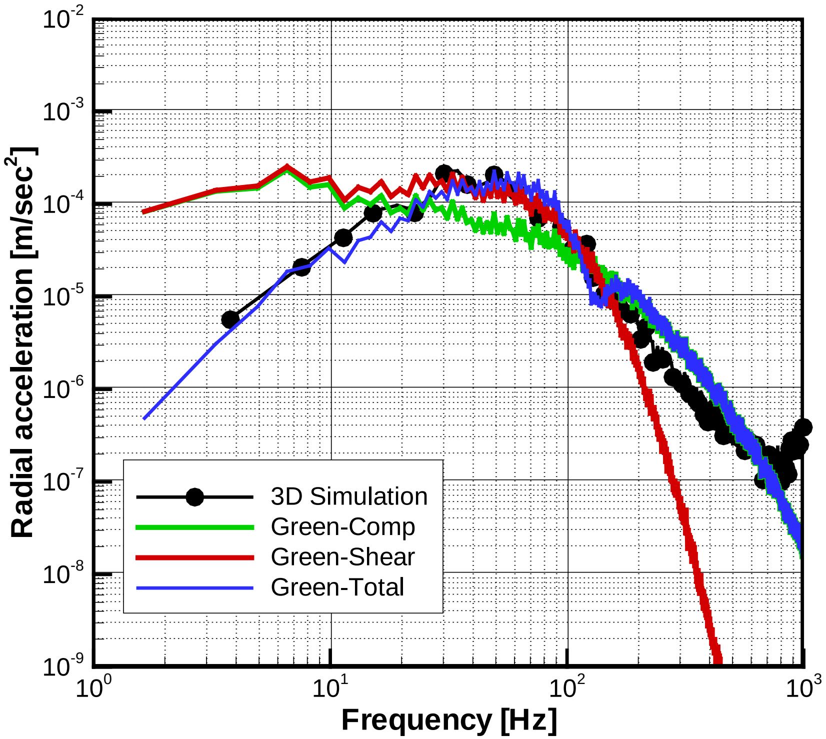
$$k_p = \omega / c_p, \quad c_p = \sqrt{(\lambda + 2\mu)/\rho}$$

$$k_s = \omega / c_s, \quad c_s = \sqrt{\mu / \rho}$$

Evaluation of Radial Acceleration

$$a_m(\vec{r},\omega) = \sum_k (i\omega)^2 G_{mn,k}(\vec{r}_k,\omega) F_{n,k}(\omega), \quad F_{2,k}(\omega) = P_k(\omega)\Delta A$$



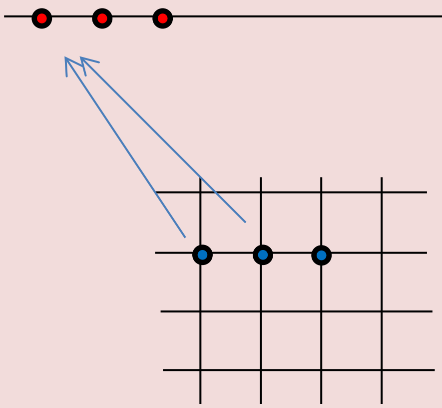


Oblique shear waves contribute significantly to the stethoscopic signal!

Source Localization

Surface measurements

$u_{1,}\ u_{2,}\ ....u_M$



Source mapping

$F_{1,}\ F_{2,}\ ....F_N$

$$u_m = \sum_{n=1}^{N} G(x_m; x_n) F_n$$

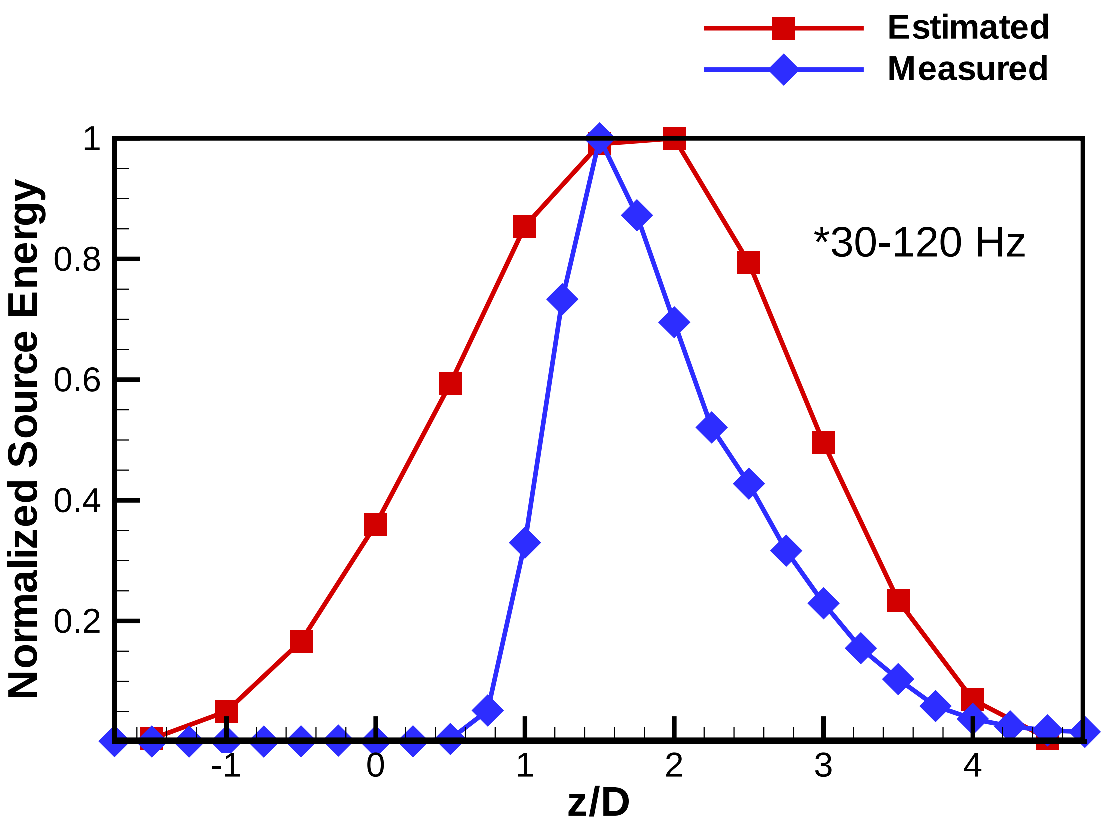
$$\begin{bmatrix} u_1 \\ \vdots \\ u_M \end{bmatrix} = \mathbf{G} \begin{bmatrix} F_1 \\ \vdots \\ F_N \end{bmatrix}$$

G: M by N complex matrix

$$[F] = \mathbf{G}^{+}[u]$$

G^{+}: Pseudo inverse of **G**

Source Localization

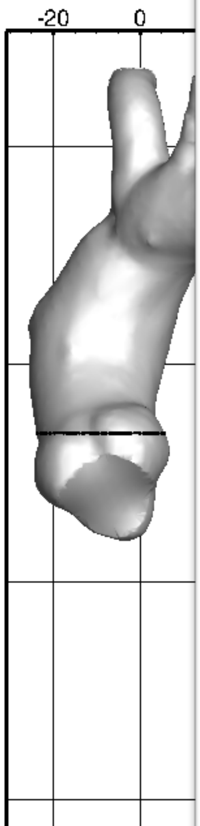


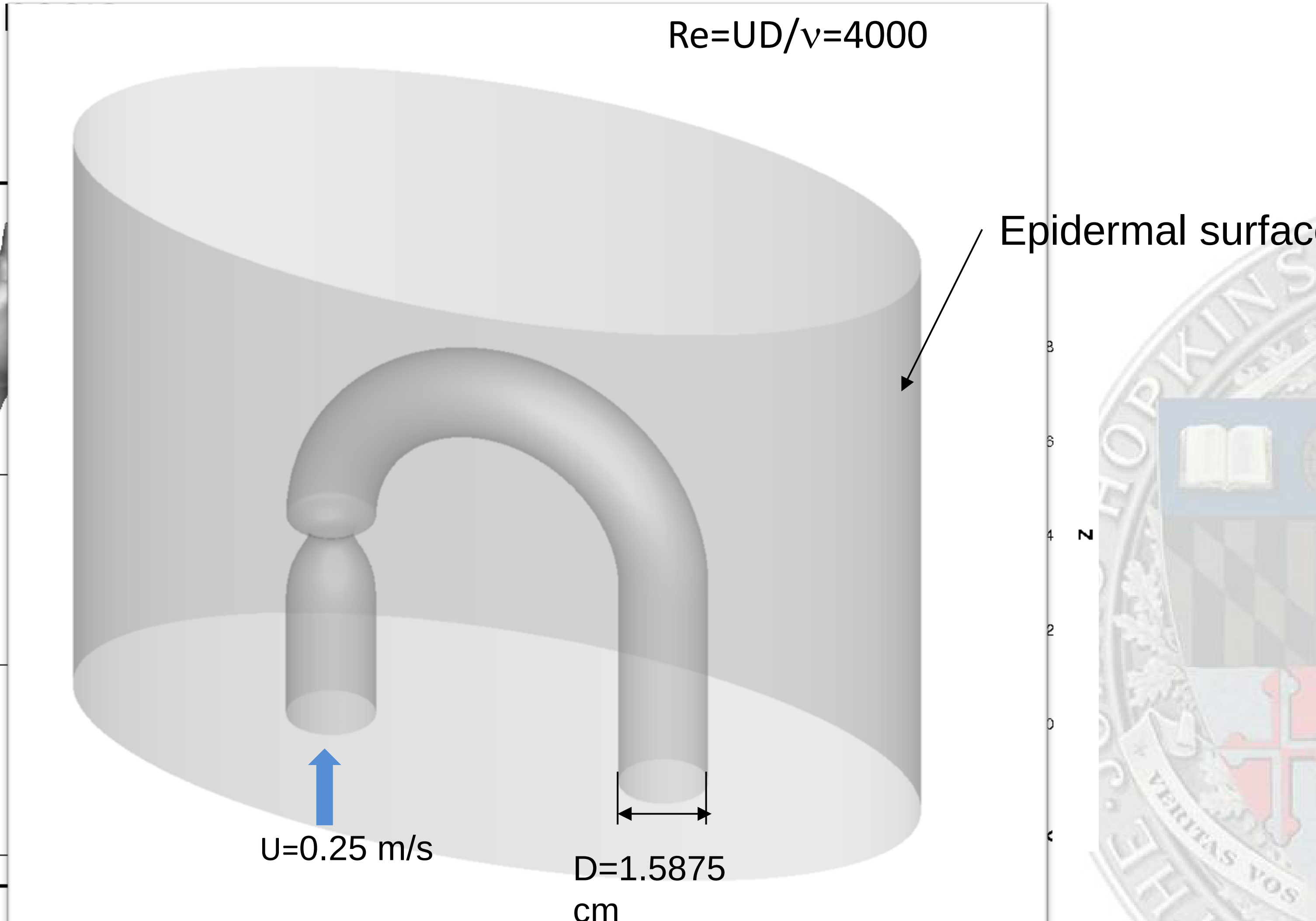
Proceeding towards using a multi-sensor stethoscopic array (StethoVest) for automatic murmur localization

Computational Modeling

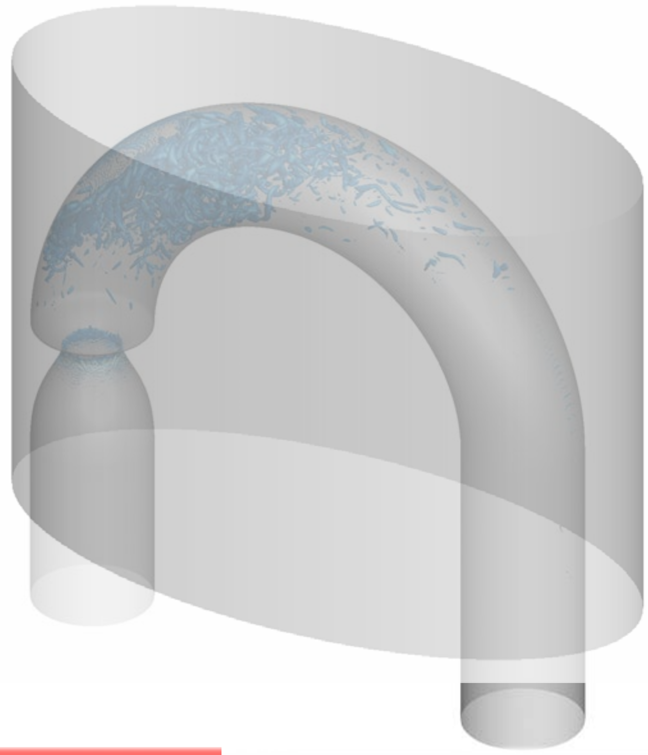
Aortic ste

Patient





Computational Modeling



Fluid Solver: Vicar Code, sharp interface IBM

$$\frac{\partial U_i}{\partial t} + U_j \frac{\partial U_i}{\partial x_j} = -\frac{1}{\rho_f}\frac{\partial P}{\partial x_i} + \nu \frac{\partial^2 U_i}{\partial x_j^2}$$

$$\frac{\partial U_i}{\partial x_i} = 0.$$

See: Mittal, R., *et al.,* JCP, 2008

Acoustic Solver:

$$\frac{\partial p_{ij}}{\partial t} + \lambda \frac{\partial v_k}{\partial x_k}\delta_{ij} + \mu\left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i}\right) = 0$$

$$\frac{\partial v_i}{\partial t} + \frac{1}{\rho_s}\frac{\partial p_{ij}}{\partial x_j} = \frac{\eta}{\rho_s}\frac{\partial}{\partial x_j}\left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i}\right).$$

v_i – structure velocity.
λ, μ – 1st and 2nd Lame's constants.
ρ_s – density.
K – bulk modulus, = 1.04 GPa.
G – shear modulus, = 18.39 KPa.
η – viscosity, = 14.0 Pa s.

Numerical methods:
- Interior nodes:
  - 6th –order compact scheme
- Immersed boundary:
  - approximating polynomial method
- Time advancement:
  - 4th –order Runge-Kutta method

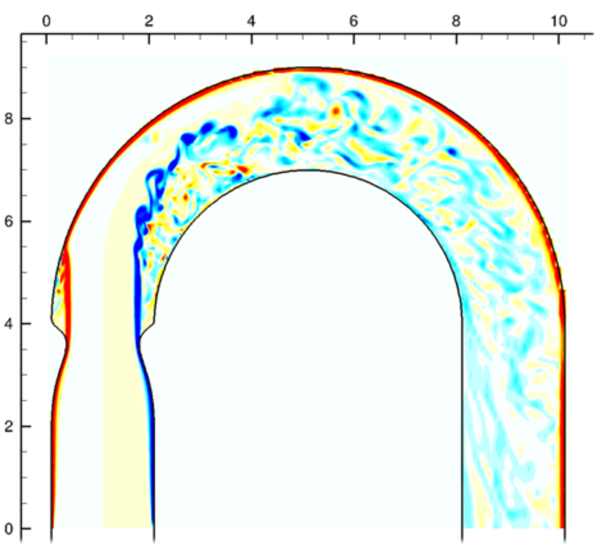
See: Seo, J. H., & Mittal, R. ,JCP, 2011

Hemodynamic Simulation Results

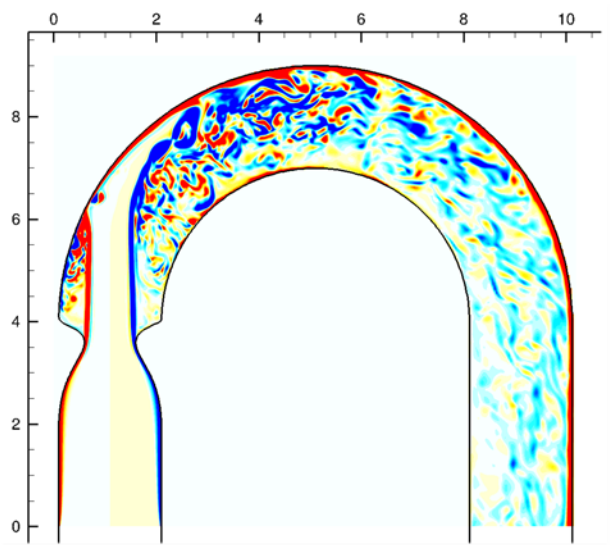
x component of vorticity

Same contour level

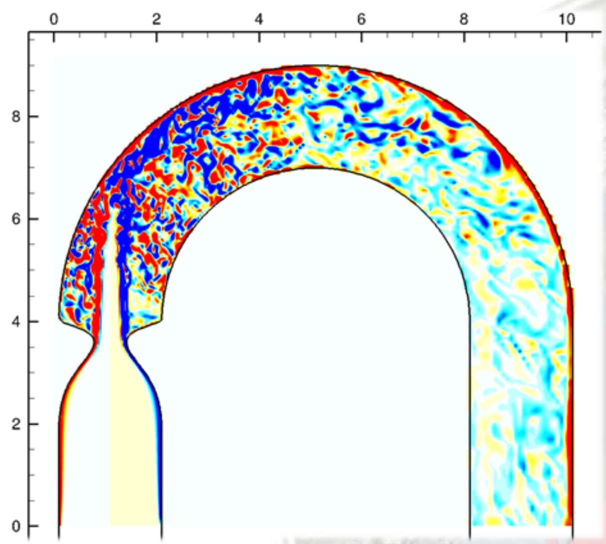
50%



75%



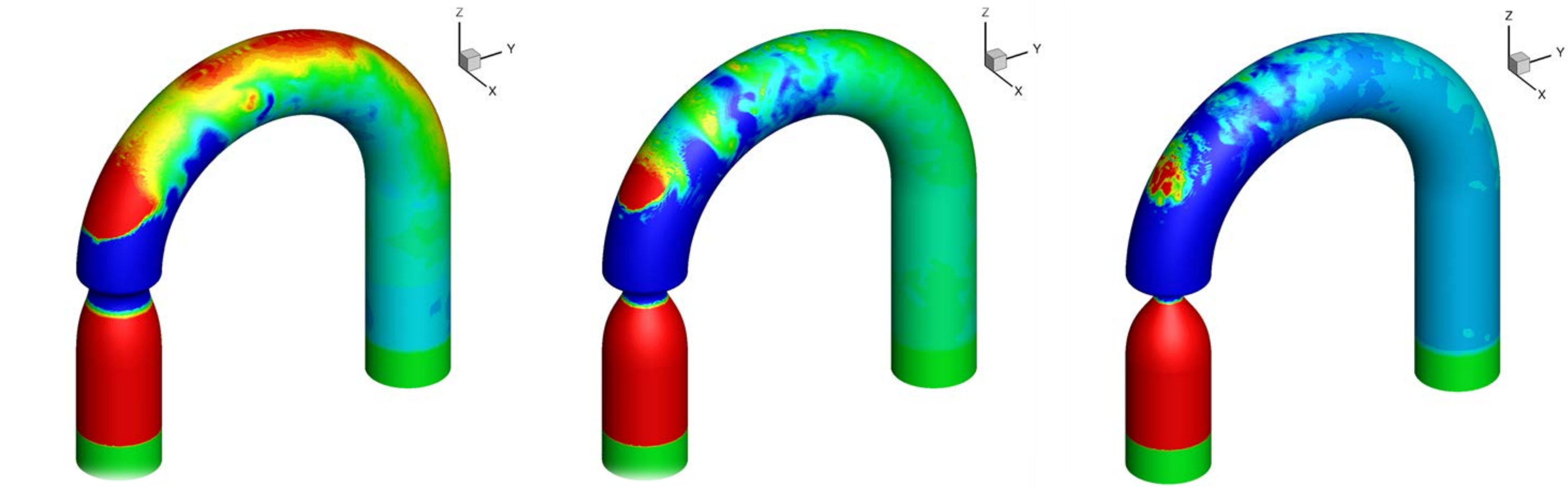
90%



Hemodynamic Simulation Results

Contour of surface pressure

50% | 75% | 90%

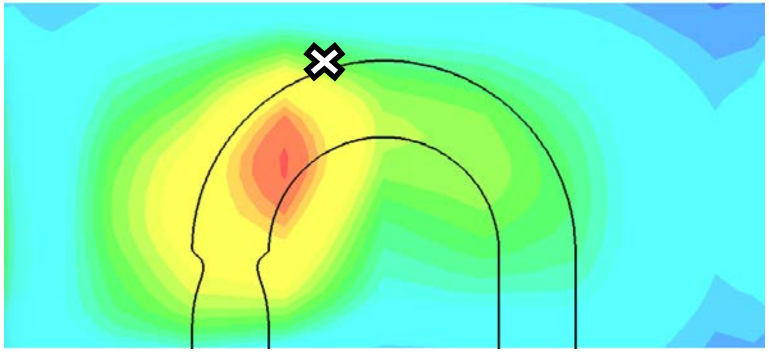


5 times smaller contour level | Baseline | 5 times larger contour level

Source Location

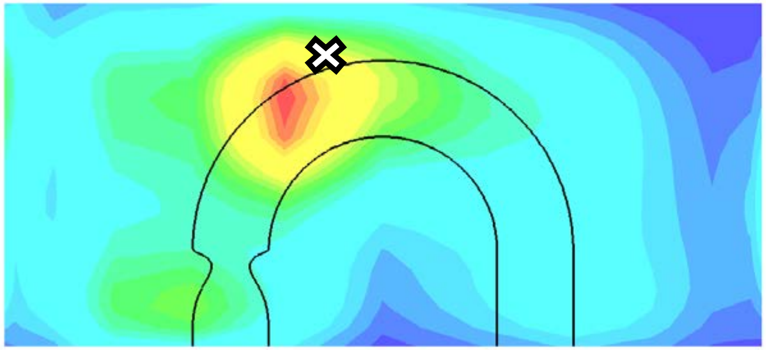
Surface Signal

50%



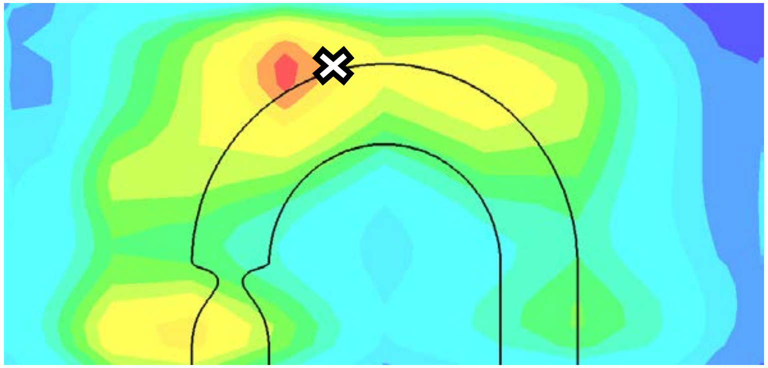
1000 times smaller contour level

75%



Baseline

90%



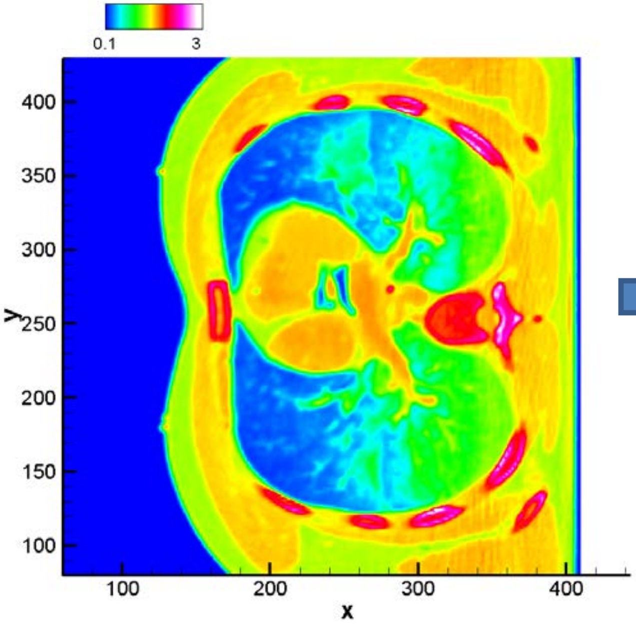
100 times larger contour level

Realistic Thorax Model

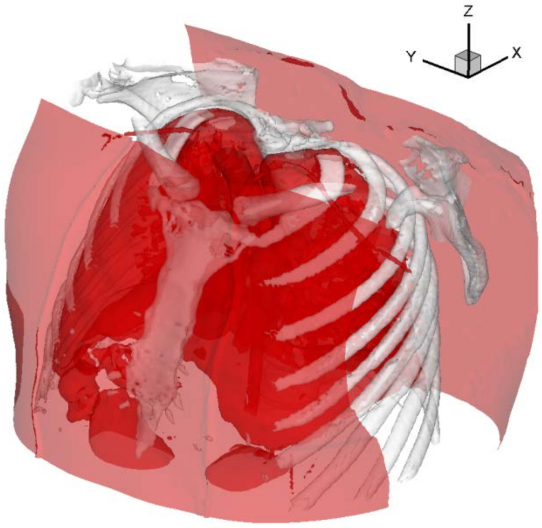
Need to account or thoracic structures on sound propagation

CT scan data
(Visible Human)

Material property
(density and speed of sound)
mapping



3D model of the thorax
(density iso-surfaces)



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