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

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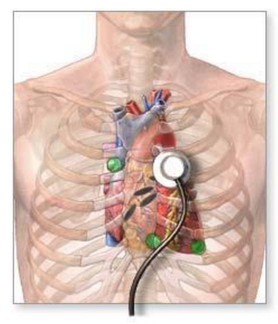
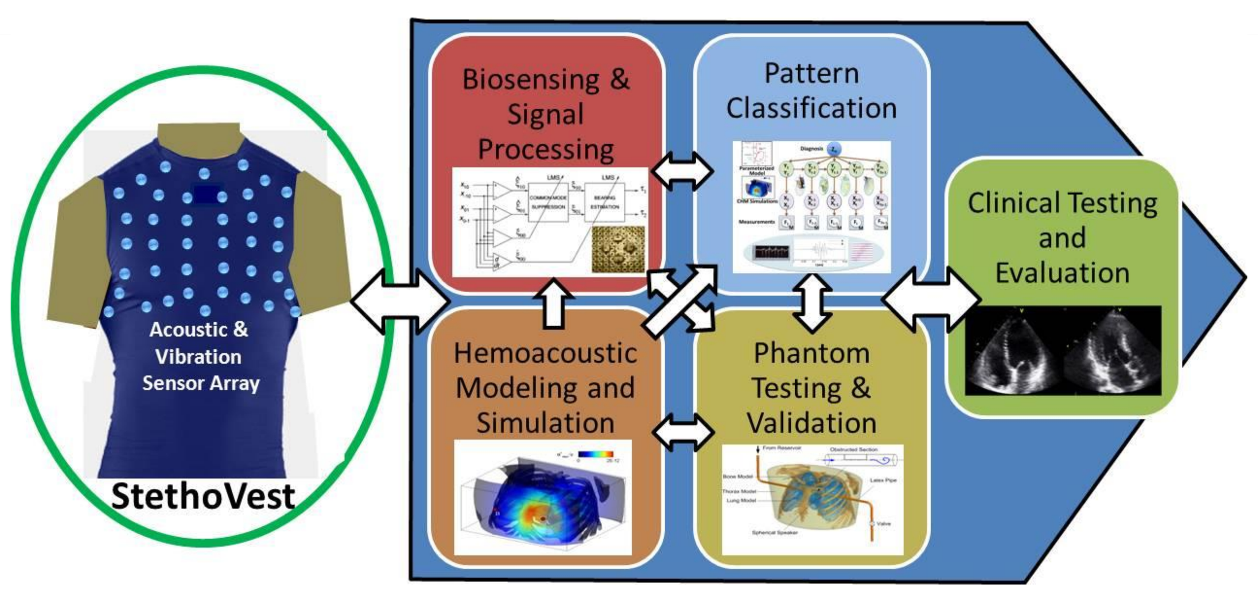
Motivation

- **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

⇔

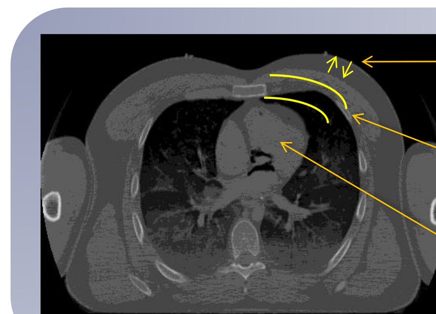
Rajat Mittal (PhD)
Mechanical Engineering
Computational & experimental modeling and analysis

⇔

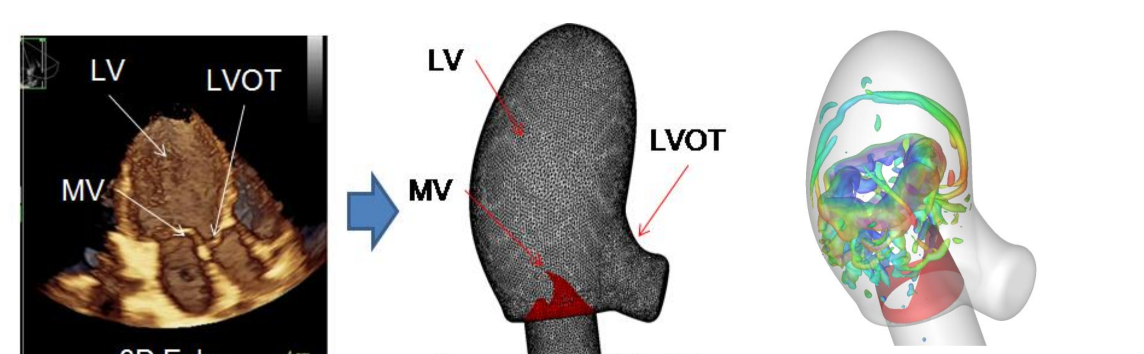
Andreas Andreou (PhD)
Electrical Engineering
Sensors, signal processing and pattern classification

High-Fidelity Hemoacoustic Modeling and Simulation

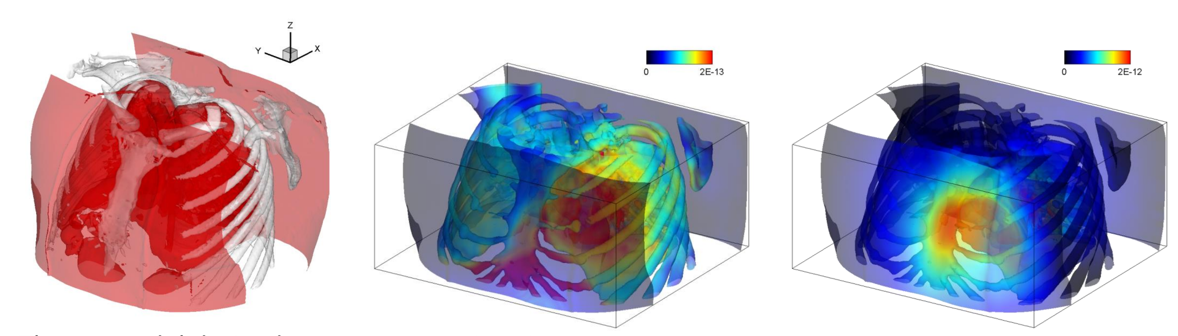
- Biophysics of auscultation involves
  - flow perturbation
  - propagation of acoustic wave through thorax (lung, bone, muscle, fat)
  - sensing by stethoscope
- Integrated multiphysics analysis required to understand the physical based of auscultation



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



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

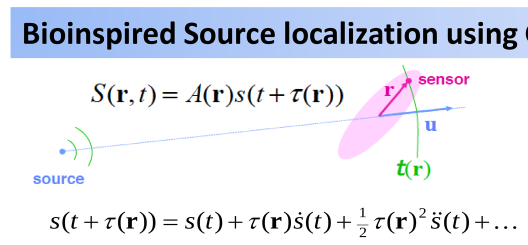
Linear viscoelastic structural wave equations

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

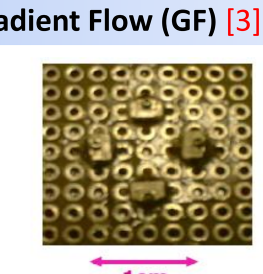
$$\frac{\partial u_i}{\partial t} + \frac{1}{\rho}\frac{\partial p_{ij}}{\partial x_j} = \frac{\eta}{\rho}\frac{\partial}{\partial x_j}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) + f_i$$

Sound Measurement, Localization and Pattern Classification

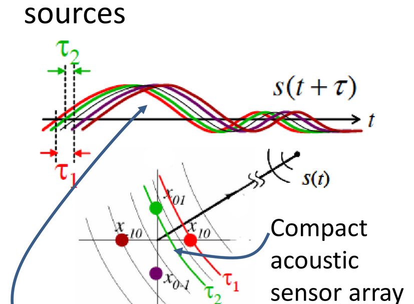
Bioinspired Source localization using Gradient Flow (GF) [3]



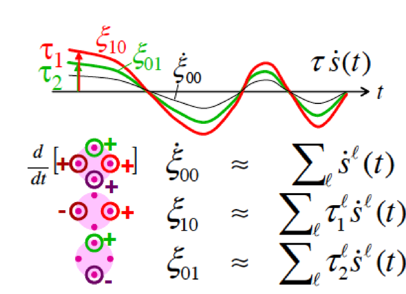
Time delayed source of traveling wave is separated into a static mixtures of the time-differentiated sources



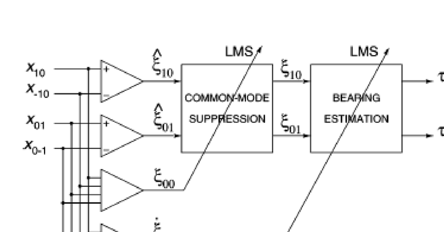
Sub-wavelength scale acoustic senor array



Measured signals from each sensor



Identification of mixture coefficients using the spatial and temporal gradients



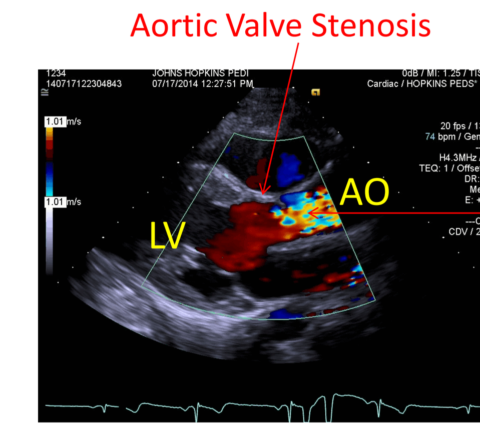
Circuit for the GF algorithm

Sensor characterization

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 H : 29	D : 29 H : 6	D : 25 H : 20	D : 35 H : 24	D : 50 H : 40
Bandwidth (Hz)	0.02 – 2000	35 – 3500	20 – 600	0.04 – 30 0	20 - 2000

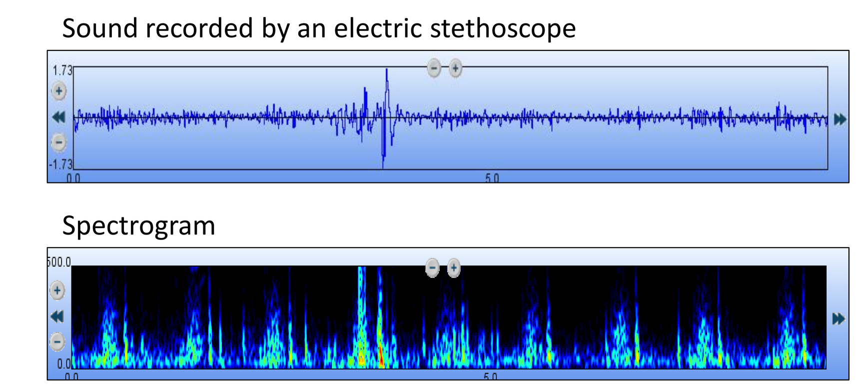
Current Progress

Aortic Stenosis Murmur



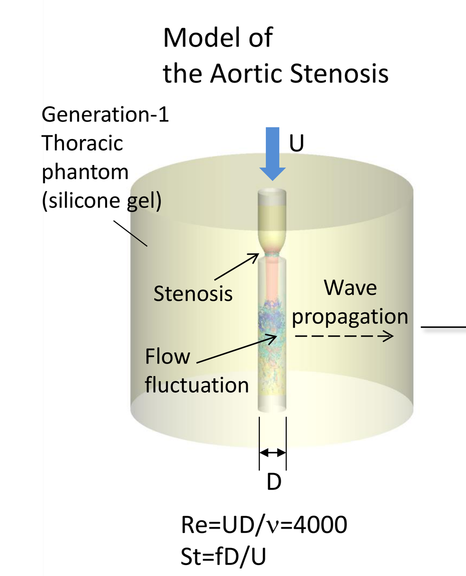
Blood flow fluctuation generates abnormal heart sound

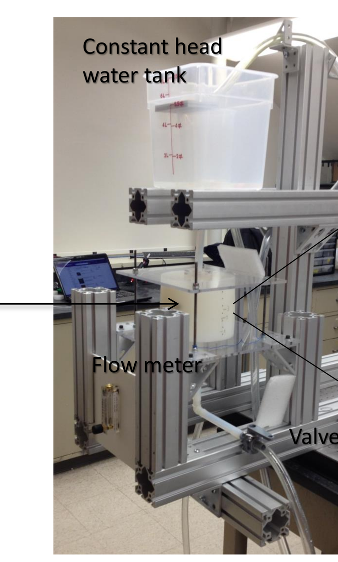
In-vivo Echocardiography

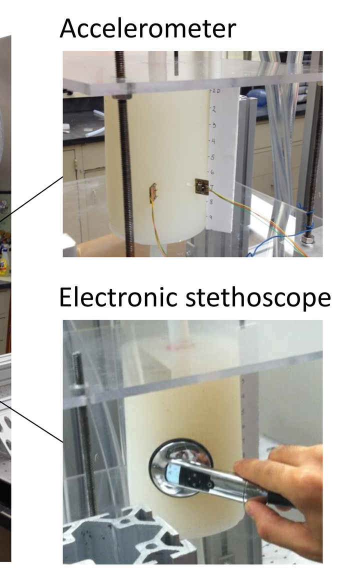


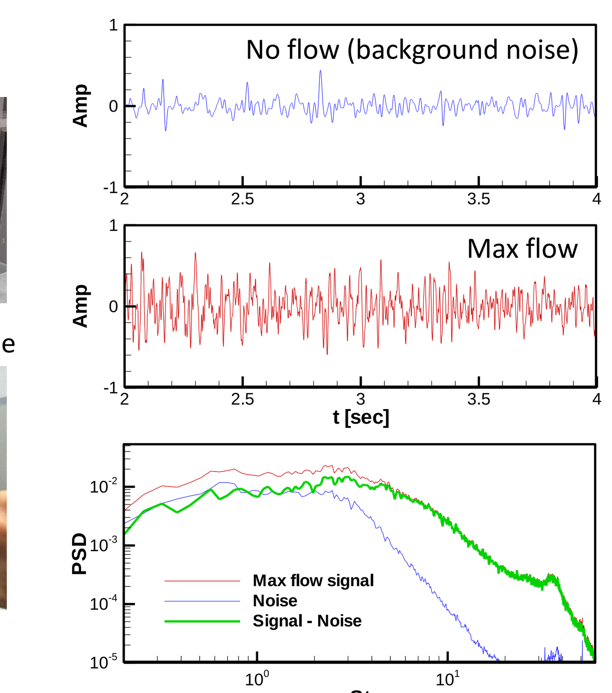
In-vivo Phonocardiography

Experimental Modeling

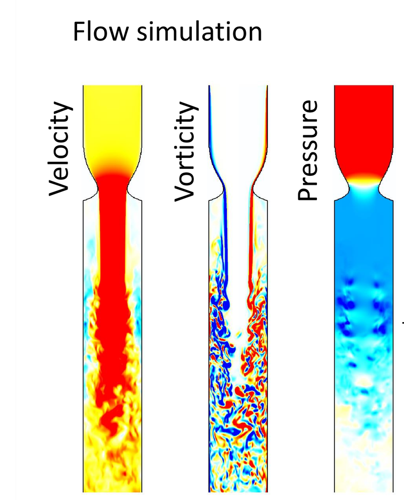


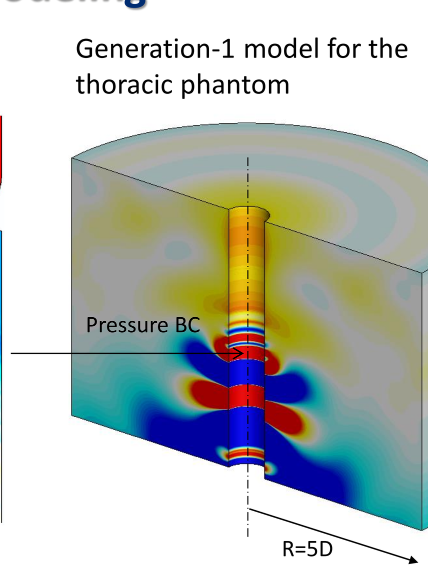


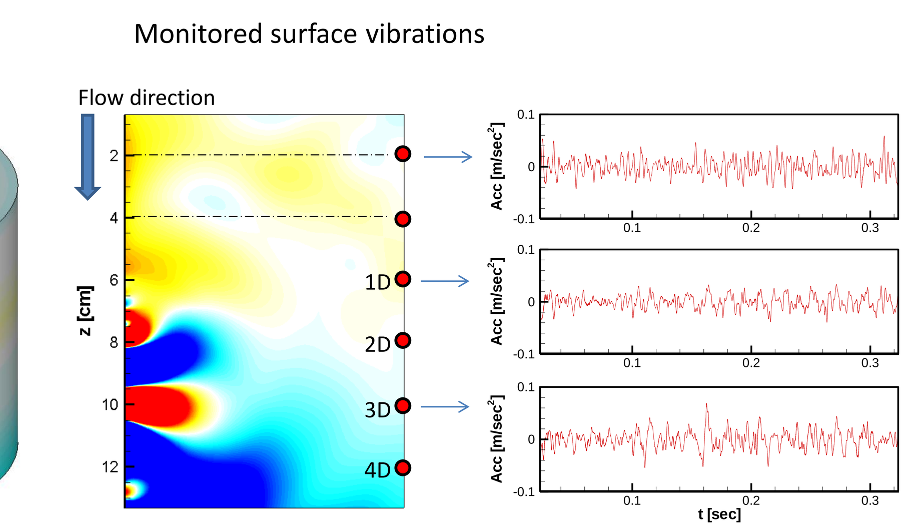


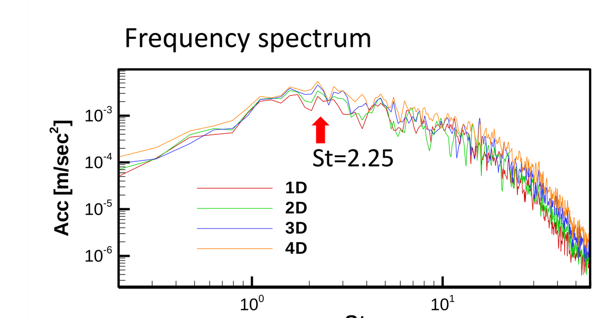


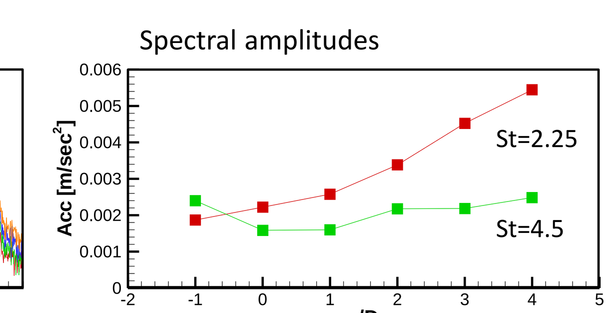
Computational Modeling

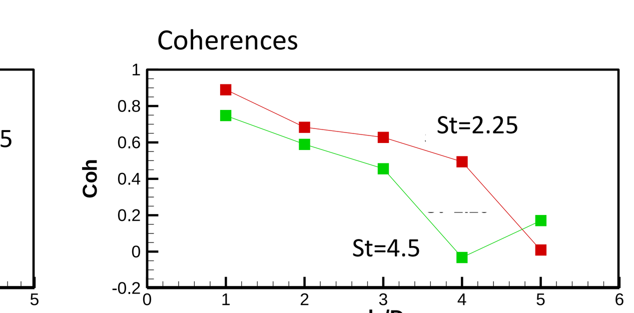












References & Misc. Information

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, Riddle L, Shamma SA, Goldberg DH, and Cauwenberghs G (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.

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Undergrad Students: Thomas Kilmer, Alexandre Laloum, Ronann Carrero

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