Modeling of MR-guided HIFU for Breast and Brain Therapy

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Overview

- High-Intensity Focused Ultrasound (HIFU) Surgery
  - Critical needs: locating the beam; full 3D temperature images; accurate beam modeling

- Beam Modeling with Hybrid Angular Spectrum (HAS) Method

- Application to Brain and Breast
  - Phase aberration correction
  - Incorporating absorption and scattering
Critical Need 1: Locating Beam

Use Acoustic Radiation Force Imaging (ARFI) with MRI at geometric focus in phantom:

ARFI

temperature

steered 5,5,5 mm in phantom:

ARFI

temperature

coronal

sagittal
Critical Need 2: Measure Temperature throughout Full 3D Volume

Ultrasound Parameters:
- 256-element transducer
- 30-s single point sonication
- 48 W

MR Parameters:
- 36 slices
- 8x undersampled
- 1.25 x 1.25 x 3.0 mm
- 1.8 sec / frame
- TR / TE = 25 / 11ms
- EPI 9
- 240 x 158 x 108 mm

Use Model Predictive Filtering with an acoustic and thermal model
Experimental Results: 3D Temperature Measurements

coronal  transverse  sagittal

ex vivo meat  agar phantom  skull segment  transducer

Nick Todd et al., Mag Res Med 2010, 63(5), 1269-1279
Critical Need 3: Accurate Ultrasound Beam Simulations

- Needed for:
  - Treatment planning
  - Safety assurance
  - Transducer design
  - Phase aberration correction (skull and breast)

Bone metastases:

InSightec Ltd, Israel
3D Ultrasound Beam Modeling Methods

• Homogeneous Media:
  – Rayleigh-Sommerfeld integral
    • Classic, accurate

• Inhomogeneous Media:
  – Finite-Difference Time-Domain (FDTD)
    • Transient and steady-state behavior, fine grid, slower
  – Hybrid Angular Spectrum (HAS)
    • Steady-state, linear, fast
    • Leapfrogs between space and spatial-frequency domains
space domain

transducer $p_t$

Rayleigh-Sommerfeld integral

$p_0$

plane 1

plane 2

plane n…

equivalent thin layers

inhomogeneous tissue

projection direction

Hybrid Angular Spectrum (HAS)

spatial-frequency domain
(angular spectrum)

FFTF

$A_1^{-1}(\alpha, \beta)$

linear propagation filter

$A_1(\alpha, \beta)$

FFT$^{-1}$
HAS Method

• Comparable to FDTD results within 2.8% (3D breast model).*

• Two orders of magnitude faster:
  FDTD – 67 min  HAS – 9.5 sec

• Example simulation:
  transducer: 1.5 MHz  beam direction
  3D model: 141 x 141 x 161

3D pressure pattern:

*wVyas, U. and Christensen, D.,
IEEE Trans UFFC, 59 (6), 1093-1100 (2012)
Application of Beam Modeling to Transcranial Treatments

InSightec 650-kHz ExAblateNeuro

Variable skull thickness in beam path leads to phase aberration
Phase Aberration Correction through Skull

512 x 348 x 488 model
0.6 x 0.43 x 0.43-mm resolution

1024-element phased array

impose negative of phase

With parallelization on GPU, total phase correction took 183 seconds
Pressure Patterns through Skull

no phase correction

Max pressure at focus - $2.4 \times 10^5$ Pa normalized to 8 W total

phase correction

Max pressure at focus - $6.6 \times 10^5$ Pa
Power Deposition Q Patterns through Skull

Max Q at focus- 2500 W/m³
Ratio $Q_{\text{focus}}/Q_{\text{skull}}$ - 0.51

Max Q at focus- 18,000 W/m³
Ratio $Q_{\text{focus}}/Q_{\text{skull}}$ - 2.4
Experimental Results for Phase Correction

- Experimental setup:
  - 3D-printed plastic skull model
  - Random variations in thickness
  - Phase shifts up to $2\pi$
Experimental Setup to Test for Phase Correction

- MRI compatible HIFU device with 256-element phased-array transducer (Image Guided Therapy, Imasonic)
- Plastic pseudoskull on bottom of agar phantom
- Temperature measurements with MRTI (prf method)
Temperature Results with/without Phase Correction

no phase correction

phase correction

coronal

transverse

sagittal
Application to Univ. of Utah Breast HIFU System

Univ. of Utah Breast-Specific Treatment Cylinder

256-channel phased-array transducer (Imasonic)

integrated 11-channel RF coil (Univ. of Utah)*

Univ. of Utah Breast-Specific HIFU System

- Siemens Trio 3T MRI
- Ultrasound power drivers
- MRI bore
- Phased-array transducer
Phase Aberration Correction in Breast

- Develop full 3D tissue model
  - Segment tissues with multiple contrasts
  - Estimate acoustic properties for each tissue type
  - Model beam propagation using HAS
  - Adjust transducer element phases

Alexis Farrer, ISTU 2013, poster 28
Example of Phase Correction in Breast

Pressure patterns

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Adding Scattering to HAS Algorithms

Provides more accurate modeling of attenuation

Models:

- **A: Implicit** \( \alpha_{abs} < \alpha_{total} \)
  - Pressure drop due to total attenuation coefficient
  - Power deposition (heating) due only to absorption coefficient

- **B: Explicit (within voxel)**
  - Explicit random scatter fraction within each voxel
  - Scattered wave modeled

- **C: Explicit (variations larger than voxel)**
  - Variations in speed of sound, attenuation, density
  - Tissue-specific with normally distributed variations
A. Implicit: Separate Attenuation into Two Components

Typical: attenuation = absorption

\[ p_2 = p_1 e^{-\alpha_{\text{total}} D_z} \]

Improved: attenuation = absorption + scattering

\[ p_2 = p_1 e^{\left( -\alpha_{\text{abs}} + \alpha_{\text{scatt}} \right) D_z} \]

- heat
- scattered power
A. Implicit: Transcranial Power Deposition Patterns

No scattering:
absorption = total attenuation
skull att = 2.1 Np/cm; brain att = 0.06 Np/cm
frequency = 1.0 MHz

With scattering:
absorption < total attenuation
skull abs = 50% att*; brain abs = 80% att*
skull sca = 50% att*; brain sca = 20% att

peak power brain/peak power skull = 0.29
peak power brain/peak power skull = 0.47

B. Explicit: Small Scatterers within Each Voxel

Scattered beam pressure pattern alone in breast (volume with scattering – volume without scattering)

$\alpha_{\text{scatter}} = 40\% \ \alpha_{\text{total}}$
C. Explicit: Larger Property Variation across Voxels

Scattered beam pressure pattern alone in breast (volume with scattering – volume without scattering)

standard deviation = 2%, correlation length = 6 mm
C. Explicit – Effect of Scattering on Focused Spot

- Peak pressure at focus = 85% of no-scattering value
- Focused spot size blurred
Future Plans

• New NIH grant: Improvements in breast system (coils, cylinder)
  – IDE approval
  – Heading toward clinical trials

• Continuing NIH grant: Rapid 3D temperature mapping in brain
  – Model Predictive Filtering
  – Estimation of tissue parameters for treatment planning and assessment

• Collaborations (FUSF): Validation of simulations
  – Mapping of CT Hounsfield units to acoustic parameters
  – Continued ARFI development
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Thank you -
Any questions?
High-Intensity Focused Ultrasound (HIFU) Surgery

Critical needs:

• Treatment planning
  – Beam localization
  – Beam modeling
    • Phase and attenuation correction
    • Beam profile/SAR prediction: Optimize delivery of energy to treatment position
    • Minimize heating of adjacent and near-field tissues

• Treatment Control
  – 3D Temperature monitoring
  – Tissue damage assessment (Todd et al., ISTU 2013 Tuesday)

3D MR-ARFI; 3D MRTI

3D MRTI (MR Temperature Imaging)
3D MRI temperature measurements

MPF: Experimental results

2-D Skull Surface Projection

Coronal

- Temperature Rise (°C)
- Time (sec)
- Focus
- Skull Surface

Color Scale:
- 5° C
- 4
- 3
- 2
- 1
- 0
- -1
- -2

Utah Center for Advanced Imaging Research
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HAS for beam phase correction

3D Vibe with Contrast

axial  sagittal  coronal

- Develop fully 3D tissue model
  - 3D MRI covering full volume
  - 1-mm isotropic resolution, ZFI to 0.5 mm spacing
HAS for beam phase correction

- Develop fully 3D tissue model
  - Multiple image contrasts
  - Zero-fill interpolate to 0.5-mm isotropic spacing

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HAS for beam phase correction

- Develop fully 3D tissue model
  - Segment tissues

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HAS for beam phase correction

- Estimate acoustic properties for each tissue type


<table>
<thead>
<tr>
<th>Tissue Type</th>
<th>Density (kg/m³)</th>
<th>Speed of Sound (m/s)</th>
<th>Attenuation (Np/cm*MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>1000</td>
<td>1500</td>
<td>0</td>
</tr>
<tr>
<td>Skin</td>
<td>1100</td>
<td>1537</td>
<td>0.28</td>
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<tr>
<td>Breast fat</td>
<td>928</td>
<td>1436</td>
<td>0.07</td>
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<tr>
<td>Fibroglandular tissue</td>
<td>1058</td>
<td>1514</td>
<td>0.09</td>
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<tr>
<td>Tumors/Fibroadenoma</td>
<td>1041</td>
<td>1584</td>
<td>0.081</td>
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<tr>
<td>Nipple cover</td>
<td>937</td>
<td>1480</td>
<td>0.086</td>
</tr>
</tbody>
</table>
HAS phase aberration correction in pseudoskull

- Calculated phase offsets to match measured thickness from HAS model
HAS beam modeling

256 element phased array (Imasonics, Inc.)
1 MHz, 13cm radius of curvature
Hybrid Angular Spectrum (HAS) method
Focal spot ~ 2mm x 13mm

Generally thinner than reality
Adding scattering to HAS:

- Creates a more realistic picture of transcranial heating
- Provides more accurate model of beam propagation in scattering media
- Will lead to:
  - more accurate understanding of beam focusing for all HIFU applications
  - More accurate SAR prediction