# Mapping the Cardiac Acousteome: Biosensing and Computational Modeling Applied to Smart Diagnosis and Monitoring of Heart Conditions

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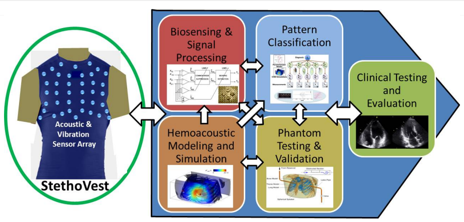
## Motivation

- **Cardiac Auscultation:** science and art of diagnosing heart conditions via the stethoscope
- Potent, non-invasive diagnostic modality limited by:
  - incomplete understanding between cause effect (sound)
  - human-in-the-loop
  - sequential (uni-site) measurement technique
  - high level of noise
  - large array of heart sounds
  - declining auscultatory skills [1]

- **Vision:** Rescue this valuable diagnostic modality from obsolescence by deploying new tools and ideas from computational science, biosensing and signal processing.

## Objectives




**Goal: Develop an approach to automated heart sound measurement and localization via a compact acoustic sensor array (the "StethoVest")**

1. Develop image-based computational hemoacoustic models (CHM).
2. Validate CHMs and develop/test generative (model based) statistical pattern recognition algorithms for abnormal heart conditions using thoracic phantoms.
3. Investigate the physics of murmurs associated with aortic valve (AV) disease using integrative biosensing-CHM approach.
4. Evaluate acousteome-map based screening for hypertrophic obstructive cardiomyopathy (HOCM)

## Impact

- Revolutionize the management of heart disease
  - Inexpensive, non-invasive, accurate
  - Screening of wide range of heart conditions
  - 24/7 continuous, at-home health monitoring
  - Deployable in rural and underserved areas
  - Leverages telemedicine, bioinformatics & wearable sensor revolution
  - Health care: reactive, expensive and hospital-centric → smart, proactive, patient-centric and cost-effective
- Advance medicine, mechanics and modeling, computing, electrical engineering, biosensing, and BIGDATA science.
- Training of undergraduates, graduate students and postdocs in a highly cross-disciplinary environment

## Technical Approach

### Team

**W. Reid Thompson (MD)**
**Theodore Abraham (MD)**
*Cardiologists*
Clinical studies and measurements

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**Rajat Mittal (PhD)**
*Mechanical Engineering*
Computational & experimental modeling and analysis

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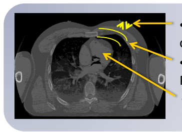
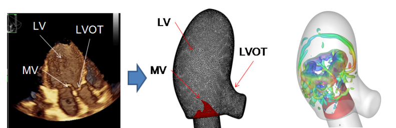
**Andreas Andreou (PhD)**
*Electrical Engineering*
Sensors, signal processing and pattern classification

### High-Fidelity Hemoacoustic Modeling and Simulation

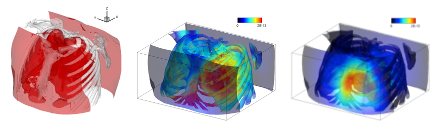
- Biophysics of auscultation involves
  - flow perturbation
  - propagation of acoustic wave through thorax (lung, bone, muscle, fat)
  - sensing by stethoscope
- Integrated multiphysics analysis required to understand the physical based of auscultation



- Surface fluctuation on the chest
- Structural wave Propagation
- Pressure Fluctuation in the Heart




3D Echo | Computational heart model | Hemodynamic simulation



Thorax model derived from the CT scan data | Simulated acoustic pressure distribution | Simulated acoustic velocity distribution

**Coupled flow and wave propagation simulations [2]**

**Incompressible Navier-Stokes equations**

$$\nabla \cdot \vec{U} = 0$$

$$\frac{\partial \vec{U}}{\partial t} + (\vec{U} \cdot \nabla)\vec{U} + \frac{1}{\rho_0}\nabla P = \nu_0 \nabla^2 \vec{U}$$

⬇ Flow simulation results are supplied as BC or source term

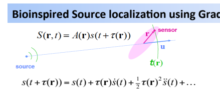
**Linear viscoelastic structural wave equations**

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

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

### Sound Measurement, Localization and Pattern Classification

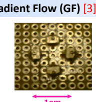
**Bioinspired Source localization using Gradient Flow (GF) [3]**



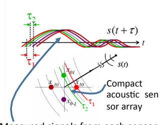

$$S(r,t) = A(r)s(t + \tau(r))$$

$$s(t + \tau(r)) = s(t) + \tau(r)\dot{s}(t) + \tfrac{1}{2}\tau(r)^2\ddot{s}(t) + \ldots$$

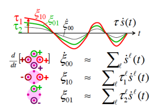
Time delayed source of traveling wave is separated into a static mixtures of the time-differentiated sources



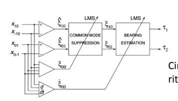

Sub-wavelength scale acoustic senor array




Measured signals from each sensor



Identification of mixture coefficients using the spatial and temporal gradients



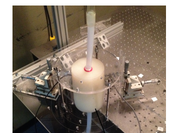
Circuit for the GF algorithm

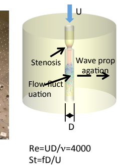
**Characterizing different sensors [4]**

| Transducer | HP 21050A | TSD 108 | MA 250 | TH 306 | DS32a |
|---|---|---|---|---|---|
| Photograph |  |  |  |  |  |
| Manufacturer | Hewlett Packard | BIOPAC | Fukuda Denshi | Fukuda Denshi | ThinkLabs |
| Physical Dimensions (mm) | D : 28<br>H : 29 | D : 29<br>H : 6 | D : 25<br>H : 20 | D : 35<br>H : 24 | D : 50<br>H : 40 |
| Bandwidth (Hz) | 0.02 – 2000 | 35 – 3500 | 20 – 600 | 0.04 – 300 | 20 - 2000 |

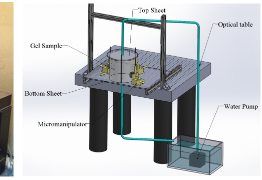
## Year Two Progress

### Experimental Study [4]



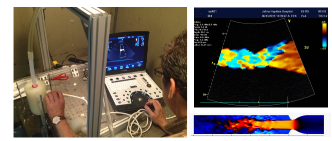



Generation-1 Thoracic phantom (silicone gel)




Experimental Set-up

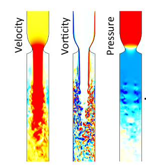
**Future/Ongoing experimental studies**



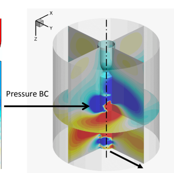
Ultrasound Doppler Imaging vs CFD results

Generation-2 Thoracic phantom (silicone gel and Foam) Modeling tissue and lung

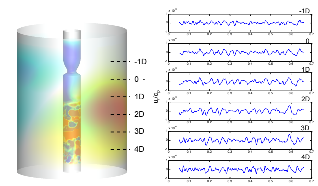
### Computational Modeling



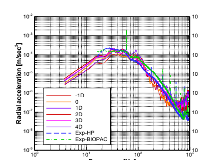

Flow simulation



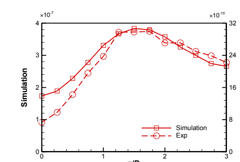

Generation-1 model for the thoracic phantom




Monitored surface vibrations




Comparison of Frequency Spectra




Energy mapping at different locations downstream of the constriction

## References & Misc. Information


**References**

1) Kumar K, Thompson WR. Evaluation of cardiac auscultation skills in pediatric residents. *Clin. Pediatr* (Phila). 2013 Jan; 52(1):66-73. doi: 10.1177/0009922812466584. Epub 2012 Nov 26.
2) Seo, J. H. and Mittal, R. (2011) A High-order Immersed Boundary Method for Acoustic Wave Scattering and Low-Mach Number Flow-Induced Sound in Complex Geometries, *J. Comput. Phys*. Vol. 230, 1000-1019.
3) Julian P, Andreou AG et al (2004) A comparative study of sound localization algorithms for energy aware sensor network nodes, *IEEE Trans Circuits Syst I*: Reg Papers, 51(4):640-648.
4) Bakhshaee H, Garresu G et al, Mechanical design, instrumentation and measurements from a hemoacoustic cardiac phantom, DOI: 10.1109/CISS.2015.7086901



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**Undergrad Students:** Nate Welsh

**Project homepage:** http://engineering.jhu.edu/fsag/nsf_sch_project_homepage/