Ultrasonic Computed Tomography

- Medical *ultrasound computed tomography*, taken literally, describes the first *pulse echo* ultrasound images (early 50's).
- The term US CT or UCT is used with systems detecting the *transmitted* waves (as in X CT)
- Late 70's, done with movement of single element transducers, later with arrays
- UCT gives quantitative tissue properties, not possible with Pulse Echo

I hope to convince:

- B mode images represent boundaries in tissue properties
- The transmission component of UCT systems allows discrimination of tissues by their bulk properties
  - speed of sound (c)
  - attenuation coefficient (α)
  - density (ρ).
- Any other imaging mode can be made better if you have a map of those properties, particularly “c”
FDA Approved Transmission Tomo Systems for Dx

Typically with synthetic aperture

- Virtual synthetic aperture
- Recons Initially straight line like x-ray CT
- Then bent ray
- Then 2D full wave physics
- Now some 3D recons

Background

- Malignant lesions typically have an elevated sound speed and attenuation coefficient in comparison to other tissues.

Speed of sound and attenuation coefficient of different breast tissues

[Graph showing speed of sound and attenuation coefficient for different breast tissues]
SOS-corrected Stiffness Imaging -2

Table 1. Quantitative Sound Speed and Bi-RADS Criteria for Different Masses

<table>
<thead>
<tr>
<th>Mass/Tissue</th>
<th>Shape</th>
<th>Mass Margin</th>
<th>Sound Speed</th>
<th>Stiffness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cyst</td>
<td>Oval/round</td>
<td>Well circumscribed distinct margin</td>
<td>similar to water</td>
<td>Soft (baker)</td>
</tr>
<tr>
<td>Fibroadenoma</td>
<td>Usually oval/</td>
<td>Usually circumscribed</td>
<td>similar or higher than water</td>
<td>Soft or very soft</td>
</tr>
<tr>
<td>Cancer</td>
<td>Irregular</td>
<td>Microlobulated, indistinct, angular, spiculated</td>
<td>usually greater than water and dense parenchyma</td>
<td>Less than water</td>
</tr>
<tr>
<td>Fatty Tissue</td>
<td>Any shape</td>
<td>n/a</td>
<td>Less than water</td>
<td>Soft</td>
</tr>
<tr>
<td>Dense Parenchyma</td>
<td>Any shape</td>
<td>n/a</td>
<td>Greater than water</td>
<td>Medium SNR</td>
</tr>
</tbody>
</table>

- Attenuation Imaging
  - Attenuation coeff, waveform recon is
    - Higher resolution
    - Less stable than SOS
    - Needs good SNR
  - With accurate reflection and SOS images, can use them & known tissue properties to guide the \( \alpha \) recon.

Helmholtz Eqn., \( k = \omega / c \)

\[(\nabla^2 + k^2)u(\omega, c) = f(\omega)\]

\( u \) is FT of complex valued wavefield

Big matrix inversion for inverse problem solution

Minimize cost function

\[ E(w, c) = \frac{1}{2} \delta d^\dagger \delta d \]

\( \delta d = u - d \) is the data residual, \( d \) the measured field.

Complex SOS \( c = c_r + ic_i \)

Attenuation coeff.

\[-20\ln_{10} 2\pi c_i c_r^2 (dB/mm)\]

Semi Summary

- Transmission tomography, only US -> high res. SOS and physical density maps
- These maps necessary to correct other US imaging modes - > high resolution, quantitative, sensitive, spatially correct
  - Doppler, quasistatic, and shear wave complex elastography,
  - CEUS, texture and speckle measures, photoacoustics
  - Breast, scrotum; soon brain, limbs
- When we find out how good US can be, ...
  - Register whole brain, abdomen, MSK, heart, neck US to CT or MR for corrections
  - Use until body changes too much

Multimodality breast imaging in same and different systems

Breast Light and Ultrasound Combined Imaging (BLUCI)
Transmission & Reflection Ultrasound 360º vs Mammo Geometry

- Breast is suspended in H2O
- With suction stabilizer, can match breast length from breast CT or MR
- Must be large enough to fit largest breast or parts imaged
- Low enough frequency for high SNR through longest dimension, ~20 cm
- Crawl onto table

- Combined DBT/Ultras info
- Max thickness 8-9 cm, adjustable
- Allows higher frequency
  - can penetrate
  - smaller phase shifts
  - smaller area of sources reaching a detector
- Faster recons?
- Transmission requires a priori info.

22 cm dia

In Pulse Echo, Dual Sided:
With small, old transducers, obtained 90% coverage of the breast.
98-100% should be possible.

16 cases with cysts

- Linear fits to simple cysts (black) and complex cysts and solid masses (white)
- 7 cyst cases where mass detectable in single-sided images
- Contrast to noise 67% greater in dual sided images

Eric Larson, et al., Ulit Med Biol 017
Invenia/DBT Fusion
Selenia or Gen II DBT

Single-sided

Lobular CA In Situ

Clinical US, Logiq 8

Invenia Fusion

LCC DBT
LMLO DBT

Invenia ABUS – DBT Fusion

10 Subjects
5 invasive cancers – 4 of them Lobular Carcinomas
All visible on Invenia except:

<table>
<thead>
<tr>
<th>Lesion</th>
<th>Mammo</th>
<th>DBT</th>
<th>ABUS</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Invasive Lobular Ca. (ILC)</td>
<td>N</td>
<td>Y</td>
<td>N</td>
<td>Too deep</td>
</tr>
<tr>
<td>6 mm palpable ILC</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>Too deep, only on hand US</td>
</tr>
<tr>
<td>Complex Cyst</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>Too far back</td>
</tr>
</tbody>
</table>

• Results from combined system are much easier to interpret than from separate.
• Clinical transducer housing limits access near chest wall.
• Imaging in complex tissues only to 4 cm at 10 MHz.
  • Use of a lower frequency setting, or dual-sided imaging would be helpful.

Need dual sided, long transducer, combined system, then could do transmission tomography as well as pulse echo imaging.
Ray-Based Sound Speed Image Reconstruction Algorithm for Ultrasound Limited Angle Tomography For Mammographic Geometry

- Only 1 experimental number, arrival time
- Wavefield recon. requires full received waveform including some scattering

Object’s region of interest (ROI)

Sound speed image reconstruction algorithm

SOS With Dual-Sided US Scanner

- Transmission mode imaging with a priori information (e.g. from segmentation of B-mode image)[5]

SOS (Sound Speed) measurement

Segmented B-mode as a priori info

Reconstructed speed of sound images

Manually supervised and corrected and automated segmentations of fibroglandular tissues

Automated segmentation agreed with BI-RADS density classification by radiologist in 86% of 21 cases.

Manually supervised and corrected classification on 8 cases showed good tissue by tissue agreement.

SE – misclassified pixels as % of all breast pixels
TC – Intersection of sets of manual and automated segmented pixels/union of those sets

SOS Effects of Mis-Segments

Up to ±5% δ SOS for
r/±4 mm radius error, r

Mis-segmentation of
object size

Mis-segmentation of
object position

Mis-segmentation of
nearby object

Up to ±2% δ SOS for
5 mm r, d1 & d2


Inclusion of a Priori Information in Full-Aperture, Full-wave Inversion Quasi 3D Speed of Sound Image Reconstruction

SOS images, in and off center slices, with and without a priori information, presumably from pulse echo images

Yunhao Zhu, Rungroj Jintamethasawat, et al., AIUM, 2017

Existing Reconstruction Algorithm

Speed of Sound Reconstruction Method with A Priori Information

\[ \min_c \left( (d - g(x))^T C_2 (d - g(x)) + (x - c_2)^T C_p (x - c_2) \right) \]

Regularizer acting as a prior information

- \( C_W \): covariance matrix adjusting level of tissue homogeneity
- \( C_p \): data covariance matrix
- \( C_{C_{ij}} = p_{ij} \sigma^2 \) for speed of sound pixels i and j correlated with correlation coefficient \( p_{ij} \), where \( \sigma \) is an allowable change of pixel value
- \( c_2 \): initial speed of sound guess

7/31/2018
Proposed Reconstruction Algorithm

- For total-variation regularization (smoothing) need to split the objective function. Adding the auxiliary term $u$:
  \[
  \min \left\{ (d - g(w))^2 + (w - u)^2 + \lambda \|w\|_1 \right\}
  \]

- Then the objective function can be separated into two sub-problems:
  \[
  \min_{u} \left\{ (d - g(w))^2 (d - g(w)) + (w - u)^2 (w - u) \right\}
  \]
  \[
  \min_{c} \left\{ (c - u)^2 (c - u) + \lambda \|w\|_1 \right\}
  \]

- Both sub-problems are solved alternately

Iterative Reconstruction Workflow

1. Compute RF data
2. Compute deviation
3. Update SOS map
4. Stopping criterion met?
   - Yes: Acquired RF data
   - No: Compute misfit error

Results

Madsinh breast phantom

- Waveform inversion without artifact suppression
- Waveform inversion without artifact suppression
- Bent-ray inversion with artifact suppression
- Bent-ray inversion without artifact suppression
Limited Angle Attenuation Imaging 2D & 3D

- The wave is refracted at impedance discontinuities, reflected towards receiver Rx 2 or away from the undistorted path, or scattered.
- Either can be in or out of the image plane.
- Perform a forward model on the 2D SOS image or 3D stack of SOS images.
- Calculate the energy deflected to miss the receiver elements.
- Subtract that energy from the assumed incident wave.

Note:

- Limited Angle Attenuation Imaging 2D & 3D
- In 2D Model, a priori information is available.
- Weighted least squares model.
- Cylinder in water using a weighted least squares model with a priori information.
- Our linear array problem is more similar to Delphinus than QT ultrasound system, with its capture of some out of plane scattering.

Results

<table>
<thead>
<tr>
<th>Rx 1</th>
<th>Rx 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.35</td>
<td>2.35</td>
</tr>
<tr>
<td>2.35</td>
<td>2.35</td>
</tr>
<tr>
<td>2.35</td>
<td>2.35</td>
</tr>
</tbody>
</table>

Positive contrast: In plane refraction
Negative contrast: In plane refraction
Positive contrast: Out of plane refraction

Bulk Attenuation Coefficient of Tissue

Limited angle attenuation images, with L4-7 transducer, of an attenuating, 13 mm dia., cylinder in water using a weighted least squares model with a priori information.

Our linear array problem is more similar to Delphinus than QT ultrasound system, with its capture of some out of plane scattering.

Numerical breast phantom with masses located off from the imaging plane

\[ \text{SNR} \quad \text{dB/cm}/\text{MHz} \]

\[ \leq 1 \text{ dB/MHz} \]

\[ \leq 2 \text{ dB/MHz} \]

Summary

- Transmission tomography, and US - high res. SOS and physical density maps
- These maps necessary for some other US imaging modes - high resolution, quantitative, sensitive, spatially correct
- But, 3D, 4D, uS, etc., high res. US needs maps of SOS and density images for its software to function well
- We can do the latter well now, it is the other moving parts that need work.

- Prone US & CT or MR of breast vs. combined US & DBT
  - Which is better in which cases - a question between two promising futures
    - Not obvious
      - Short path, low energy vs full aperture in both modalities
      - Convenient standing or sitting vs crawling onto table
    - Do the comparative study, rather than a big one between one of these four modalities and the obvious pair, (where much of our meager clinical trials money goes for short term gain)
    - How get there:
      - Public investment, NIH, etc.
      - User Demand, small companies, or big companies invest heavily to replace what they already sell.
  - Where is the right time?
    - BCT approved for large clinical research studies in USA (2015), for sale in Canada, Australia, European Union
    - Prone UCT FDA approved
    - Combined US & DBT – 5-6 years out

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