Quantitative Ultrasound Imaging: A Historical Perspective

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Motivation

Study Causes of Pre-Term Birth
(Cervical Assessment)

New Imaging Modalities
For Early Detection
And Classification
of Breast Masses

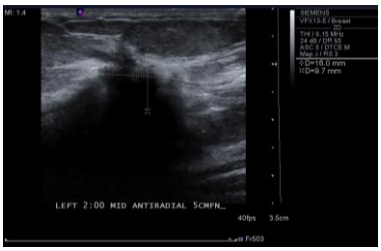
Motivation & Applications

The Clinical Problem

- **1 in 8 women get breast cancer**
  - 2nd most common cancer among women
- **Breast screening with ultrasound (ACRIN 6666)**
  - US is very sensitive
  - Not sufficiently specific
- **Standard for diagnosis – Biopsy**
  - 75% of biopsy results are benign
  - Most costly per capita component of breast cancer screening program
- **More quantitative information from ultrasound imaging**
  - Results are more comparable among imaging systems and sites
  - Imaging becomes more useful for monitoring progression of disease and treatment
  - Easier for healthcare providers to communicate in quantitative statements

Motivation & Applications

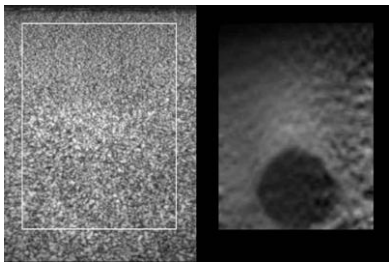
Typical Clinical Breast Ultrasound



Clinicians use images to describe lesion morphology
This lesion is described as "Hypo-echoic" and "Shadowing"

Motivation & Applications

Real-time Freehand Scanning



B-mode Ultrasound | Elasticity (Mechanical Strain)

Methods & Modeling

Generalized Image Formation Model

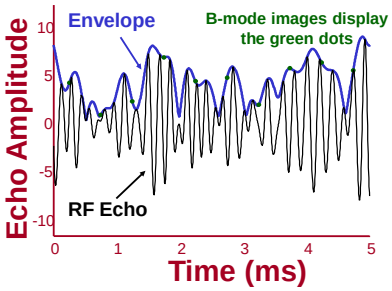
Imaging System Properties → **RF Echo Signal** ← Soft Tissue Properties

RF Echo Signal → Ultrasonic (B-mode) Image

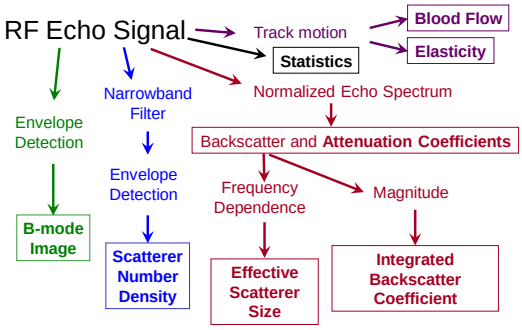
Methods & Modeling

Standard B-mode Imaging

Valuable information is discarded in B-mode imaging



Methods & Modeling



Methods & Modeling

Quantitative Ultrasonic Imaging

- **Analogous to MRI**
  - B-mode ultrasound is like proton density imaging in MRI
    - Images of signal strength
  - MRI has other methods of acquiring and processing data to obtain more information
    - T1 and T2 weighted imaging
    - Diffusion tensor imaging
    - Functional MRI
- **Quantitative ultrasound (QUS)**
  - Attempts to perform QUS have been around much longer (~60yrs)
  - It is a much more difficult problem than in MRI

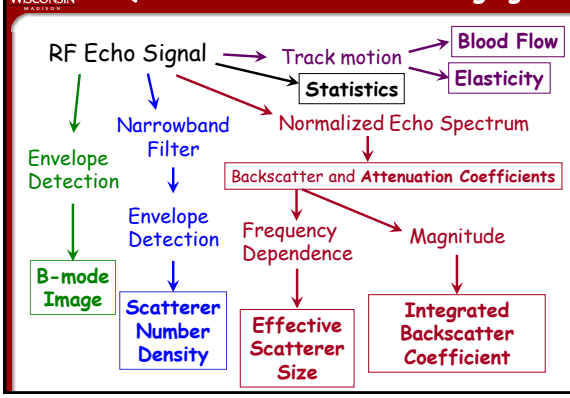
Methods & Modeling

- **We've known for many decades about the limiting conditions in acoustic wave propagation**
  - Compare the size of the scattering source (d) with the acoustic wavelength (l)
    - $\lambda << d$ "specular reflection" (Snell's law)
    - $\lambda >> d$ "Rayleigh scattering" (proportional to $f^4 d^6$)
- **Physics is more interesting between these limiting conditions**
- **Use models for acoustic interactions with tissue to extract physically descriptive parameters**
  - Quantitative ultrasound (QUS)

Quantitative Ultrasonic Imaging (QUS)

- **Multiple Parameters**
  - No "Silver Bullet" (no single parameter is sufficient)
- **Parameters that are Physically-Descriptive**
  - System-Independent
- **Parameters that are Uncorrelated**
- **Parameter combination determined by rigorous statistical arguments**
  - Parameter Selection Based on Hotelling Trace
  - Performance Evaluated with ROC Analysis

Quantitative Ultrasonic Imaging



Approaches to QUS

- To estimate a physically-based absolute parameter that describes acoustic scattering we compare our data to a model
  - A model for what?
- The acoustic backscatter coefficient is an absolute measure of acoustic scattering (echo signal) from a region of interest
  - What is the backscatter coefficient?
  - How can it be estimates/measured?

Models for Acoustic Scattering

- With few assumptions notably:
  - The scattering sources are at a large distance compared to the dimensions of the volume contributing to scattering
  - The scatterers are small compared to the acoustic beam
  - The Born approximation (total pressure ≈ incident pressure)

$$P_s(\mathbf{r}) \simeq \frac{k^2}{4\pi}\frac{P_I e^{ikr}}{r}\int_V \left[\gamma_\kappa(\mathbf{r}_o) + \gamma_\rho(\mathbf{r}_o)\cos\Theta\right] e^{-i\mathbf{K}\cdot\mathbf{r}_o}\, d\nu_o$$

where P_I is the *incident* pressure

P_s is the *scattered* pressure

$\gamma_\kappa = \left(\frac{\kappa_e - \kappa_0}{\kappa_0}\right)\delta\rho$ are the compressibility differences in the scattering volume

$\gamma_\rho = \left(\frac{\rho_e - \rho_0}{\rho_0}\right)\mathbf{v}$ are the density differences in the scattering volume

Θ is the angle between the incident and scattered pressure waves

$\cos\Theta = \hat{\mathbf{i}}\cdot\hat{\mathbf{o}}$

$\mathbf{K} = \mathbf{k}_s - \mathbf{k}_i = k(\hat{\mathbf{o}} - \hat{\mathbf{i}})$

Models for Acoustic Scattering

- We can derive an equation that relates the scattered pressure to the "scattering amplitude"

$$P_s(\mathbf{r}) \simeq \frac{k^2}{4\pi}\frac{P_I e^{ikr}}{r}\int_V \left[\gamma_\kappa(\mathbf{r}_0) + \gamma_\rho(\mathbf{r}_0)\cos\Theta\right] e^{-i\mathbf{K}\cdot\mathbf{r}_0}\, d\nu_0$$

$$\Phi(\mathbf{K}) = \frac{k^2}{4\pi}\int_V \left[\gamma_\kappa(\mathbf{r}_0) + \gamma_\rho(\mathbf{r}_0)\cos\Theta\right] e^{-i\mathbf{K}\cdot\mathbf{r}_0}\, d\nu_0$$

Morse and Ingard call this the "scattering amplitude"

$$P_s(\mathbf{r}) = \frac{P_I e^{ikr}}{r}\Phi(\mathbf{K})$$

- The differential scattering cross section per unit volume in the (180°) backscatter direction is (bsc)

$$\sigma_b = \left|\Phi(2k)\right|^2 / V$$

Sources of Acoustic Scattering

- Inhomogeneities in Acoustic Impedance
  - Density and compressibility differences
- Easily Defined in Test Materials (Phantoms)
  - Spherical glass beads of known properties
  - Calculate the scattering properties from first principles
- Less well-defined in tissues
  - Use very simple models (Gaussian correlation function)
  - Develop more sophisticated models

Models for Acoustic Scattering

- **Model for backscatter**
  - Discrete scatterer model

$$\sigma_b = C\, f^4\, d^6\, \overline{N}\, \gamma^2\, F(f,d)$$

  - Continuum model (continuously varying impedance distribution)

$$\sigma_b = \frac{k^4 \langle \gamma^2 \rangle}{16\pi^2} \int_{\mathcal{V}} d^3\mathbf{\Delta r}\, B_\gamma(\mathbf{\Delta r})\, e^{i2k\Delta r}$$

From Models to Measurements

- **We derived an equation relating the scattered pressure to the acoustic backscatter coefficient (bsc)**
  - The bsc is an absolute measure of "echogenicity"
- **Next we derive a model that describes the scattered pressure in terms of the echo signals we actually record with an ultrasound system**

From Models to Measurements

- 1973: RA Sigelmann and JM Reid, J Acoust Soc Am, 53:1351–1355
- 1981: M O'Donnell and JG Miller, J. Appl. Phys., 52(2):1056–1065
- 1983: FL Lizzi, M Greenebaum, EJ Feleppa, M Elbaum, and DJ Coleman, J Acoust Soc Am, 73(4):1366–1373
- 1981: EL Madsen, MM Goodsitt, and JA Zagzebski, J Acoust Soc Am, 70(5):1508–1517
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- 1984: EL Madsen, MF Insana and JA Zagzebski, J AcoustSoc Am, 76(3):913–923
- 1984: TM Burke, MM Goodsitt, EL Madsen, and JA Zagzebski, Ultrasonic Imaging, 6:342–347
- 1986: WJ Davros, JA Zagzebski, and EL Madsen, J Acoust Soc Am, 80(1):229–237
- 1986: MF. Insana, EL. Madsen, TJ Hall, and JA Zagzebski, J Acoust Soc Am, 79(5):1230–1236
- 1989: TJ Hall, EL Madsen, JA Zagzebski, and EJ Boote, J Acoust Soc Am, 85(6):2410–2416

Models for the Measured Echo

- **Following the methods initially described by Fred Lizzi and colleagues, we relate the average "normalized" power spectrum of the echo signals to experimental parameters**

$$W(k) = \frac{A_o^2 k^6}{(2\pi R_I)^4} \int_{\mathcal{V}} d^3\mathbf{\Delta r} \quad B_H(\Delta x, \Delta y)\, B_g(\Delta z)\, B_\gamma(\mathbf{\Delta r})\, e^{i2k\Delta r}$$

$B_H(\Delta x, \Delta y)$ is the autocorrelation function for the pressure field
$B_g(\Delta z)$ is the autocorrelation function for the gate that selects echo data
$B_\gamma(\mathbf{\Delta r})$ is the autocorrelation function for the tissue scattering properties

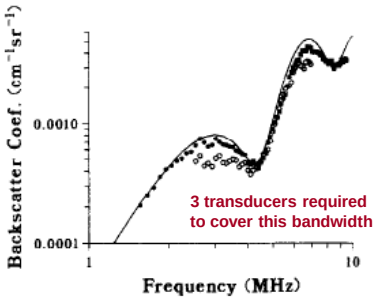
- **With some very reasonable assumptions (operating in the focal zone) we can directly relate this to the bsc**

$$W(k) = (1.36 A_o\, z_c / R_I^2)\, \sigma_b$$

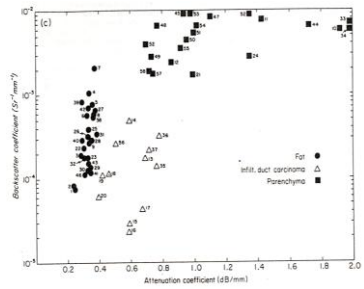
A_o describes the transducer aperture
z_c is the effective gate duration
R_I is the on-axis distance from the transducer to the gate center

Compare Theory and Experiments

- Data fit detailed models (e.g. Faran's theory) when sufficient information is available to accurately model scattering



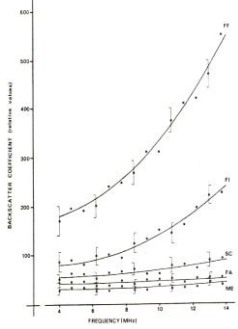
QUS (Backscatter & Attenuation)



D'Astous and Foster, Ultrasound Med Biol 12(10):795—808, 1986

Breast QUS

Landini, et al., Ultrasound Med Biol 13(2):77—83, 1987



Fibro-fatty

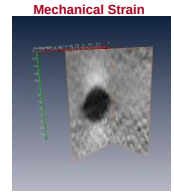
Fibrosis

Scirrhous carcinoma

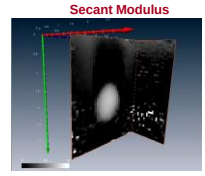
Fatty

What Do We Do? – Develop/Test

Mechanical Strain



Secant Modulus



Benefits of CMUTs
- Higher center frequency possible
- Broader bandwidth
- 3D/4D motion tracking & imaging

Conclusions

- Quantitative Ultrasound (QUS) techniques have advanced considerably over the past 2—3 decades
  - Substantial advances in modeling and algorithms
    - New methods for "old" parameters
    - New parameters that appear to provide robust estimates
  - Substantial improvements in clinical hardware
    - Increased transducer center frequencies
    - Increased bandwidth and electronic SNR
    - 2D arrays (3D/4D imaging) on the horizon
- A solid understanding of the underlying physics as well as the underlying biological processes and variability are essential to advance the field
- Prospects for the future look VERY bright!