Acoustic Radiation Force Based Imaging: An Overview

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Disclosures

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Learning objectives

• To understand the differences between acoustic images, qualitative elasticity images, and quantitative shear wave images
• To understand the tradeoffs between resolution and accuracy in shear wave imaging
• To understand the limitations of the assumptions made by time-of-flight based algorithms
Elasticity Imaging

Generate images portraying information about the stiffness (elasticity) of tissue:
1) Mechanical excitation
   • External
   • Physiological
   • Focused acoustic radiation force
2) Image tissue response
   • Ultrasound
   • MRI
   • Optical
3) Generate image of tissue stiffness
   • Relative stiffness
   • Quantify tissue stiffness (shear wave speed or elastic moduli)

Why image mechanical properties?
• Manual palpation by clinicians – what do they feel?
  – Masses (e.g. breast, liver, prostate)
  – Pathology (e.g. cirrhotic liver)
  – Large inherent mechanical contrast between soft tissues
• Palpation has limitations:
  – Physical location
  – Size of palpable structure
  – Doctor-to-doctor variability (“hard”, “soft”)
  – Repeatability

Why use acoustic radiation force?
• Focused within organ of interest
• Small strain

Typical soft tissue material properties

<table>
<thead>
<tr>
<th>Material</th>
<th>Young's Modulus, E (kPa)</th>
<th>Shear Modulus, µ (kPa)</th>
<th>Shear Wave Speed (m/s)</th>
<th>Bulk Modulus, K (GPa)</th>
<th>Ultrasonic Wave Speed (m/s)</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fat</td>
<td>0.3</td>
<td>0.1</td>
<td>2.0 - 2.5</td>
<td>1.49 - 1.54</td>
<td>1490 - 1540</td>
<td></td>
</tr>
<tr>
<td>Liver</td>
<td>3.0 - 30</td>
<td>0.3 - 8</td>
<td>0.5 - 2.8</td>
<td>2.2 - 2.5</td>
<td>1490 - 1540</td>
<td>Skeletal Muscle</td>
</tr>
<tr>
<td>Prostate</td>
<td>6.7 - 50</td>
<td>1.4 - 3.9</td>
<td>2.0 - 2.5</td>
<td>1490 - 1540</td>
<td>1490 - 1540</td>
<td>Myocardium</td>
</tr>
<tr>
<td>Fibrotic Liver</td>
<td>30 - 150</td>
<td>3.2 - 10</td>
<td>2.0 - 2.5</td>
<td>1490 - 1540</td>
<td>1490 - 1540</td>
<td></td>
</tr>
</tbody>
</table>

Shear modulus and shear wave speed provide more inherent contrast than bulk modulus and ultrasonic wave speed.

Acoustic Radiation Force

Force generated by a transfer of momentum from an acoustic wave to the medium through which it is propagating, caused by absorption (predominantly) and scattering in soft tissue. Force magnitude typically ~3 g/cm³

\[ F = \frac{2\alpha}{c} \]

\( \alpha = \) absorption coefficient
\( \bar{I}_T = \) temporal average intensity
\( c = \) speed of sound


FEM: Homogeneous Medium

\[ F = \frac{2\alpha}{c} \]

\( \mu = 1 \) kPa, movie duration = 10 ms


Acoustic Radiation Force Impulse (ARFI) Imaging (qualitative)

- Displacement inversely proportional to stiffness
- Relative stiffness (as with strain images)
- Not operator dependent

- Radiation force occurs with all wave propagation
- Increased intensity to move microns
- Diagnostic or HIFU transducers
Typical ARFI excitation:
Frequency = 2–6 MHz
Intensity (sppa\(^{0.5}\), linear) = 1500 – 3000 W/cm\(^2\)
Mechanical Index = 1.5–3.0
Duration < 1 msec
Temperature rise = 0.03–0.1 °C
Tissue Displacement = 10–15 µm

**ARFI – Prostate Imaging**

- Prostate cancer (PCA) facts
  - Affects 1/6 men in the US
  - 2nd leading cause of cancer death in men
- Prostate cancer diagnosis
  - Initially screened through DRE and PSA
  - Confirmed through TRUS guided needle biopsy
    - PCA not visualized in ultrasound
    - Random or systematic sampling
    - Low detection rates
- ARFI imaging a potential tool for targeting needle biopsy and monitoring lesion growth/response to treatment

http://www.cancer.org/Cancer/ProstateCancer/DetailedGuide/prostate-cancer-key-statistics

**Prostate Anatomy and Pathology**

- Normal Prostate
- Adenocarcinoma
  - Grade 5
  - Grade 3
- http://www.ajronline.org/content/188/5/1373/F1.large.jpg
**ARFI - Monitoring Thermal Ablation**

- Thermal ablation increases tissue stiffness
  - Ablated tissues no distinct in ultrasound images
- Elasticity methods can monitor thermal ablation processes:
  - Radio Frequency ablation (RFA)
  - High intensity focused ultrasound (HIFU) ablation
- Cardiac ablations are commonly performed to eliminate aberrant electrical conduction pathways

**In vivo Human Cardiac ARFI imaging of RFA**

- Human Left Atrium (Roof-line)
- AcuNav intra-cardiac transducer and separate RF ablation catheter
- AcuNav imaging catheter in fixed position, moved ablation catheter for ARFI imaging
- Images courtesy of Dr. Pat Wolf
Shearwave Speed Quantification

- Excite tissue with a dynamic stress:
  - Vibrating table or punch
  - Acoustic radiation force
- Evaluate resulting tissue response/shear wave propagation
- Shear wave speed related to shear modulus (i.e. material stiffness), and structures within tissue


Wave Propagation in Soft Tissues

Ultrasound (Pressure)
1540 m/s

Transverse (Shear) 1-5 m/s

Particle motion
Wave propagation

http://www.kettering.edu/~drussell/Demos/waves/wavemotion.html

Estimate shear wave speed with linear regression

Assumptions:
- Known direction of propagation
- Linear, isotropic, homogeneous material

Palmeri et al. UMB, 2008.
**Liver Biopsy**

- Diagnostic gold-standard
  - Invasive
    - Infection
    - Hemorrhage
    - Pain
  - Limited sampling
  - Costly (time and money)
  - Not suitable for longitudinal monitoring of disease progression / resolution

- Can a non-invasive liver stiffness estimate be used as a surrogate measure of liver fibrosis?

**Shear Modulus vs. Fibrosis Stage**

- 4.24 kPa F0-2:F3-4 threshold
- 90% sensitivity
- 90% specificity
- 0.90 AUC

Palmeri et al., J Hepatology (55), 2011

**Commercial Radiation Force Methods**

Products now in commercial market (not in US):
- Siemens 'Virtual Touch Tissue Quantification'®
  - rEI® (qualitative (ARFI) images)
  - qEI® (quantitative SWS measurements)
  - SVI® (quantitative images)
  - Initial release – abdominal probe, now additional probes
- Super Sonic Imagine, SSI Aixplorer® (quantitative images)
  - Initial release - breast probe, now additional probes
Liver Stiffness/SWS Quantification/Fibrosis

Over 400 articles in clinical literature evaluating performance of qEI™ in the context of liver fibrosis staging

Good diagnostic accuracy for the noninvasive staging of liver fibrosis

Friedrich-Rust, J. Viral Hepatitis, 2012
Toshima, J. Gastroenterol, 2011
Crespo, J. Hepatology, 2012
Sporea, Med. Ultrason, 2010

Heterogeneity in thresholds – why?
- Depth within Liver
- Disease etiology (CHC, CHB, NASH/NAFLD)
- Other sources of increases in stiffness (i.e. inflammation, congestion)

SWS Behavior in Heterogeneous Material

Vertical Layer – resolution and precision

Regression kernel size:

- 2 mm kernel
- 5 mm kernel

Resolution (mm)

\[ \Delta \Delta \Delta \] RMS (m/s)
Matched C-plane In Vivo Prostate Images

- Quantitative SWS image is lower resolution
- Concordance between darker ARFI regions and higher SWSs

SSI – Multi-center Breast Lesion Evaluation

939 breast masses; limited SSI to evaluation of BI-RADS 3 and 4a:
- Increased specificity of breast mass assessment from 61.1% (397 of 650) to 78.5% (510 of 650), with \( P < 0.001 \)
- Insignificant improvement in sensitivity

Berg et al. Radiology: 262(2); 2012

Summary – Radiation Force Based Elasticity Imaging

- Clinically available
  - Qualitative methods (ARFI imaging)
  - Quantitative methods (shear wave speed)
- Need large-scale clinical studies and research validation of the quantitative methods
  - monitoring disease progression?
  - monitoring response to therapy?
- Standardization among manufacturers – RSNA/QIBA efforts
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Duke ARFI/Ultrasound Team

3D Shear Wave Imaging Setup
Shear Wave Propagation in Excised Canine Muscle

Muscle SWS (m/s)

- $c_{\parallel} = 3.9 \text{ m/s}$
- $c_{\perp} = 2.5 \text{ m/s}$

Matched C-plane In Vivo Prostate Images

ARFI (Qualitative) SWS (Quantitative 0-6 m/s)

- Quantitative SWS image is lower resolution
- Concordance between dark ARFI regions and higher SWS