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Mechanical Design, Instrumentation and Measurements from a Hemoacoustic Cardiac Phantom

Hani Bakhshaee+, Guillaume Garreau*, Gaspar Tognetti*, Kourosh Shoele+, Ronann Carrero+, Thomas Kilmar+, Chi Zhu+
William R. Thompson++, Jung Hee Seo+, Rajat Mittal+, Andreas G. Andreou*
*Department of Electrical and Computer Engineering, Johns Hopkins University,
++Department of Pediatrics, Johns Hopkins University School of Medicine
+Department of Mechanical Engineering, Johns Hopkins University,

Outline

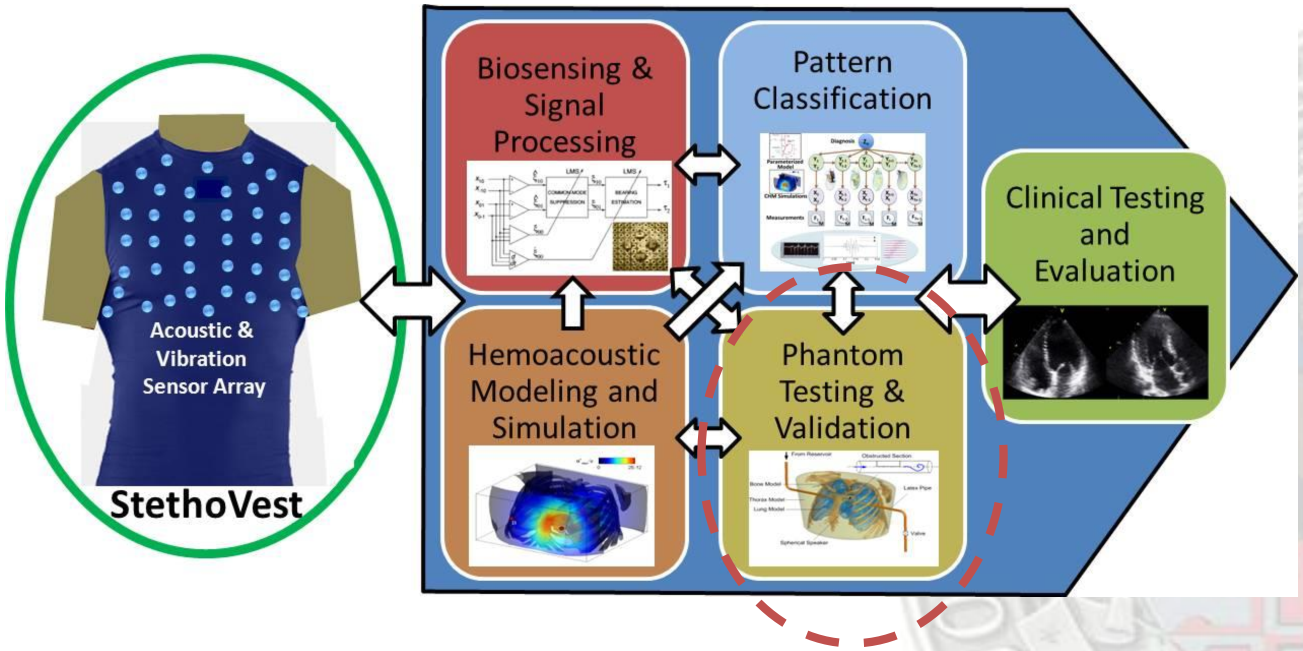
- Brief overview
- Phantom design
- Hemoacoustic computational simulations
- Comparison between experimental and computational results
- Future versions of the phantom

Overview

- **Heart disease**:
  - Most consequential disease in the industrialized world
  - Annual US expenditure on heart disease exceeds half a trillion dollars

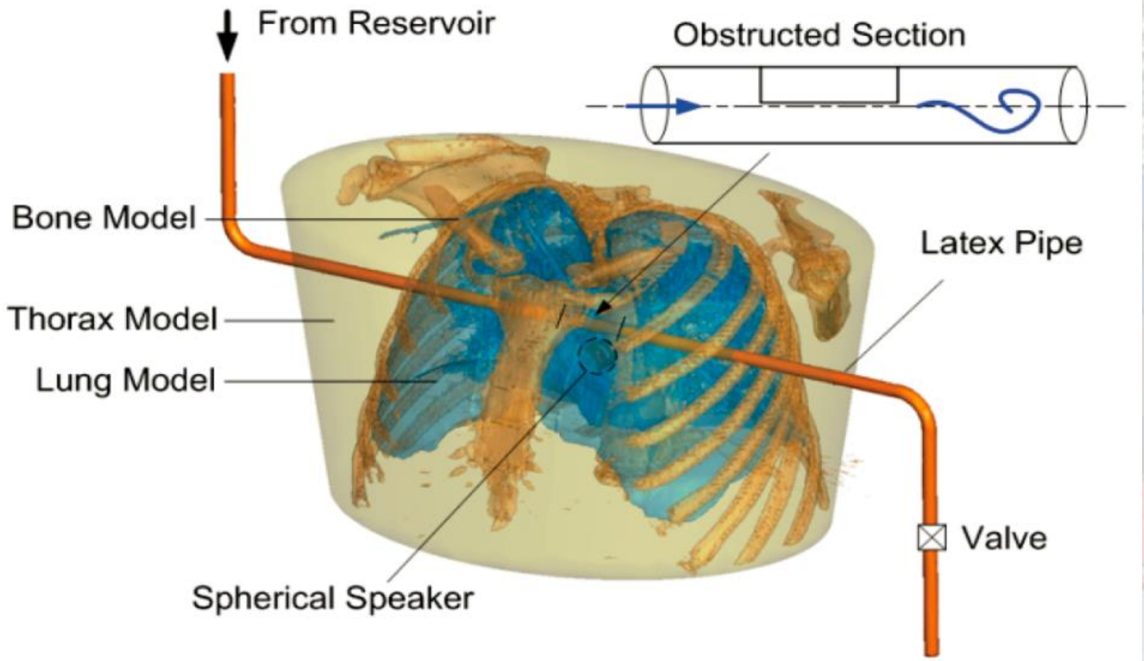
- **Cardiac auscultation**:
  - Been around for 200 years
  - Limitations: subjective, inaccurate

- Automated cardiac auscultation via a wearable acoustic array (the"StethoVest"):
  - Expensive → Cost-effective
  - Reactive-→Proactive,
  - Hospital centric →Patient centric



Developing the thoracic phantom

- The phantom will be used to validate the codes and to examine the sensors
- To design the phantom the following items should be considered :
  - Tissue mimicking homogeneous material and characterization
  - Murmur generating embedded fluid-circuit
  - Measurements : Variety of acoustic sensors



Material selection

- Acoustic and mechanical properties should be similar

- Examples of previous tissue-mimicking materials in the literature
  - Agar
  - Silicone
  - Polyvinyl alcohol gel (PVA) and
  - Polyacrylamide gel (PAA)

Acoustic property of the material

Table 2. Sound velocities, densities, impedances, and acoustic attenuation coefficients of silicone, agar, PVA and PAA in comparison to the values of human tissues and literature values.

Material	Velocity, c_S (10^3 m s^{-1})	Density, ρ (10^3 kg m^{-3})	Impedance z (10^6 kg m^{-2} s^{-1})	Acoustic attenuation coefficient, α (dB cm^{-1})	Frequency (MHz)	References
Human breast tissue	1.43–1.57	0.99–1.06	1.42–1.66[b]	9.5 –12.6	7	Duck 1990
Human skin	1.54[a]	1.11–1.19	1.71–1.83[b]	9.2 ± 2.2	5	Duck 1990
Silicone	1.03 ± 0.06[c]	1.07 ± 0.03	1.10 ± 0.05[c]	14.0 ± 1.4	5	our measurement
				14.7 ± 1.6	7	
PVA	1.57 ± 0.02[c]	1.10 ± 0.05	1.74 ± 0.08[c]	2.9 ± 0.1	5	our measurement
				3.2 ± 0.1	7	
	1.58 ± 0.03	1.07 ± 0.02	1.71 ± 0.06	2.1	5	Kharine *et al* 2003
PAA (10%)	1.58 ± 0.05[c]	1.09 ± 0.09	1.73 ± 0.08[c]	0.7 ± 0.1	5	our measurement
				0.7 ± 0.1	7	
	–	1.02 ± 0.01	–	0.4 ± 0.1	5	Prokop *et al* 2003
Agar 2%	1.50 ± 0.03[c]	1.04 ± 0.11	1.57 ± 0.08[c]	0.4 ± 0.1	5	our measurement
				0.5 ± 0.1	7	
	1.54	–	–	–	–	Browne *et al* 2003

Acoustical properties of selected tissue phantom materials for ultrasound imaging, K Zell et al , 2007

Mechanical Property

Table 1. Soft materials used in the study.

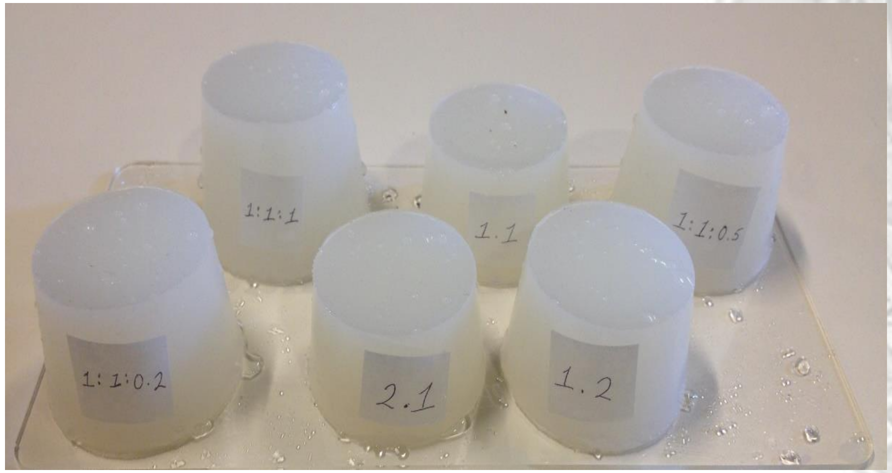
No.	Material, manufacturer, city, state	Density (g ml^{-1})	Softener volume range[a] (%)	Modulus range[a] (kPa)	Approximate cost per gallon
1	SR-1610, Douglas and Sturgess, San Francisco, CA	1.15	0–58[b]	25–660	$100
2	Dragon skin, Smooth-On, Easton, PA	1.08	0–78[b]	20–850	$85
3	Ecoflex 00-10, Smooth-On, Easton, PA	1.03	0–50[b]	15–110	$105
4	HS-IV, Dow Corning, Midland, MI	1.11	0–48[b]	20–570	$140
5	Candle Gel, Endless Possibilities, Oklahoma City, OK	0.98	n/a	50	$35
6	Tin-Sil, US Composites, West Palm Beach, FL	1.07	0–82[b]	10–1400	$200
7	Semicosil 921, Wacker Solutions, Adrian, MI	1.10	n/a	25	$110
8	8116SS plastic, M-F Manufacturing, Ft. Worth, TX	0.99	0–56[c]	15–200	$40
9	CF11, Nusil Technologies, Carpinteria, CA	1.04	n/a	204	$240

 Elastic properties of synthetic materials for soft tissue modeling. Mansy Et al, 2007

Silicone rubber

- Silicone rubber, Ecoflex 010 (Smooth-on)
  - Easy to produce ,
  - extremely stable
  - non-toxic and
  - negligible shrinkage

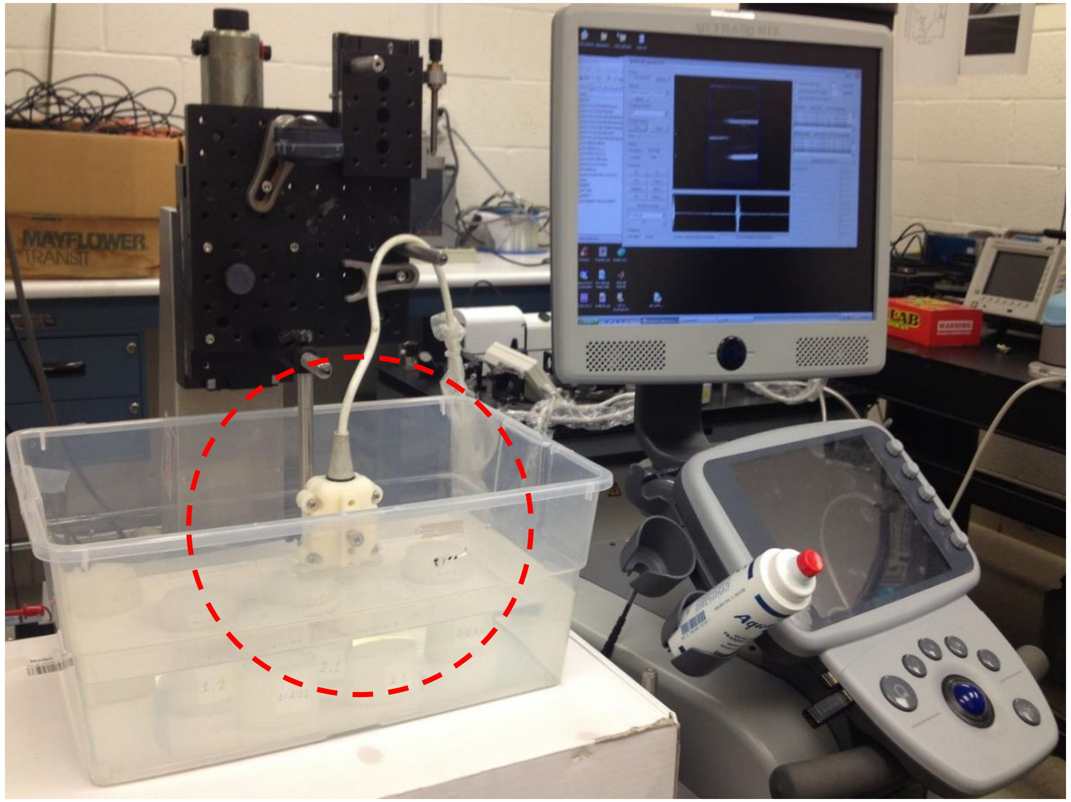
- Procedure to make :
  - Mixing Part A part B,
  - Adding Silicon thinner,
  - Degassing for 3-4 min in (-29 in Hg) to remove air bubbles

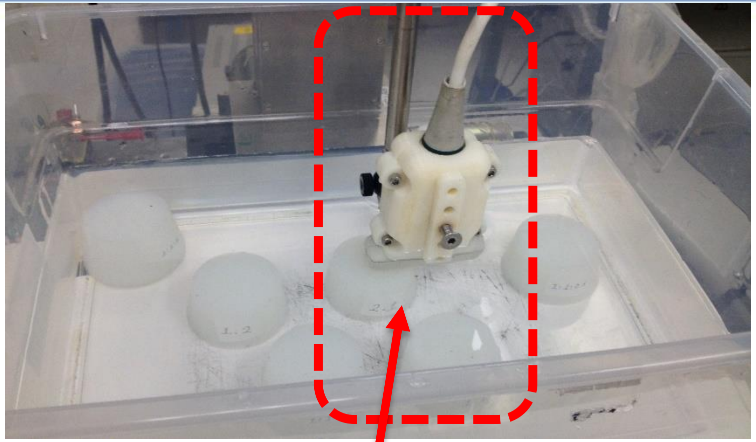


Material characterization

Speed of sound

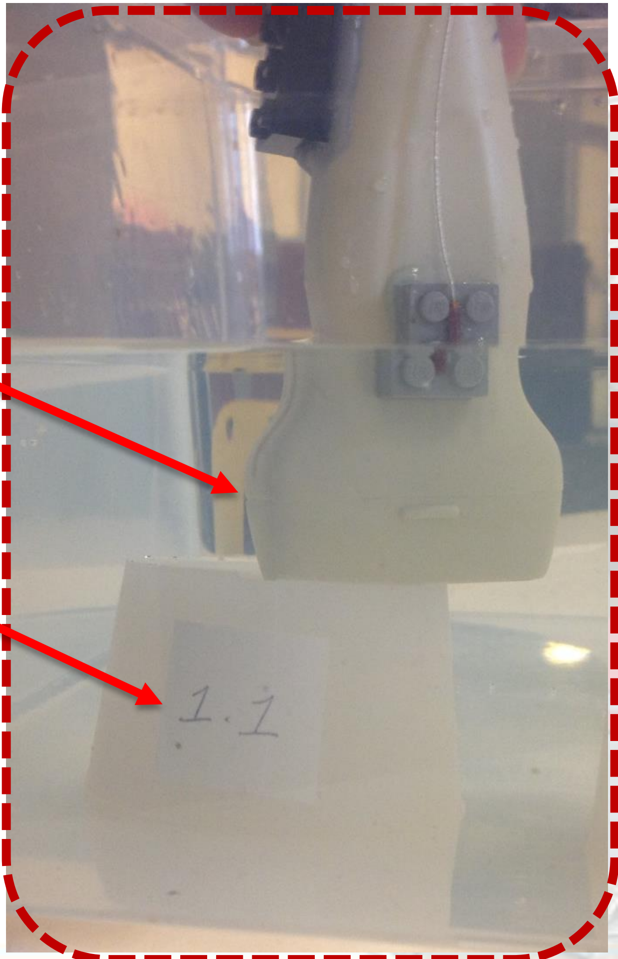
Speed of sound : 993-1043m/s





Ultrasound Probe

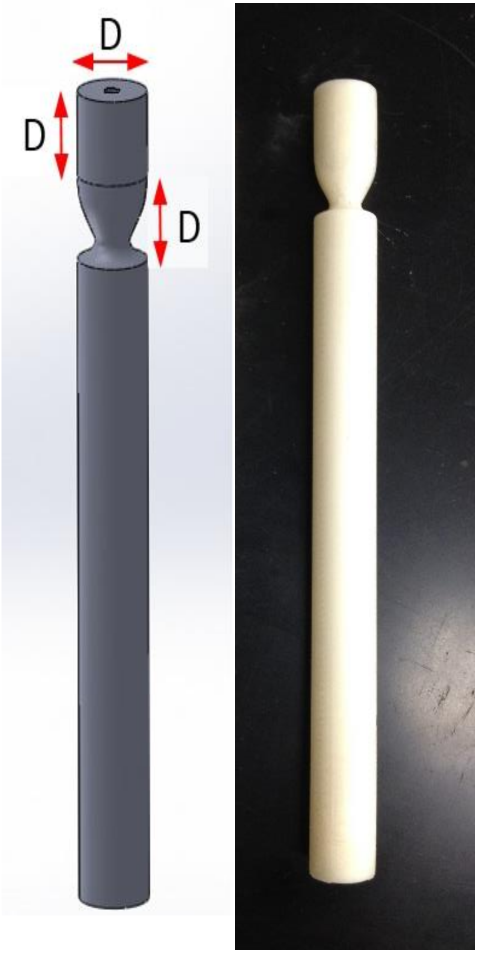
Gel sample



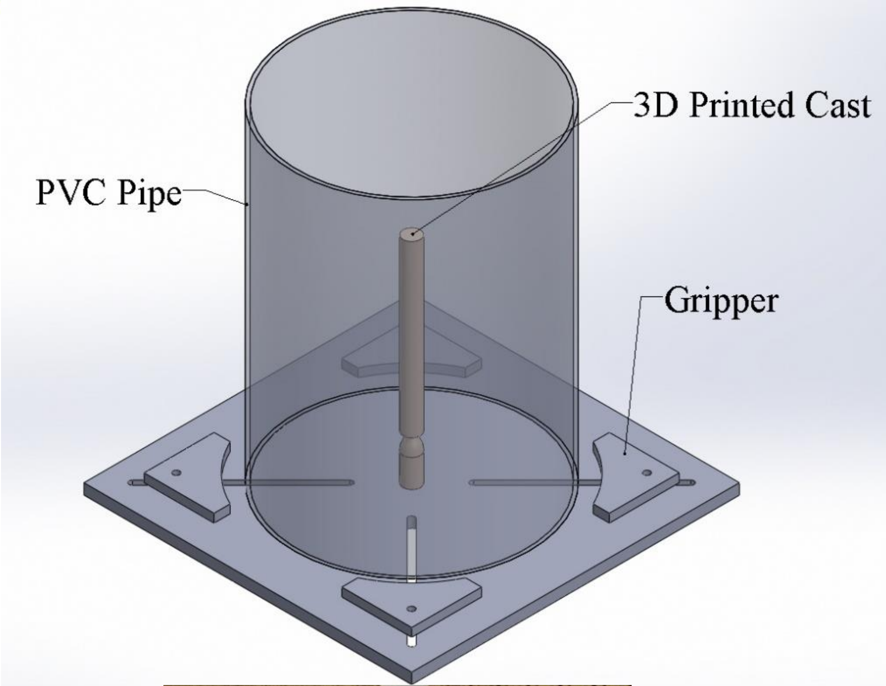
The ratio of sound speeds are equal to the inverse ratio of the depth seen in the ultrasound image

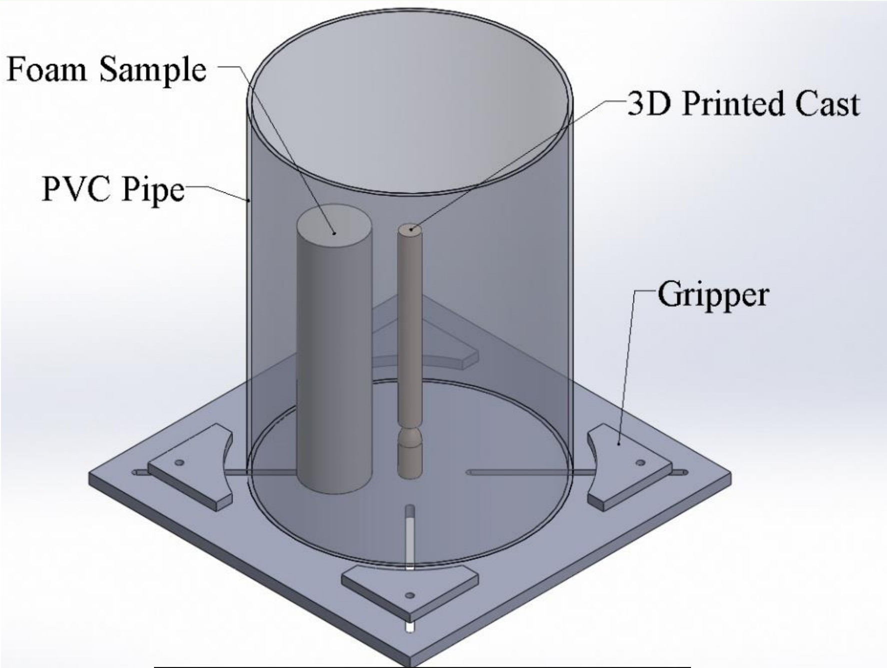
Thanks to Dr. Emad Boctor and Fereshte Alamifar

Murmur generating

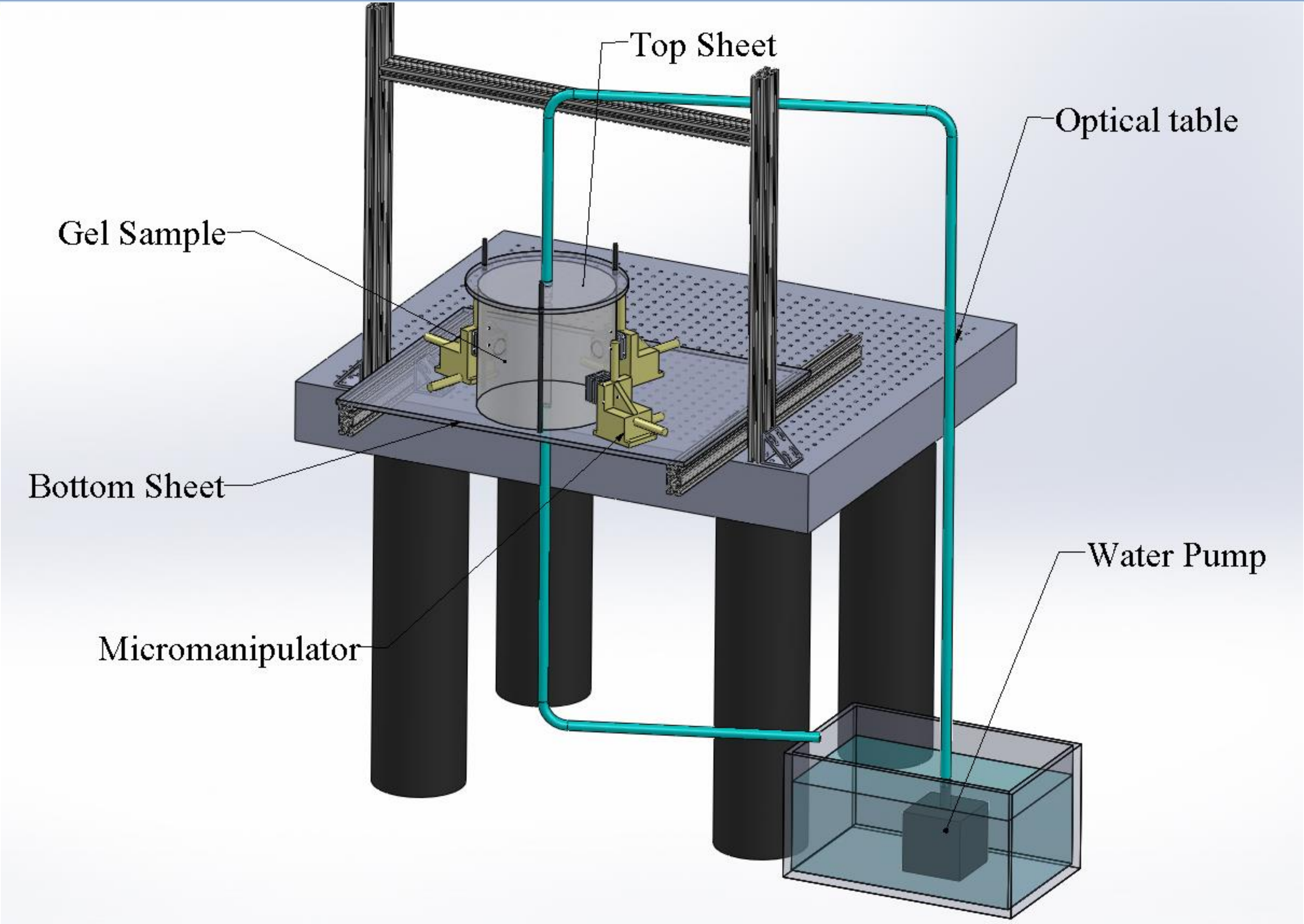


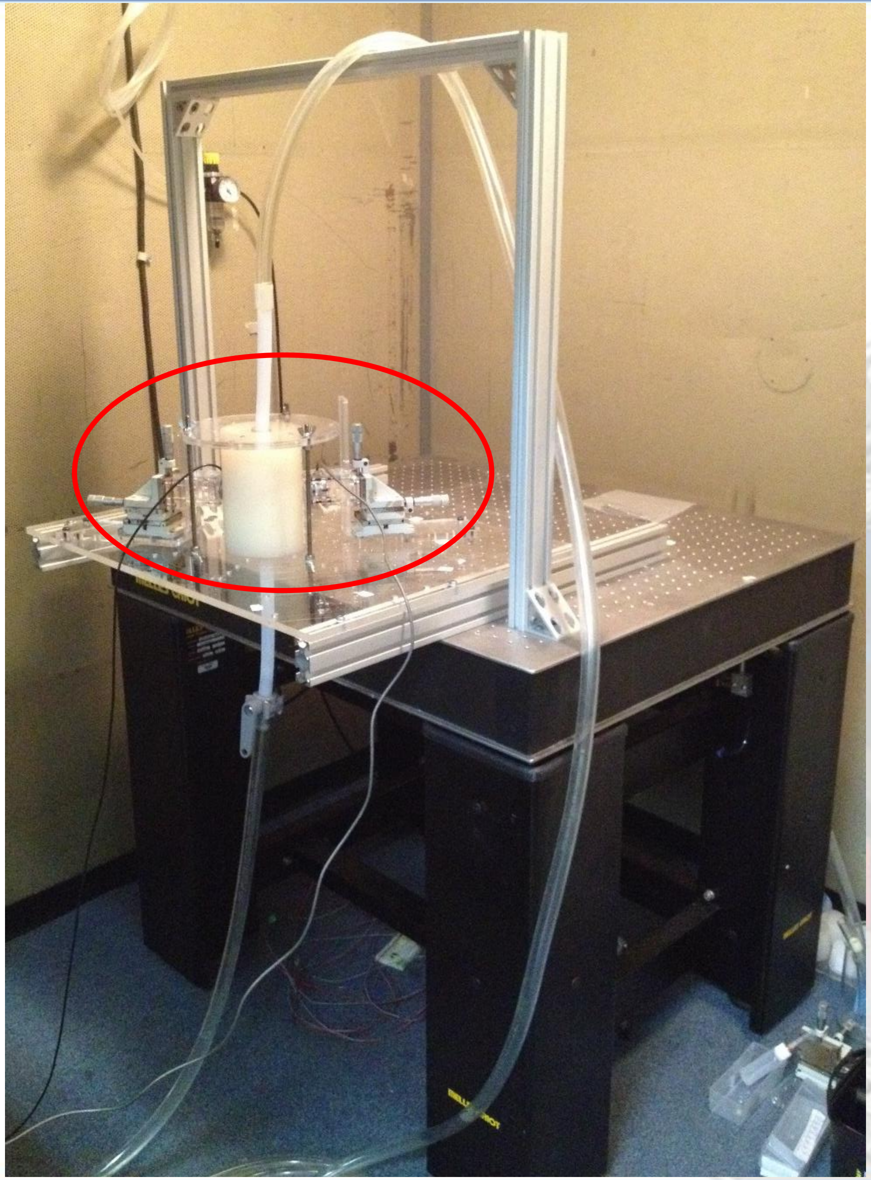
3D printed Cast



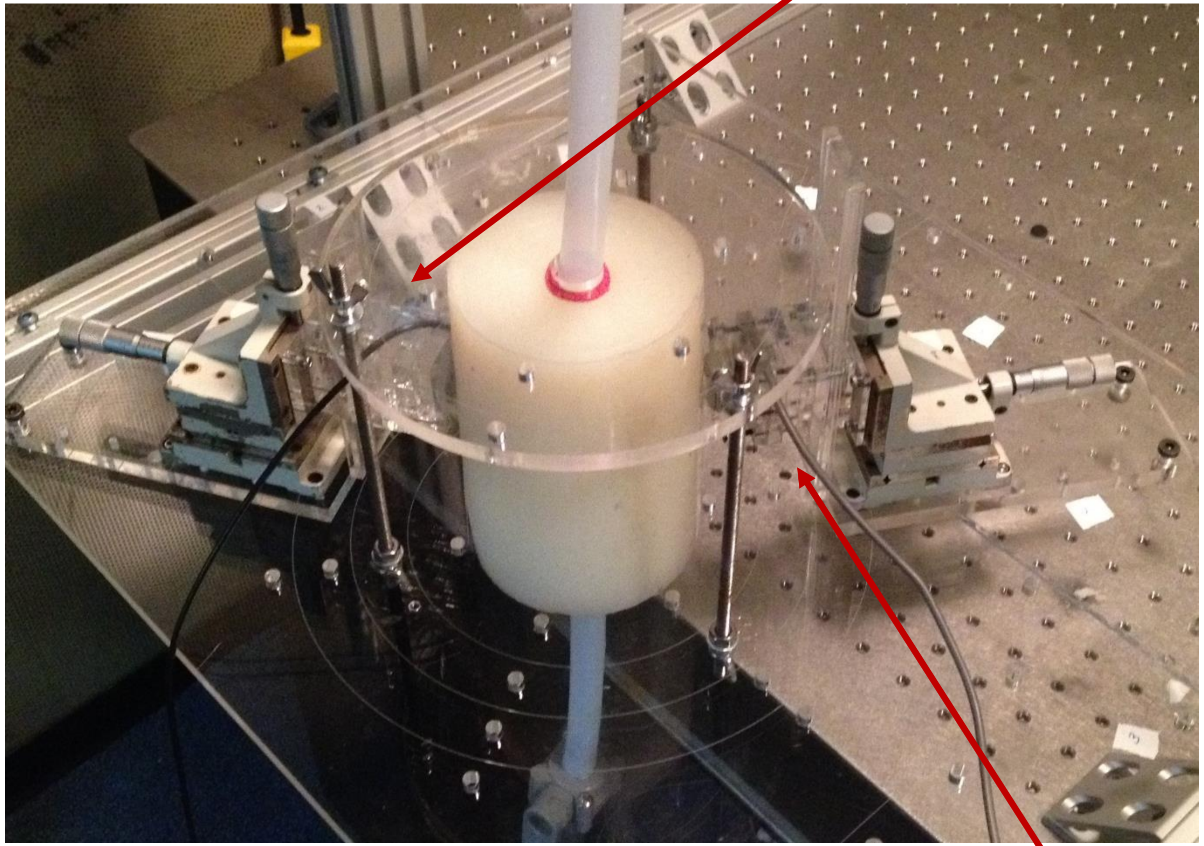


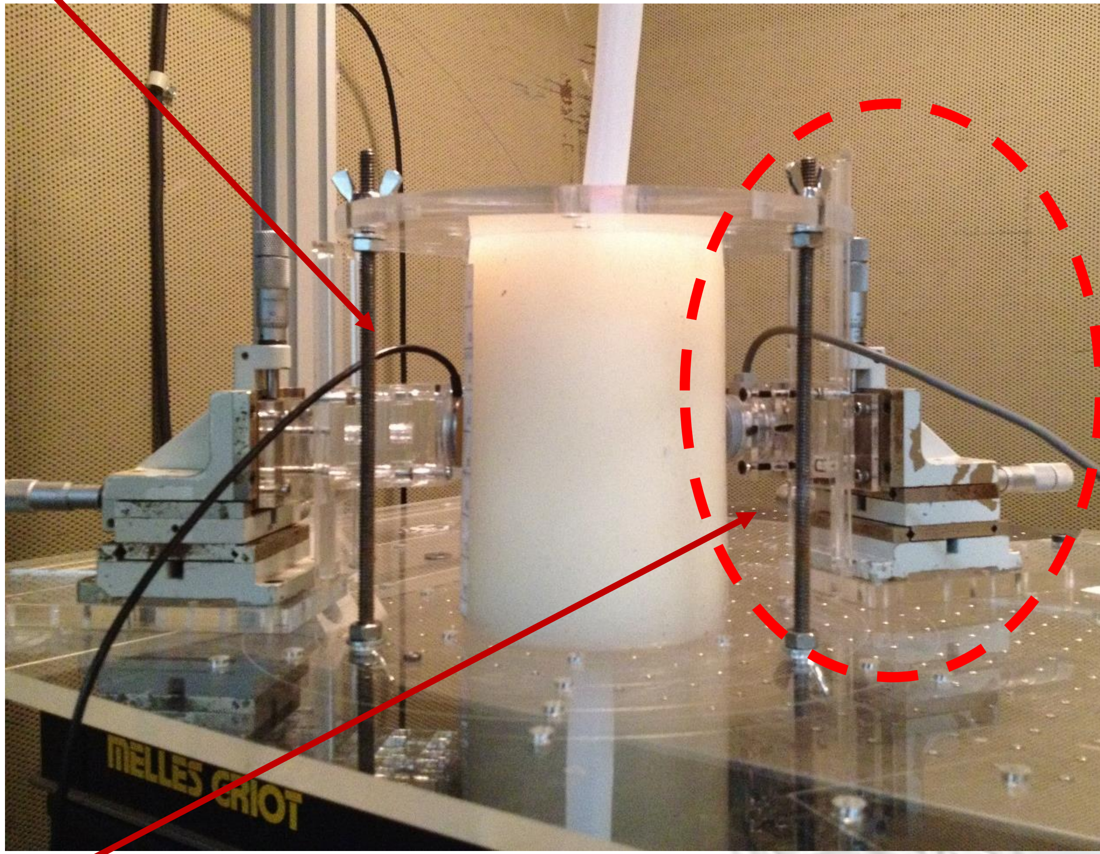
Fluid Flow Circuit





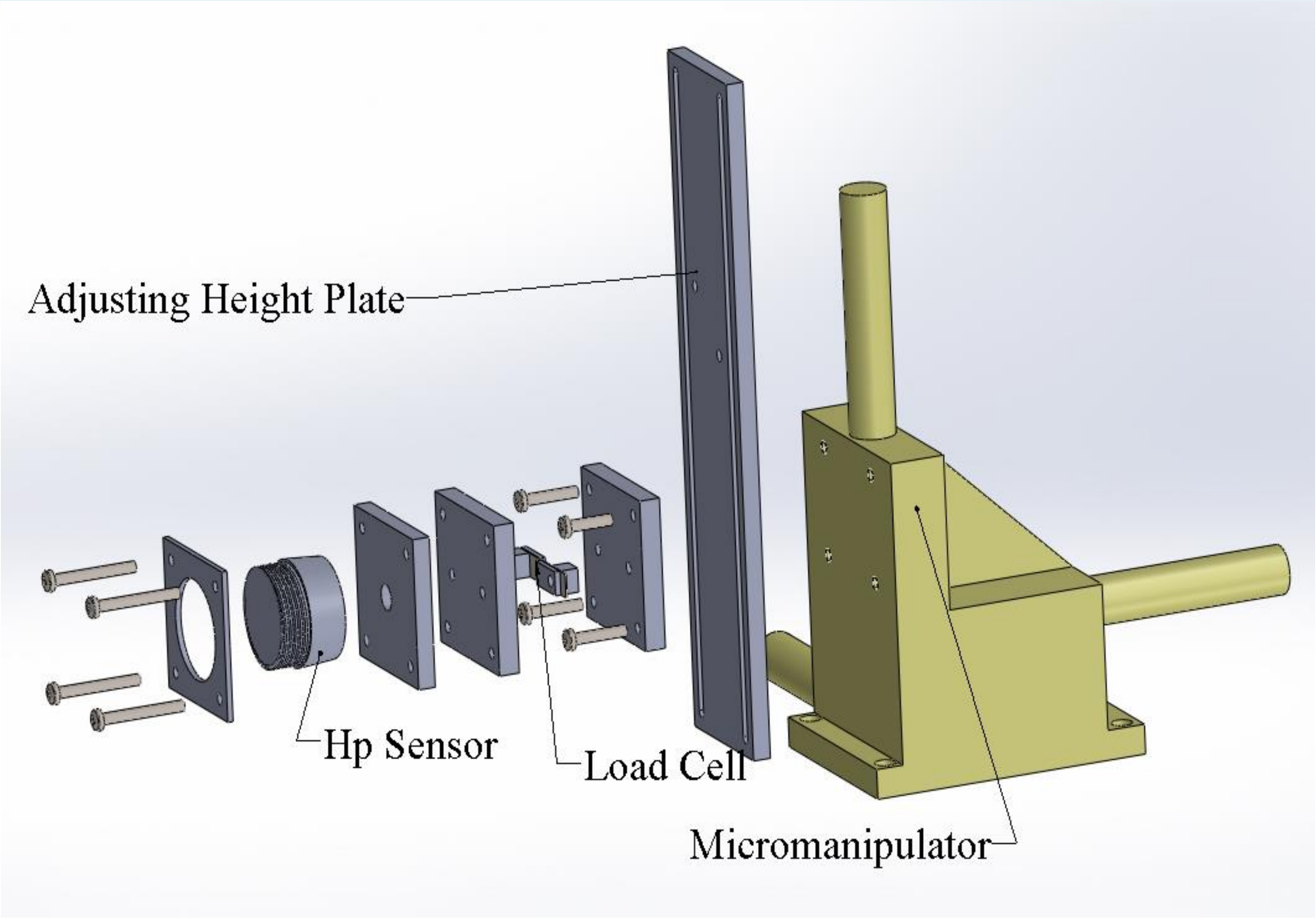
Bipac sensor attached to the Micromanipulaor

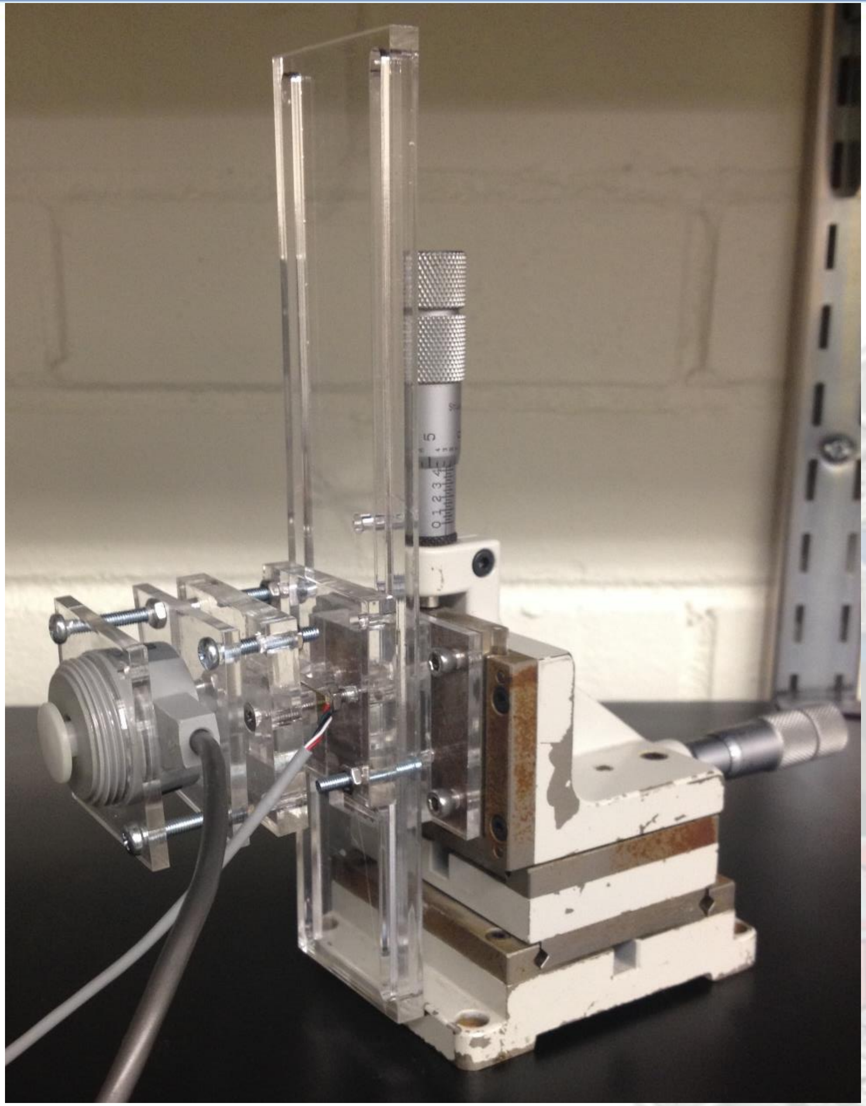




HP sensor attached to the Micromanipulaor

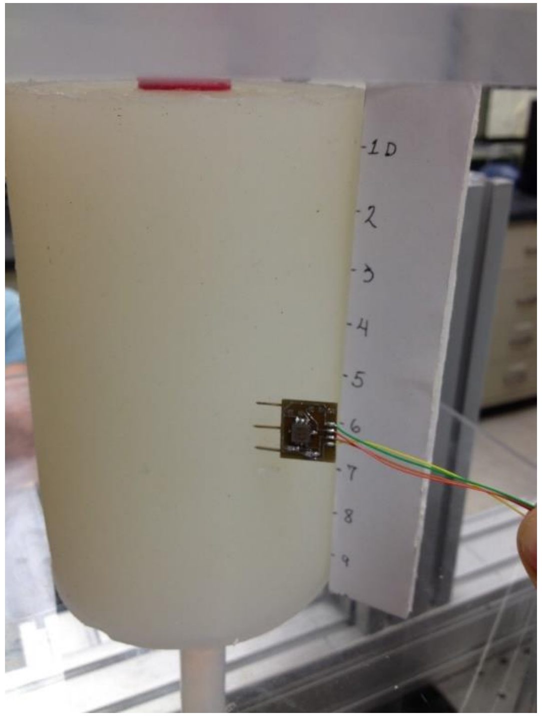
Micromanipulators

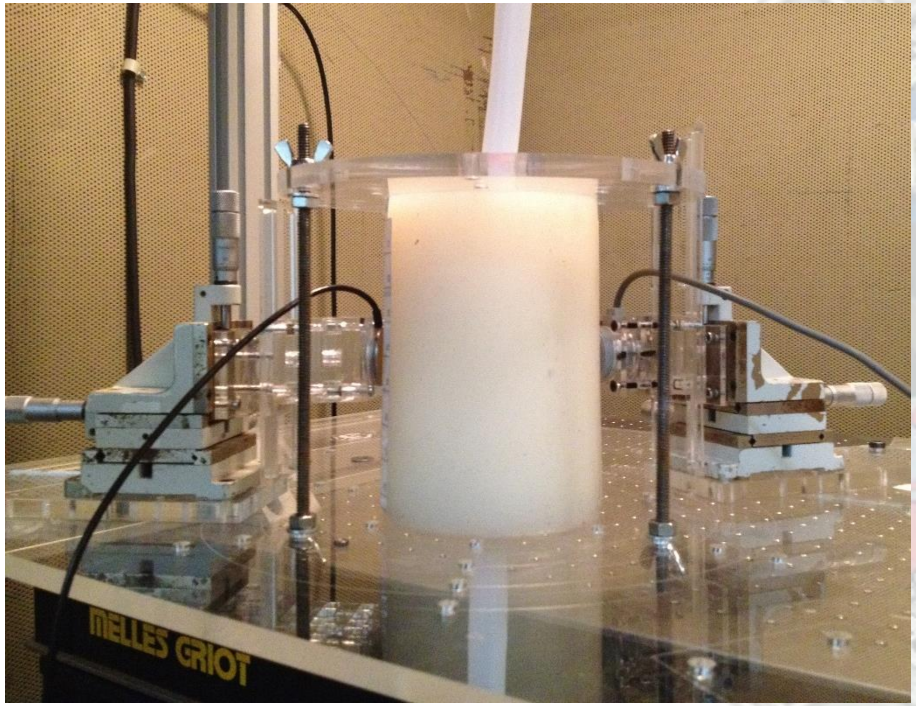




Measurements

- Different acoustic sensors used in the phantom tests.
  - A: Commercially available electronic stethoscope.
  - B: Accelerometers
  - C: HP 21050A sensor mounted on a micromanipulator.
  - D: Biopac sensors





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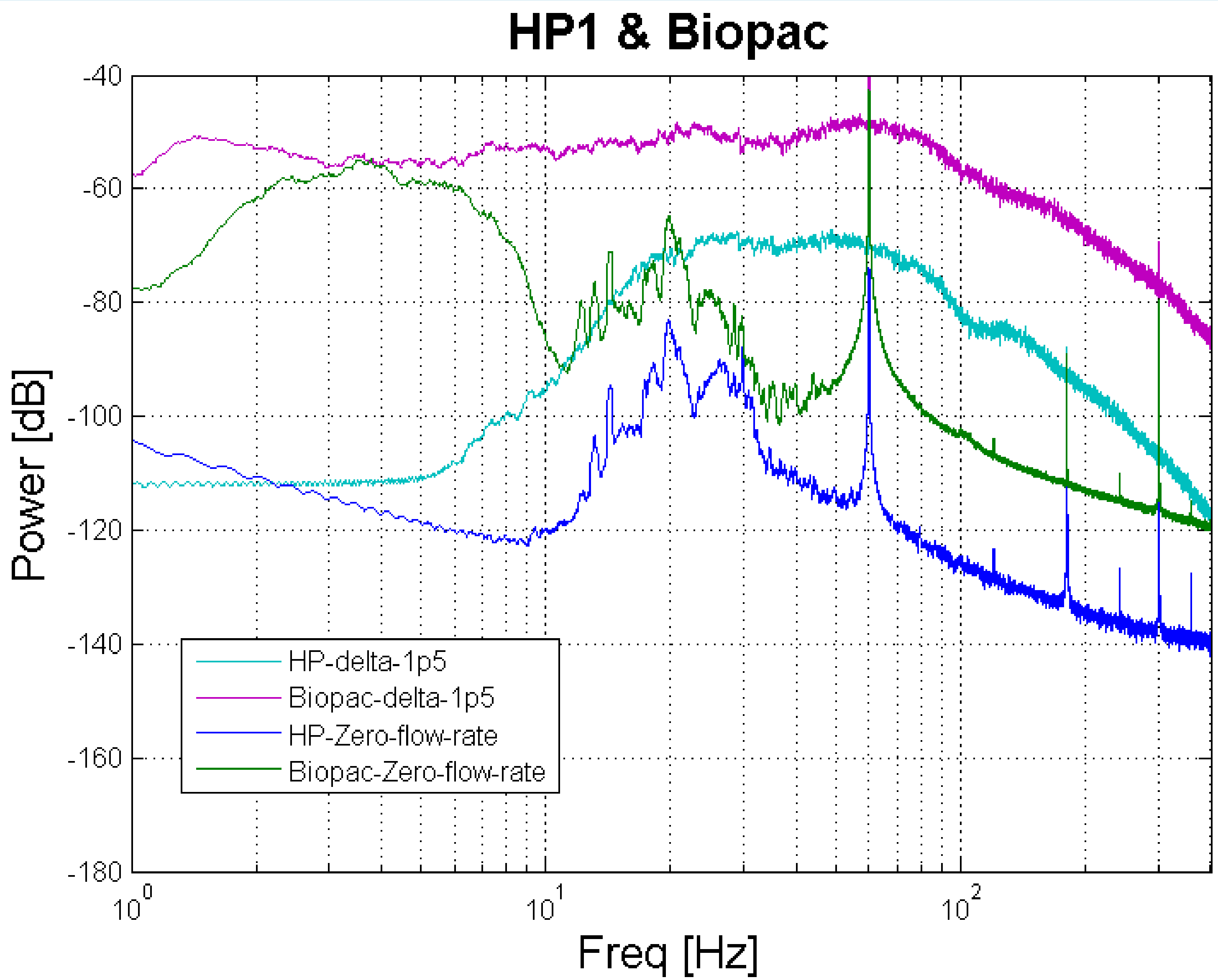
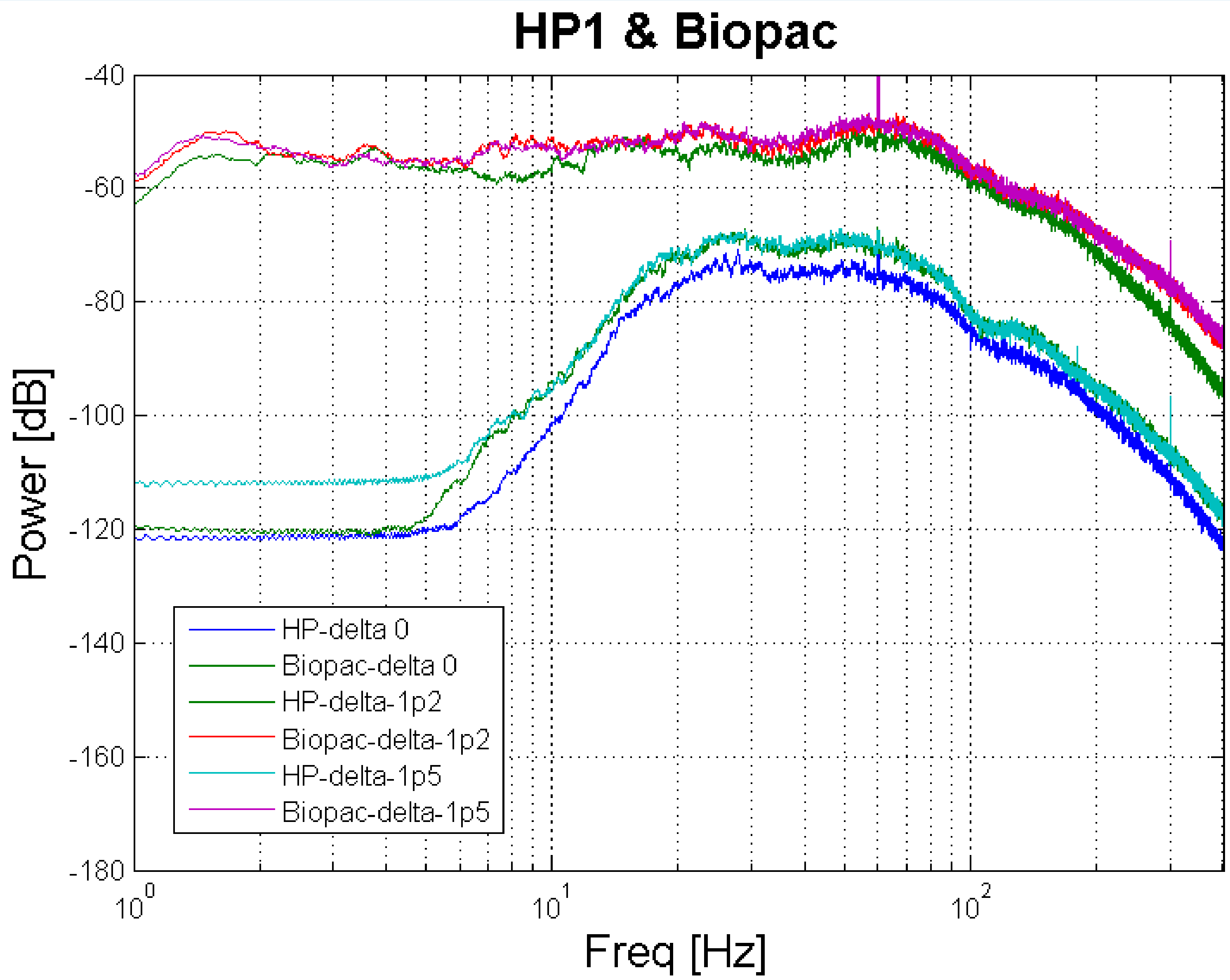
Sensor selection …



- Pump was turned on and off
- Clear difference between two diagrams for HP and Biopac
- Poor SNR for stethoscope and the accelerometer

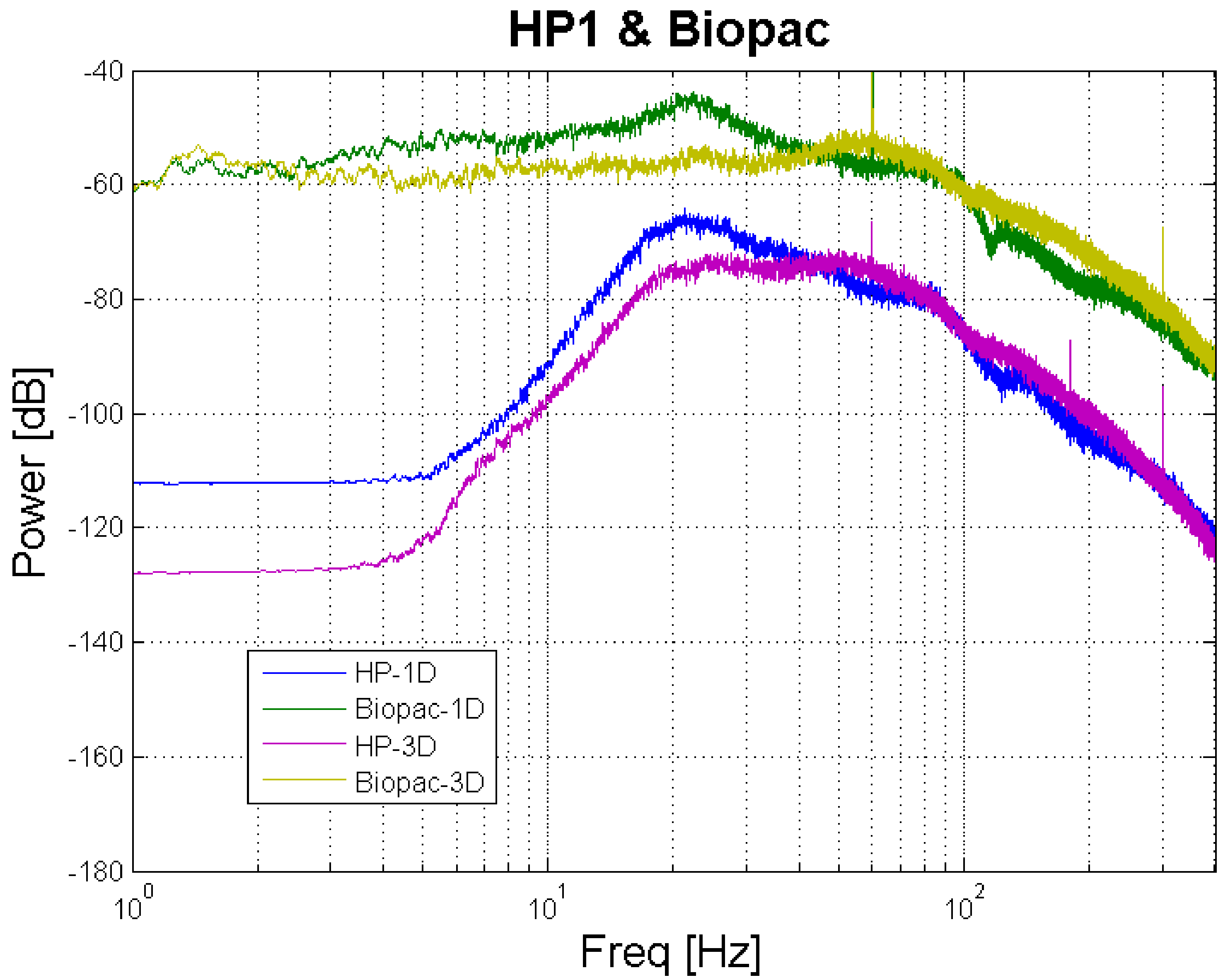
Effect of Indentation



To compare the effect of indentation :

- Reference position :Sensors touching the sample
- Gradual increase in the indentation
- Indentation = 0, 0.03, 0.06, 0.09, 0.12 and 0.15 in ~ 0 : 0.76 :3.81 mm
- After 0.12, no differences were observed

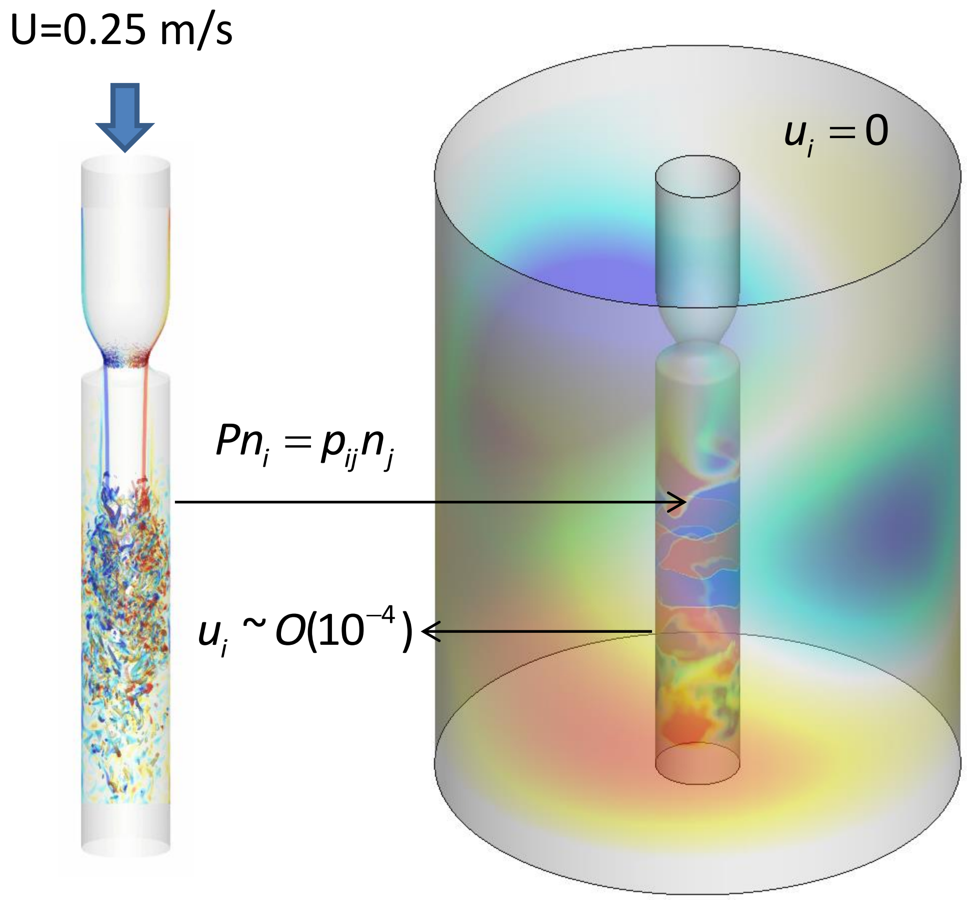
Distance after the constriction



Computational model

By Dr. Jung-Hee Seo

Hemoacoustic Simulation



Hemodynamics
IBM, Incompressible N-S

Structural wave eq.
For viscoelastic material

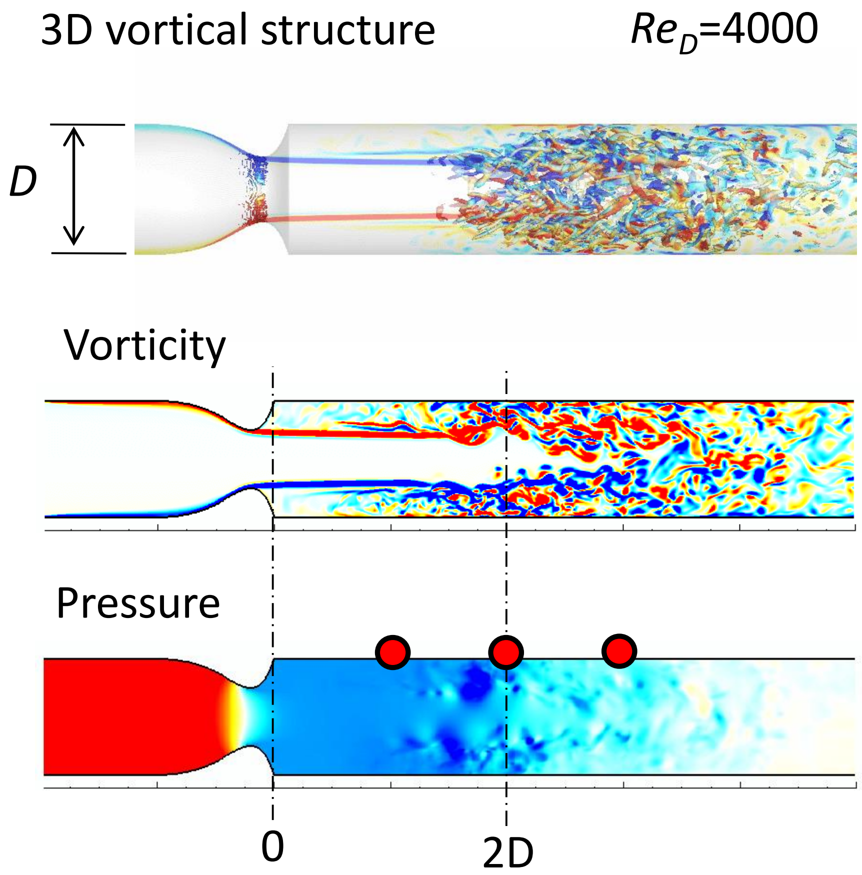
Generalized Hooke's law
Kelvin-Voigt model

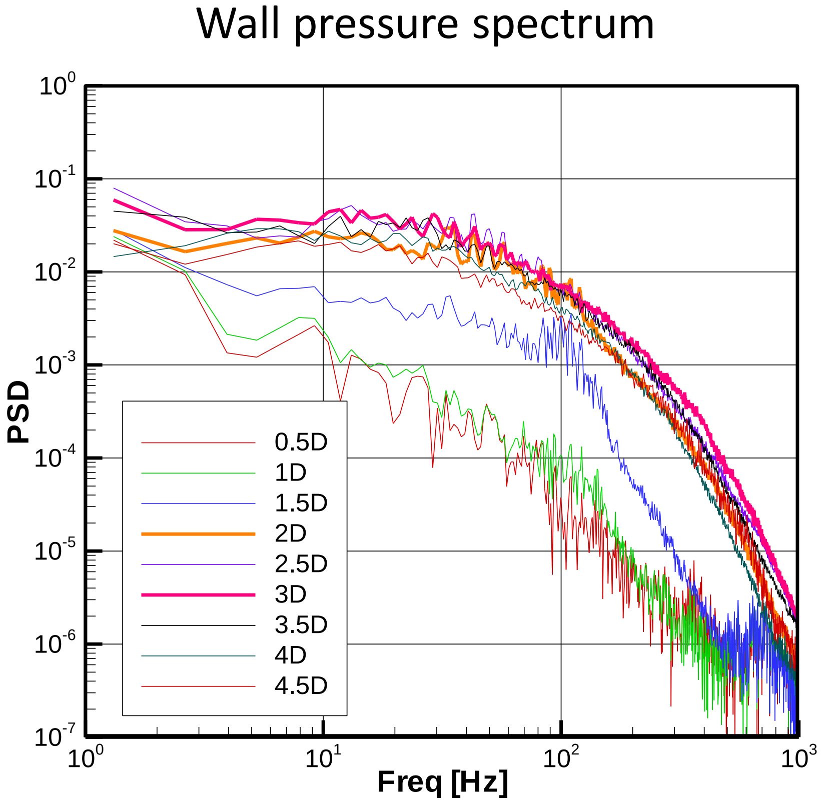
$$\frac{\partial p_{ij}}{\partial t} + \lambda \frac{\partial u_k}{\partial x_k} \delta_{ij} + \mu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) = 0$$

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

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

Hemodynamic Simulation Results

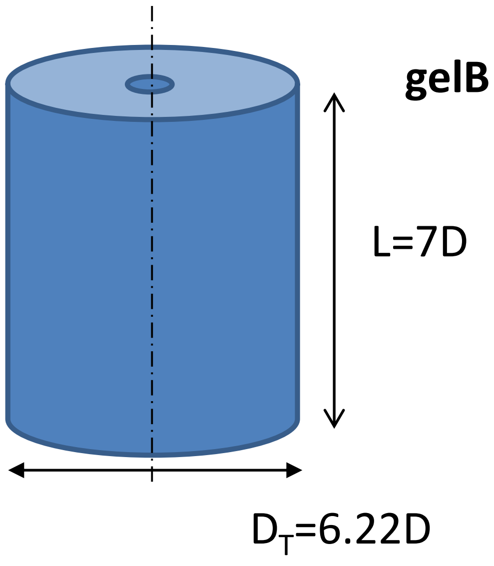




Pressure fluctuation is responsible for the murmur generation

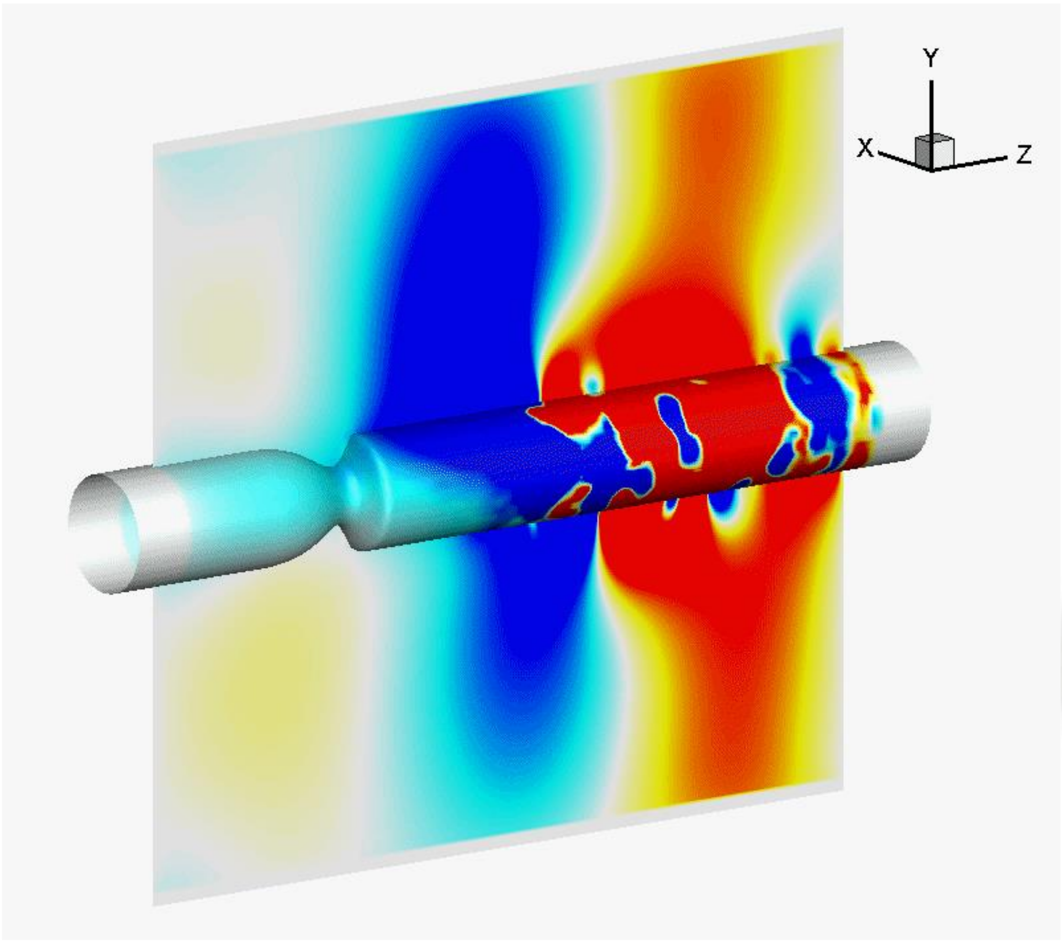
Strong pressure fluctuations are observed beyond 2D downstream of the stenosis

3D Elastic Wave Simulation

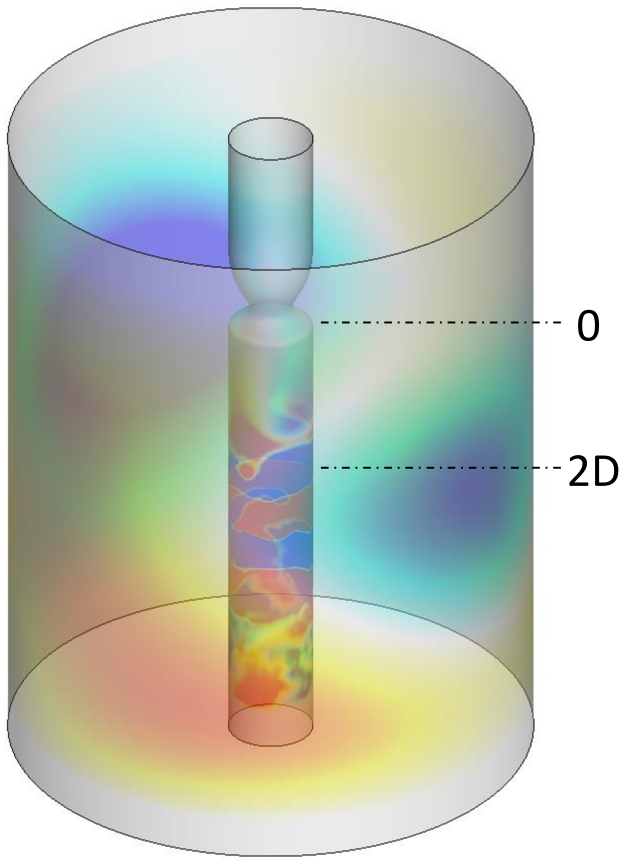


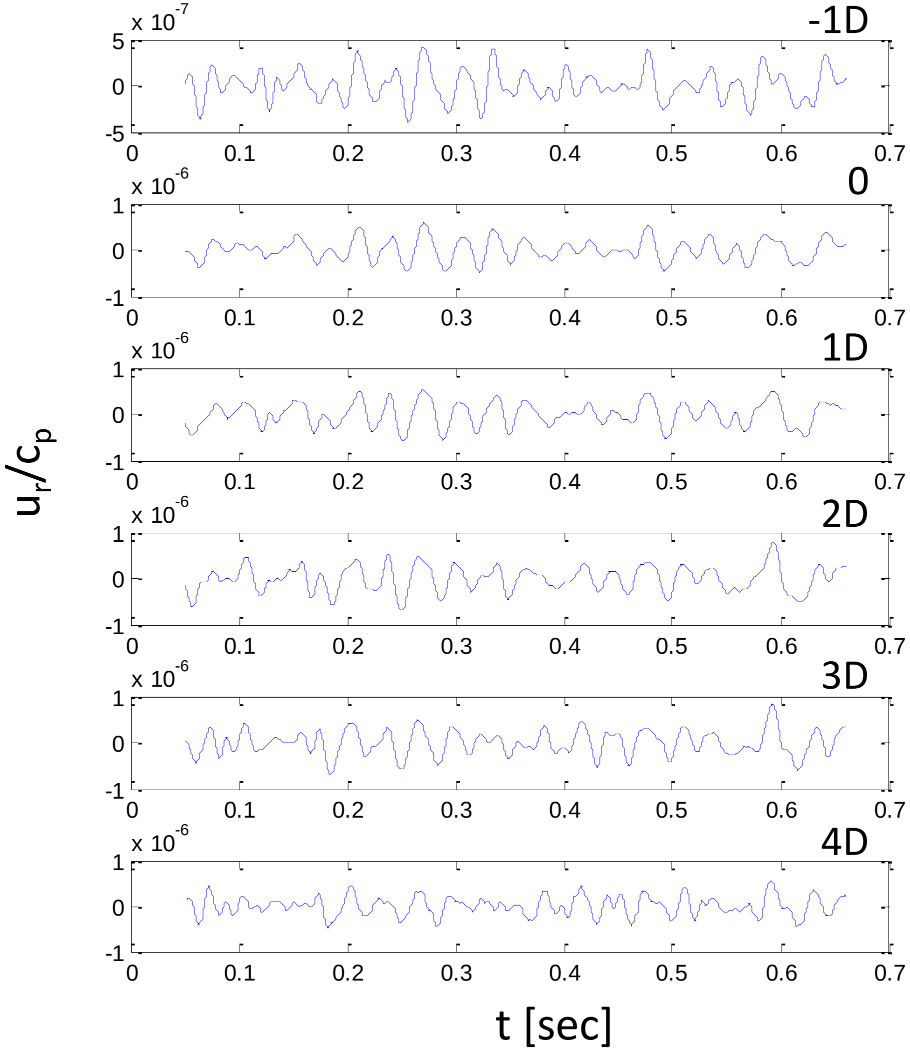
- 200x200x320 (12.8 M)
- Compression wave speed is reduced by an order (100 m/s)
- Shear wave speed remains the same (4.2 m/s)
- 200 hrs with 256 cores for real time 0.8 sec

Radial velocity fluctuation

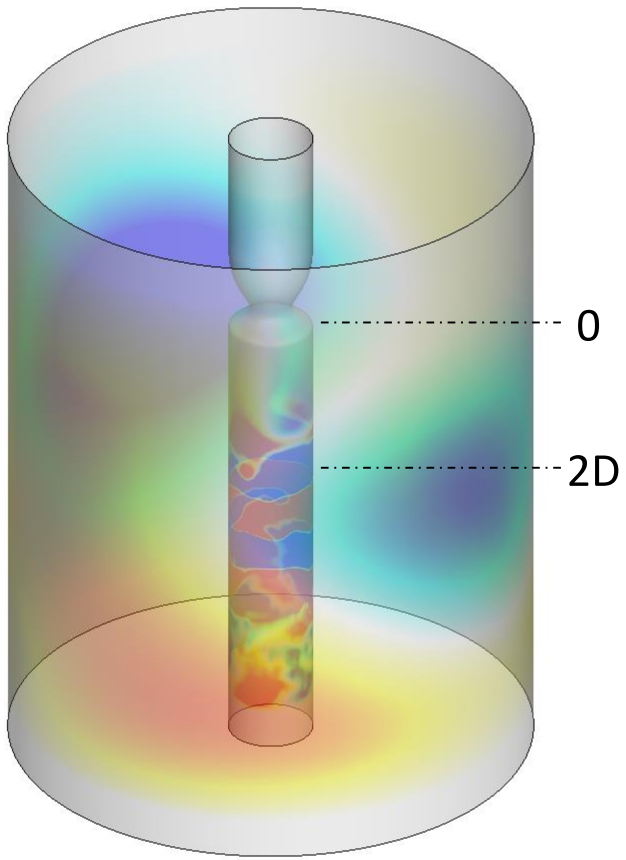


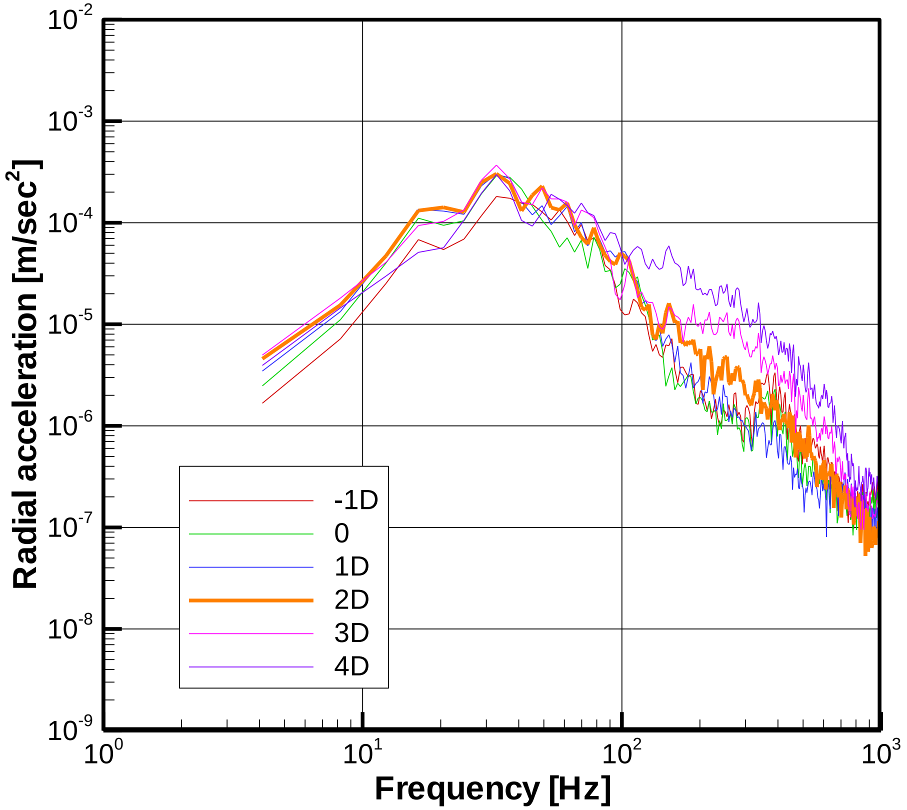
Surface Velocity Fluctuations





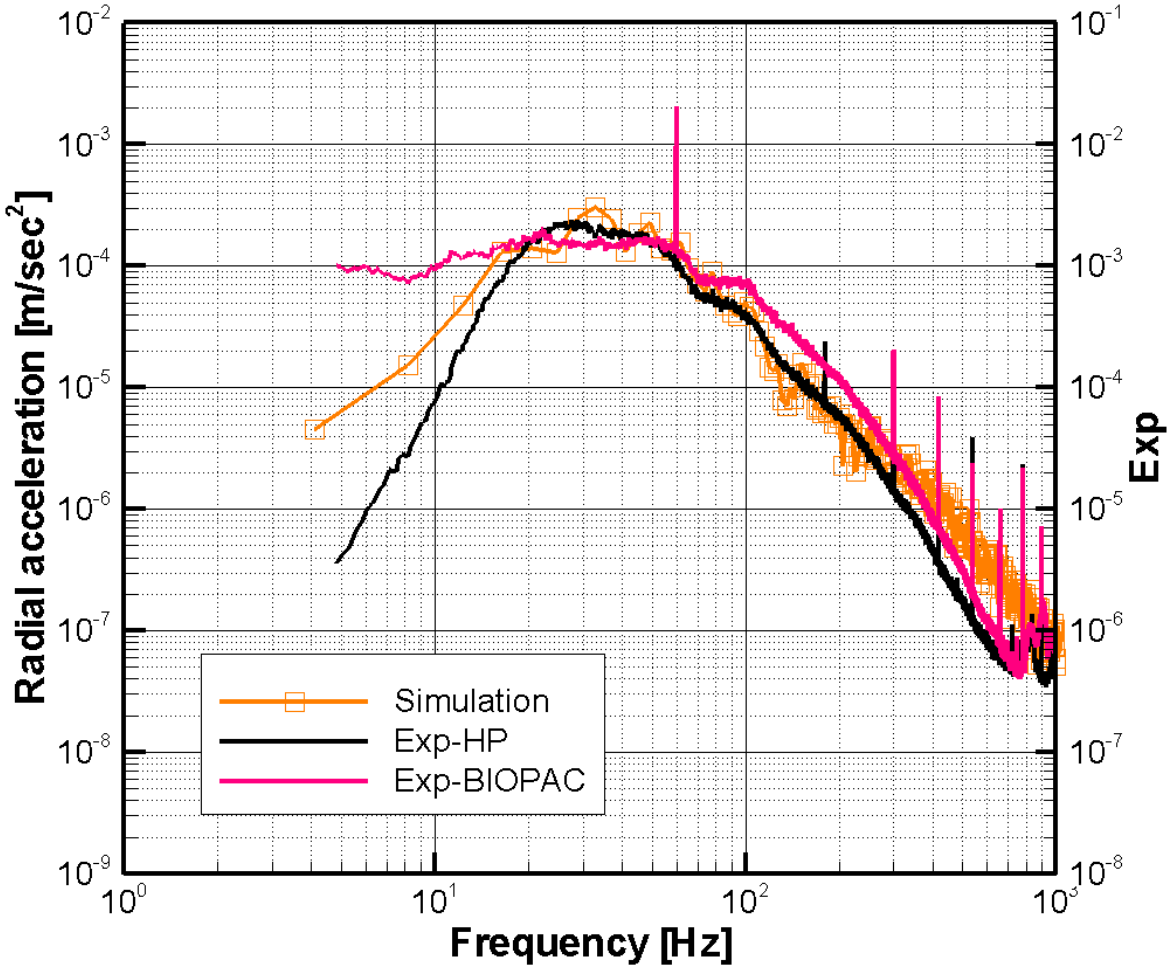
Surface Acceleration Spectrum





Comparison

- The frequency spectrum of the measured acceleration at the downstream location is plotted along with the computational ones



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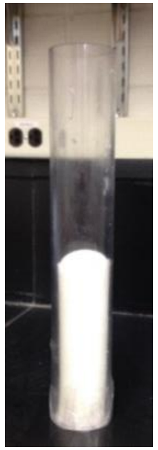
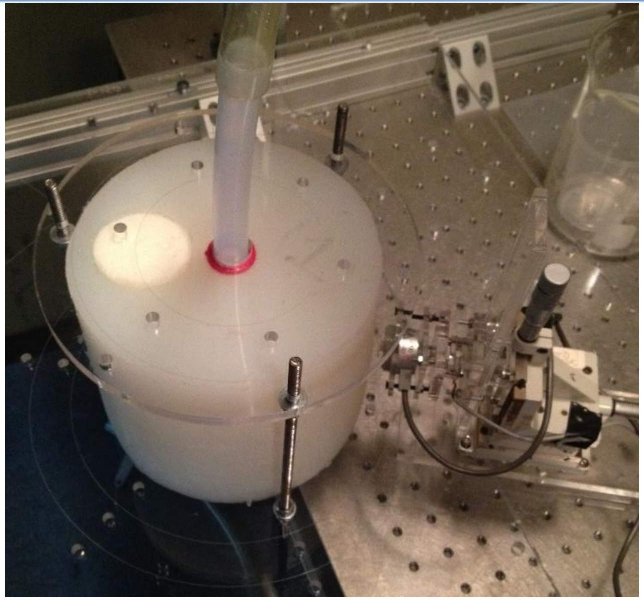
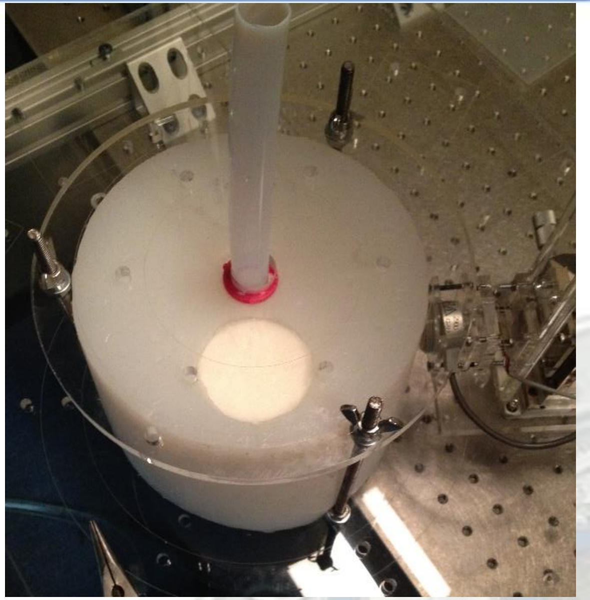
Future versions

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







Summary

- Different steps to make the Cardiothoracic phantom were explained
  - Material selection and characterization
  - Murmur generating embedded fluid-circuit
  - Measurements options

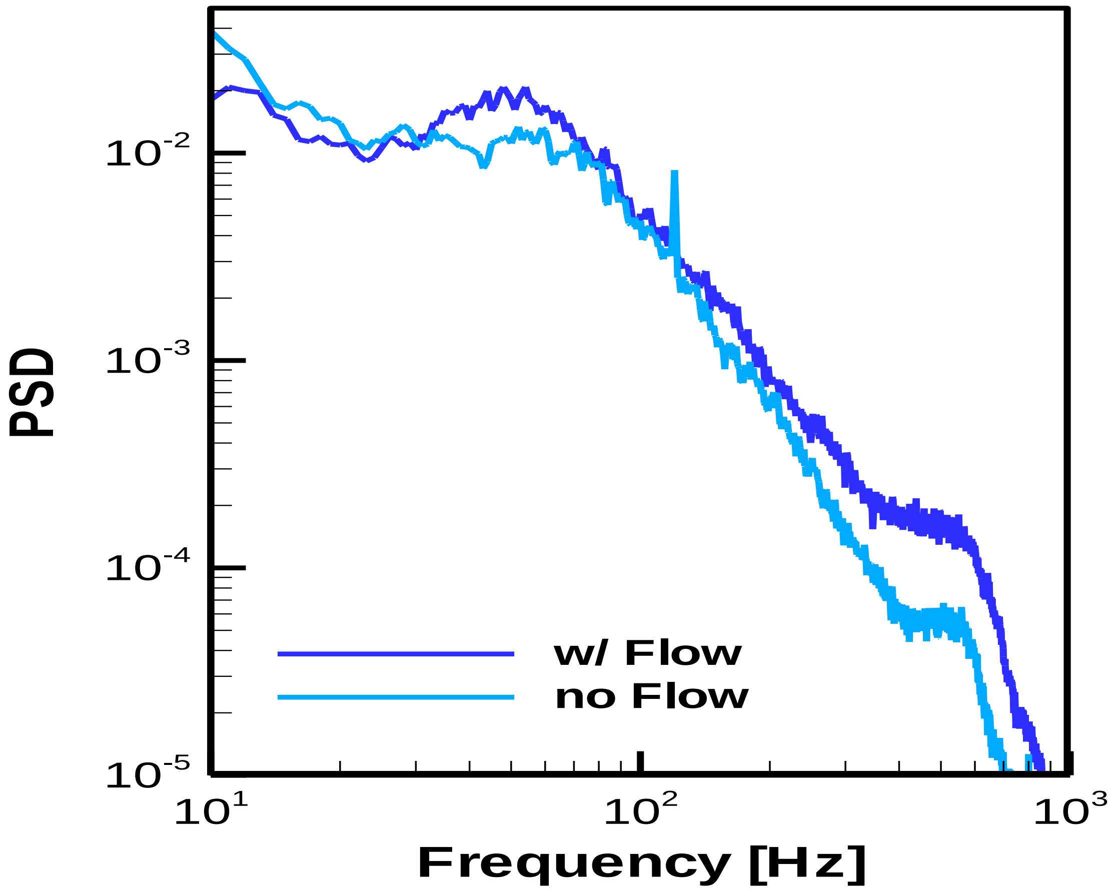
- Hemoacoustic simulation results were presented and compared with those from experiment
  - Good agreement was seen based on the preliminary results

Acknowledgment

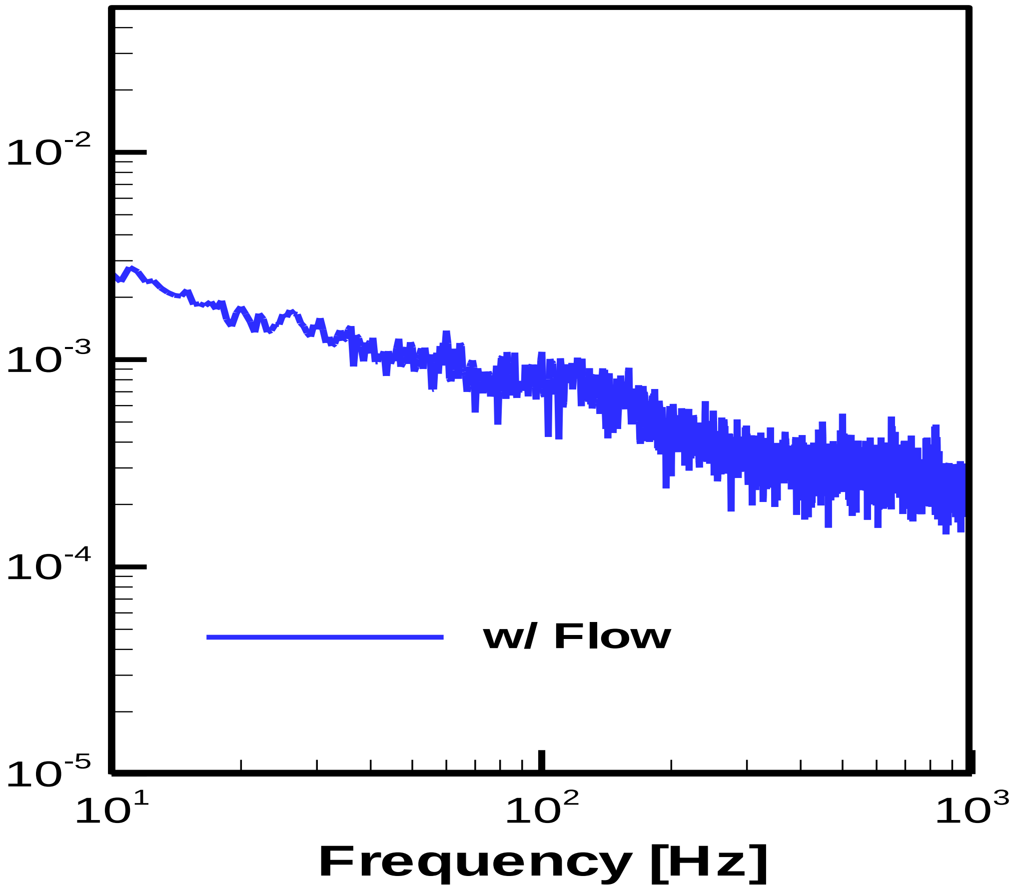
- Dr. Emad Boctor and Fereshteh Alamifar
- NSF for funding

Thank you

Sensor selection



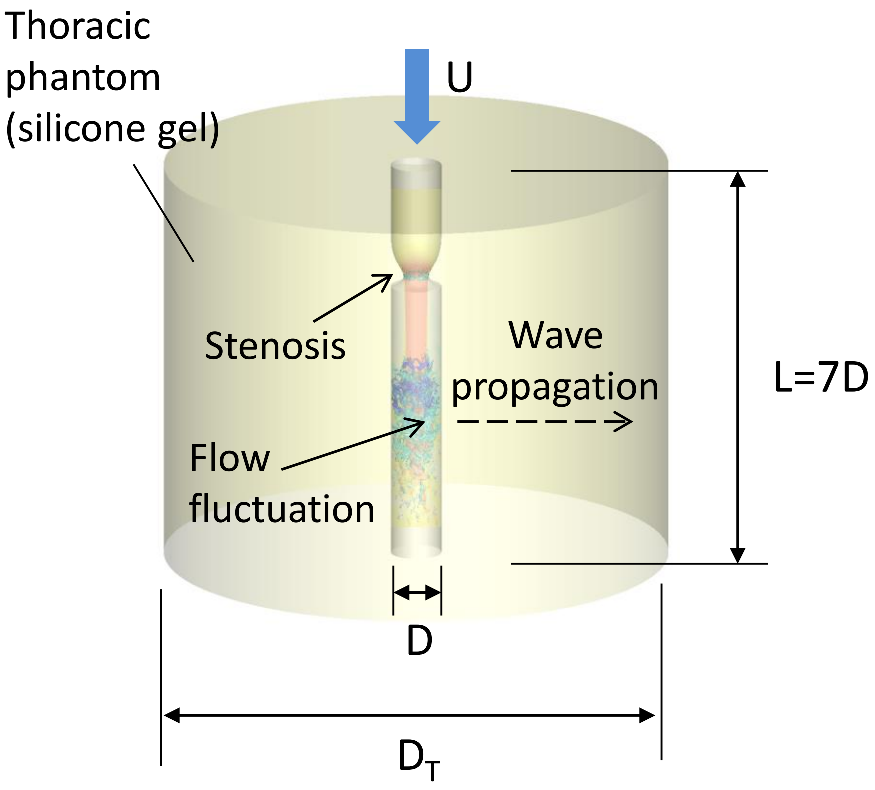
A: Electronic stethoscope



B: Accelerometers

Model for the Aortic Stenosis Murmur

For the joint computational/experimental study



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

EcoFlex-10

$\rho=1040\ kg/m^3$
$K=1.04\ GPa\ \ (c_b=1000.0\ m/s)$
$G=18.39\ kPa\ \ (c_s=4.2\ m/s)$
$\mu=14\ Pa\ s$

$U=0.25\ m/s$
$D=1.5875\ cm$
$D_T=9.84\ cm$ (gelA), $16.51\ cm$ (gelB)

c.f.
Biological soft tissue:
$K=2.25\ GPa\ (c_b=1500\ m/s)$
$G=0.1\ MPa\ (c_s=10\ m/s)$
$\mu=0.5\ Pa\ s$