Mechanical Design, Instrumentation and Measurements from a Hemoacoustic Cardiac Phantom

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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)
### 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.

<table>
<thead>
<tr>
<th>Material</th>
<th>Velocity, $c_S$ (10³ m s⁻¹)</th>
<th>Density, $\rho$ (10³ kg m⁻³)</th>
<th>Impedance $z$ (10⁶ kg m⁻² s⁻¹)</th>
<th>Acoustic attenuation coefficient, $\alpha$ (dB cm⁻¹)</th>
<th>Frequency (MHz)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Human breast tissue</td>
<td>1.43–1.57</td>
<td>0.99–1.06</td>
<td>1.42–1.66</td>
<td>9.5–12.6</td>
<td>7</td>
<td>Duck 1990</td>
</tr>
<tr>
<td>Human skin</td>
<td>1.54ᵃ</td>
<td>1.11–1.19</td>
<td>1.71–1.83</td>
<td>9.2 ± 2.2</td>
<td>5</td>
<td>Duck 1990</td>
</tr>
<tr>
<td>Silicone</td>
<td>1.03 ± 0.06⁵</td>
<td>1.07 ± 0.03</td>
<td>1.10 ± 0.05⁶</td>
<td>14.0 ± 1.4</td>
<td>5</td>
<td>our measurement</td>
</tr>
<tr>
<td>PVA</td>
<td>1.57 ± 0.02⁶</td>
<td>1.10 ± 0.05</td>
<td>1.74 ± 0.08⁶</td>
<td>2.9 ± 0.1</td>
<td>5</td>
<td>our measurement</td>
</tr>
<tr>
<td></td>
<td>1.58 ± 0.03</td>
<td>1.07 ± 0.02</td>
<td>1.71 ± 0.06</td>
<td>3.2 ± 0.1</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>PAA (10%)</td>
<td>1.58 ± 0.05⁶</td>
<td>1.09 ± 0.09</td>
<td>1.73 ± 0.08⁶</td>
<td>0.7 ± 0.1</td>
<td>5</td>
<td>Kharine et al 2003</td>
</tr>
<tr>
<td></td>
<td>–</td>
<td>1.02 ± 0.01</td>
<td>–</td>
<td>0.4 ± 0.1</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Agar 2%</td>
<td>1.50 ± 0.03⁶</td>
<td>1.04 ± 0.11</td>
<td>1.57 ± 0.08⁶</td>
<td>0.4 ± 0.1</td>
<td>5</td>
<td>Prokop et al 2003</td>
</tr>
<tr>
<td></td>
<td>1.54</td>
<td>–</td>
<td>–</td>
<td>0.5 ± 0.1</td>
<td>7</td>
<td>Browne et al 2003</td>
</tr>
</tbody>
</table>
### Table 1. Soft materials used in the study.

<table>
<thead>
<tr>
<th>Material, manufacturer, city, state</th>
<th>Density (g ml(^{-1}))</th>
<th>Softener volume range(^a)(%)</th>
<th>Modulus range(^a) (kPa)</th>
<th>Approximate cost per gallon</th>
</tr>
</thead>
<tbody>
<tr>
<td>SR-1610, Douglas and Sturgess, San Francisco, CA</td>
<td>1.15</td>
<td>0–58(^b)</td>
<td>25–660</td>
<td>$100</td>
</tr>
<tr>
<td>Dragon skin, Smooth-On, Easton, PA</td>
<td>1.08</td>
<td>0–78(^b)</td>
<td>20–850</td>
<td>$85</td>
</tr>
<tr>
<td>Ecoflex 00-10, Smooth-On, Easton, PA</td>
<td>1.03</td>
<td>0–50(^b)</td>
<td>15–110</td>
<td>$105</td>
</tr>
<tr>
<td>HS-IV, Dow Corning, Midland, MI</td>
<td>1.11</td>
<td>0–48(^b)</td>
<td>20–570</td>
<td>$140</td>
</tr>
<tr>
<td>Candle Gel, Endless Possibilities, Oklahoma City, OK</td>
<td>0.98</td>
<td>n/a</td>
<td>50</td>
<td>$35</td>
</tr>
<tr>
<td>Tin-Sil, US Composites, West Palm Beach, FL</td>
<td>1.07</td>
<td>0–82(^b)</td>
<td>10–1400</td>
<td>$200</td>
</tr>
<tr>
<td>Semicosil 921, Wacker Solutions, Adrian, MI</td>
<td>1.10</td>
<td>n/a</td>
<td>25</td>
<td>$110</td>
</tr>
<tr>
<td>8116SS plastic, M-F Manufacturing, Ft. Worth, TX</td>
<td>0.99</td>
<td>0–56(^c)</td>
<td>15–200</td>
<td>$40</td>
</tr>
<tr>
<td>CF11, Nusil Technologies, Carpinteria, CA</td>
<td>1.04</td>
<td>n/a</td>
<td>204</td>
<td>$240</td>
</tr>
</tbody>
</table>
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: 993-1043 m/s

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

- Gel Sample
- Bottom Sheet
- Micromanipulator
- Top Sheet
- Optical table
- Water Pump
Bipac sensor attached to the Micromanipulaor

HP sensor attached to the Micromanipulaor
Micromanipulators

Adjusting Height Plate

Hp Sensor

Load Cell

Micromanipulator
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
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 ~ 0.76 : 3.81 mm
- After 0.12, no differences were observed
Distance after the constriction

HP1 & Biopac

Power [dB]

Freq [Hz]

HP-1D
Biopac-1D
HP-3D
Biopac-3D
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

\[
\frac{\partial p_{\eta}}{\partial t} + \alpha \frac{\partial u_k}{\partial x_k} \delta_{ij} + \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) = 0
\]

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

High-order IBM,
6th order Compact Finite Difference Scheme,
4 stage Runge-Kutta method
Pressure fluctuation is responsible for the murmur generation.

Strong pressure fluctuations are observed beyond 2D downstream of the stenosis.
3D Elastic Wave Simulation

- GelB

\[ L = 7D \]

\[ D_I = 6.22D \]

- 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
Surface Velocity Fluctuations
Surface Acceleration Spectrum

![Image of surface acceleration spectrum with frequency and radial acceleration on log-log scale.](image-url)
• The frequency spectrum of the measured acceleration at the downstream location is plotted along with the computational ones.
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

Thoracic phantom (silicone gel)

Stenosis

Flow fluctuation

Wave propagation

U

L=7D

D

D_T

Re=UD/ν=4000
St=fD/U

EcoFlex-10

ρ=1040 kg/m³
K=1.04 GPa (c_b=1000.0 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 (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